OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

ORNL-NSIC-65
UC-80 — Reactor Technolog

DESIGN, CONSTRUCTION, AND TESTING OF HIGH-EFFICIENCY AIR FILTRATION SYSTEMS FOR NUCLEAR APPLICATION

C. A. Burchsted and A. B. Fuller

NUCLEAR SAFETY INFORMATION CENTER
NSIC

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Preface

The Nuclear Safety Information Center was established in March 1963 at the Oak Ridge National Laboratory under the sponsorship of the U.S. Atomic Energy Commission to serve as a focal point for the collection, storage, evaluation, and dissemination of nuclear safety information. A system of keywords is used to index the information cataloged by the Center. The title, author, installation, abstract, and keywords for each document reviewed are recorded on magnetic tape at the central computer facility in Oak Ridge. The references are cataloged according to the following categories:

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Foreword

This handbook fills a large gap in the literature concerning air cleaning and filtration, the gap that encompasses design, construction, and testing of very high-efficiency air-cleaning systems. The project was originally conceived by Mr. Humphrey Gilbert of the USAEC and was sponsored by the Division of Reactor Development and Technology of the USAEC. In preparing for the project we surveyed air-cleaning systems at atomic energy facilities and industrial installations throughout the United States and Canada. We visited AEC production reactors, commercial power reactors, laboratories, radiochemical plants, reactor fuel manufacturers, clean rooms, equipment manufacturers, and one chemical-biological warfare installation. The purposes of these visits were to review current practices in high efficiency air cleaning and to define the problems in operating, maintaining, and controlling contamination release from very high-efficiency air-cleaning systems from experienced people who were dealing with such problems daily. The handbook reflects a consensus of our findings in these travels, in addition to information gleaned from the available literature.

The handbook is addressed primarily to designers and architect-engineers. We frequently observed a lack of communication and feedback from people with problems in the field to designers. Our intention is to bring to the attention of designers of future systems the kind of problems that an operator faces and what he, the designer, must do to preclude or alleviate them. We have purposely pointed out some poor practices in current design in addition to our recommendations in .he hope that such practices will go no further. To give "do's" without "dont's" may encourage some designers to offer a poor design because he mistakenly believes that "it worked before."

Those who have contributed to the handbook number literally in the hundreds and include those we consulted with and those who have given of their time in reviewing drafts or have supplied specific bits and pieces of information. We take this opportunity to thank the many friends we have made in the course of this project, particularly for their candidness in discussing problems and ways of solving those problems, and for their help in supplying photographs and information. In particular we want to thank Mr. Humphrey Gilbert and I. Craig Roberts of the USAEC for their guidance, W. B. Cottrell of ORNL for his help in getting the book published, T. F. Davis of the USAEC's Division of Technical Information for his assistance in indexing the material, J. H. Waggoner of ORNL for doing the illustrations, and Dr. M. W. First of Harvard University for his meticulous page-by-page review of the draft and suggestions for this final issue.

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Oak Ridge, Tennessee
July 10, 1969

1. Introduction

1.1 BACKGROUND

A high-efficiency air filtration system is one which has a particle collection efficiency or "arrestance" approaching 100% for 0.3-μ particles.[1] Systems fall into one of two general categories: clean-air systems, which limit the airborne contaminants reaching the critical operating area, and contaminated exhaust systems, which reduce the concentration of airborne contaminants in the air released from hazardous operating areas. This handbook deals primarily with contaminated exhaust air cleaning systems for nuclear plants, laboratories, and reactors, and other facilities in which radioactive materials are handled.

The prevention of airborne contamination is fundamental to the safe and economic operation of nuclear facilities. Although the health and safety of plant personnel and the public are primary, the high costs of decontamination in the event of an accidental release of radioactive material and the possibility of extended or even permanent shutdown of the facility are also important considerations. Radioactive substances, even in extremely low concentrations by weight or volume, represent a hazard to human health and must be closely controlled.[2] The radioactivity of such substances is often long-lived, and the few countermeasures that can be taken to neutralize it are of limited use. Radioactive substances tend to "plate out" on ducts, components, and other surfaces so that, in time, these surfaces themselves become sources of ionizing radiation and severely complicate maintenance and service of a facility. These problems are of particular concern in reactors and nuclear fuel reprocessing plants because of their potential for releasing very large amounts of radioactive materials in the event of a system malfunction or accident, and they will become even more important as such plants become larger, more numerous, and sited closer to populous areas.

1.2 SCOPE

There are no published standards for the design and construction of nuclear plant exhaust systems. Information available on the subject is mostly in the form of topical reports, technical papers, and job specifications that are not readily available. The purposes of this handbook are to summarize the available information in a manner which is useful to the designer, to point out shortcomings in current practice, and to provide guides for future design. The handbook summarizes the findings from an extensive survey of the literature and of air cleaning practices at atomic energy and industrial plants and laboratories throughout the United States and Canada. The judgments and recommendations presented reflect the experience of users and stem from conditions that exist in actual systems where problems of operation, maintenance, and system reliability are being met on a day-to-day basis, often in situations where personnel have had to live with, or adapt to, serious deficiencies in design or construction.

The handbook is limited to the mechanical design, construction, and testing of air cleaning systems. Functional design, including the sizing of systems and establishing the components required for a particular application, is beyond its scope. The design of the ventilating system, of which the air cleaning system is but one part, is also beyond the scope of the handbook except as the ventilating system affects the operation or reliability of the air cleaning system or, conversely, as the air cleaning system affects the ventilating system. Functional design of ventilating systems is covered in Safety Monograph No. 17 of the International Atomic

[1] The value of 0.3 μ is based on the availability of a reproducible, nontoxic, nonexplosive (in the concentrations used), monodispersed aerosol and on the fact that particles in the 0.1-to-0.3-μ size range are thought to be the most difficult to remove from air and gas streams.

[2] "Standards for Protection Against Radiation," *Code of Federal Regulations,* Title 10, Pt. 20 (10-CFR-20), U.S. Atomic Energy Commission.

Energy Agency,[3] *Industrial Ventilation,*[4] USA Standard Z9.2,[5] the *ASHRAE Guide and Data Book,*[6] and numerous texts. Nor does the manual cover the theory of air filtration or adsorption; these topics are discussed in a state-of-the-art report issued by the Oak Ridge National Laboratory[7] and in a textbook entitled *High Efficiency Air Filtration,* by Smith and White.[8] The use of high-efficiency air cleaning as an engineered safeguard in water-cooled nuclear reactors is discussed in USAEC report ORNL-NSIC-25.[9]

1.3 THE DESIGN PROBLEM

Even in nonnuclear applications the problems of achieving a reliable, truly efficient air cleaning system are substantial. The best filters used in conventional air-conditioning and ventilation systems have efficiencies of no more than 80 to 85% for 0.3-μ particles — that is, at least 1500 to 2000 of every 10,000 entering particles of this size would penetrate the filter. Most of the filters used have substantially lower efficiencies, some as low as 5% for these small particles. By contrast, the HEPA[10] or "absolute" filter required in high-efficiency air cleaning systems has a minimum efficiency of 99.97% for 0.3-μ particles (i.e., a maximum penetration of three particles in 10,000). Similarly, the activated-charcoal adsorbers associated with some reactor and radiochemical plant systems also require efficiencies much higher than those needed for nonnuclear applications. It is obvious that design and installation practices suitable for lower-efficiency air-conditioning and ventilation system air cleaning would be highly questionable for high-efficiency systems, and they have, in fact, proven grossly inadequate.

The problem is complicated in nuclear applications by the hazard presented by radioactive materials, even in minute concentrations. In the conventional system dust, chemical fumes, and other contaminants can usually be detected by the human senses before they reach concentrations that represent a serious threat to health or safety. The situation is quite different in nuclear systems because of the complete insensitivity of the human senses to the presence of radioactivity, even at levels which are a danger to life. The lowest threshold limit value (TLV) specified for chemical contaminants by the American Conference of Governmental Industrial Hygienists[4] is orders of magnitude higher than the maximum permissible concentration of any radioactive material.

The design problem in nuclear systems is further complicated by the very real hazard of contaminating facilities or the surrounding countryside in the event of an accidental release, as occurred in the Windscale reactor accident in Great Britain a few years ago. Many radioactive particles are of a size that may be widely dispersed by the wind and readily ingested by man, livestock, or wild animals. Because of this hazard and their tendency to adhere to the surfaces they fall on, even a small release of radioactive material, in terms of weight or volume, could shut down a costly facility for an extended period of time, or even permanently. The costs of decontamination can literally be thousands of times the losses due to ordinary hazards such as fire or explosion, as illustrated by the loss experience in a small glove box accident at an AEC laboratory:[11]

Loss due to fire:	$100
Loss due to explosion:	500
Cost of cleanup and decontamination:	76,200

The designer must have a factual appreciation for these order-of-magnitude differences between nuclear plant exhaust systems and conventional air-conditioning and ventilation systems. Concentrations of radiotoxic materials in the air cannot be maintained at safe levels if the selection, design, or layout of the equipment or installation is in the least deficient. Some operations in the past have relied to some extent on dilution of

[3] *Techniques for Controlling Air Pollution from the Operation of Nuclear Facilities,* International Atomic Energy Agency, Vienna, Safety Series No. 17, 1966.

[4] *Industrial Ventilation,* American Conference of Governmental Industrial Hygienists, Lansing, Mich., 8th ed., 1964.

[5] U.S.A. Standard Z9.2-1960, *The Design and Operation of Local Exhaust Systems,* American Standards Institute, New York, 1960.

[6] "Industrial Ventilation," chap. 3, and "Industrial Exhaust Systems," chap. 20, *ASHRAE Guide and Data Book – Applications,* American Society of Heating, Refrigeration, and Air-Conditioning Engineers, New York, 1968.

[7] G. W. Keilholtz, *Filters, Sorbents, and Air Cleaning Systems as Engineered Safeguards in Nuclear Installations,* USAEC Report ORNL-NSIC-13, Oak Ridge National Laboratory, October 1966.

[8] P. A. F. White and S. E. Smith, eds., *High Efficiency Air Filtration,* Butterworth & Co., London, England, 1964.

[9] G. W. Keilholtz, C. E. Guthrie, and G. C. Battle, Jr., *Air Cleaning as an Engineered Safety Feature in Light-Water-Cooled Power Reactors,* USAEC Report ORNL-NSIC-25, Oak Ridge National Laboratory, September 1968.

[10] HEPA = high efficiency particulate air.

[11] "Hazardous Solvent Use Causes Explosion in Glove Box," *Serious Accidents,* U.S. Atomic Energy Commission, Issue No. 261, Feb. 25, 1966.

airborne radioactive wastes with large volumes of air, followed by dispersal in the atmosphere. This practice, as nuclear plants become larger and more numerous, becomes unacceptable,[12] and most operations now place great emphasis on positive removal of radioactive fumes and particles from exhaust air and gases by means of well-designed filter and adsorber installations.

It has not been uncommon for high-efficiency air filtration systems to be designed by persons having little or no knowledge of the specialized requirements of such systems. The facility designer often has done no more than establish flow and capacity requirements, leaving the details of air cleaning system design to the mechanical designer; too frequently, the latter, in turn, has done little more than select components and establish a nominal system layout, leaving the details of installation and construction to a sheet-metal contractor. The facts that there are no published standards and that conventional installation and construction practices have proven inadequate make it very unlikely that a sheet-metal contractor will have the specialized knowledge and experience necessary to design a system of this type or be able to build one meeting the user's requirements without detailed drawings and specifications. Vital design decisions and critical construction details should be the responsibility of persons familiar with the exacting details of such systems if the result is to be an adequate, reliable, economic system.

1.4 THE COORDINATION PROBLEM

The constructor cannot be expected to supply any more than the minimums called for in the drawings and specifications. He cannot be expected to build a system having the special features and requirements of a nuclear plant exhaust system from fragmentary or incomplete design details and specifications. It is the facility designer's responsibility to interpret the owner's needs and to develop usable and accurate system criteria. It is the mechanical designer's responsibility, in turn, to interpret these criteria into detailed drawings and specifications that can be followed by workmen not having previous experience in this specialty. It is also the mechanical designer's responsibility to ensure that the system, as built, will meet the owner's needs in terms of a safe, effective, reliable, and maintainable system.

An example of poor coordination was seen in the example of a reactor exhaust system presently under construction. In the initial planning stage, the facility designer allowed a nominal 12 ft for a bank of 24 × 24 in. filters, six wide. No change in the dimension was made by the mechanical designer, and the drawings went to the constructor, who proceeded to pour concrete. The problem, of course, is that a bank of 24 × 24 in. filters, six wide, should be installed in a housing at least 151 in. wide (preferably 158 in.) in order to provide sufficient room for a reliable filter mounting frame and for ease of filter changing. This type of error should have been corrected at the mechanical design stage, before it was "cast in concrete."

It is also important for contractual relationships to be carefully defined in the specifications, and then enforced. If the constructor is to be made responsible for the performance of the completed system, the method of testing, the parties who will make and evaluate the tests, their demonstrated knowledge and experience, and the steps that will be required to correct deficiencies must all be carefully spelled out. It is not enough to merely specify that a system will meet a 99.95 or 99.97% in-place DOP test. Requirements of this nature must be carefully followed during preparation, review, and contractual acceptance of the drawings and specifications, as well as during the performance of work under the specifications, if the system is to meet its intended service requirements.

1.5 THE COST PROBLEM

Shortcuts and compromises with good design practices result in unduly high operating costs throughout the life of the system, to say nothing of reduced system reliability and performance. A common error in the planning and design of nuclear plant exhaust systems is the placement of too much emphasis on first (i.e., capital) costs in the initial planning. Minimizing capital costs often results in high operating and maintenance costs when desirable features are omitted or when sacrifices are made in the amount or quality of space provided for filters and mechanical equipment. Operating and maintenance costs, when considered over the life of the system, usually far outweigh the costs of building the system. A survey by the Harvard Air Cleaning Laboratory showed that operating and maintenance costs accounted for more than 85% of the total cost of owning nuclear plant air cleaning systems, based on 20-year amortization.[13]

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[12] J. D. Abbatt, "World Health Considerations in Airborne Pollution with Special Reference to Radioactive Wastes," *Treatment of Airborne Radioactive Wastes*, International Atomic Energy Agency, Vienna, 1968.

[13] M. W. First and L. Silverman, *Nucl. Safety* 4(1), 61–66 (September 1962).

Errors are sometimes made in choosing between candidate methods of accomplishing a desired objective because of failure to consider all aspects of cost. In estimating capital costs, for example, the costs of the filter housing, special dampers, fire-protective facilities, clothing-change facilities, and other factors are frequently overlooked in comparing the relative costs of various types of prefilter. Neglecting consideration of performance differences in the air cleaning system as a whole, lower efficiency filters might be chosen because of lower cost where just the filters, their mounting frame, and change frequency are considered. However, the differences in cost between lower and higher efficiency prefilter systems, when all factors are considered, including prolonged HEPA filter life, may be negligible and often favor the higher efficiency installation. Often in estimating labor costs, only the "do" phase of the job is considered, and the "make ready" and "put away" phases, including clothes change, health physics monitoring, and cleanup are neglected; the latter in some cases may increase the actual costs of each filter change to as much as a dollar per cubic foot per minute of installed filter capacity. Other factors frequently overlooked in cost estimates are escalations of labor and materials costs and filter change frequency with various combinations of HEPA filters, prefilters, bank size, flow rate, and so on. (A form for estimating capital and operating costs and a form that breaks a filter change down into at least its major elements are given in Appendix A.)

1.6 THE FLEXIBILITY PROBLEM

A shortcoming often encountered in nuclear plant exhaust system designs is failure to anticipate that the system may need to be changed. In nuclear reactors and other facilities that have a fixed function throughout the life of the facility, the lack of flexibility may not be a problem. In radiochemical plants, and particularly in laboratories and experimental facilities, however, change is often "the order of the day," and provision for future system changes in the initial design can pay for itself many times over. Rebuilding of radioactively contaminated ducts, filter mounting frames, and housings is costly and hazardous at best, and can be even more costly and more hazardous where some flexibility has not been left in the initial system design. Because of the radioactivity problem, the costs of modifying or rebuilding a nuclear plant exhaust system may run five to ten or more times the cost of similar work carried out under nonradioactive conditions. Provision for expansion of a system, including extra housing space, additional tie-on points, oversized filter mounting frames which provide excess filter capacity, and excess fan and motor capacity, should at least be given serious consideration in initial planning.

Temporary systems may not justify the extra capital cost of providing for flexibility. However, the designer should keep in mind that temporary systems often become permanent or are adapted for other purposes, and short cuts in the original design that make later modification difficult can be very costly to the owner in the long run.

1.7 PURPOSE

The information given in this handbook will not substitute for a basic knowledge and understanding of air-handling system design and construction. It will supplement the designer's previous knowledge in this specialized branch of the field. It is hoped that, by the use of this manual, the experienced engineer will be better able to evaluate an owner's requirements and be better able to establish essential system criteria; that an experienced mechanical designer will be better able to translate these criteria into effective system designs; and that constructors will be provided with the background to effectively carry out the intent of such designs to provide safe, reliable systems at reasonable cost. It is also the objective of this manual to provide information which may serve as a starting point for the development of future standards for nuclear plant exhaust systems and to provide "ammunition" for the engineer, the manager, and the designer for justifying the sometimes more costly, but necessary, features required for a reliable and effective high-efficiency air cleaning system.

2. Problem Areas

2.1 INTRODUCTION

The design of the air cleaning system has a direct bearing on the performance and operating costs of the ventilating system of which it is a part. Conversely, the design of the ventilating system directly affects the performance and costs of the air cleaning system. This chapter discusses, in general terms, some of the problems which have been experienced in these areas; specific solutions of these problems, however, depend on the circumstances of the individual case.

2.2 OPERATIONAL CONSIDERATIONS

2.2.1 Operating Mode

According to the requirements of the facility served, the air cleaning system may be operated full time or part time or may be held in standby for emergency service. If the facility is in operation for only one or two shifts a day, the designer has a choice between continuous and full-time operation and must evaluate the effect of daily starts and stops on the performance and life of filters and other components vs the higher power and maintenance costs for continuous operation. Experience shows that, all factors considered, continuous operation, even during off-shift hours, is the most satisfactory mode of operation for nuclear plant exhaust systems. Unless ducts, filter housings, and fan casings are leak-tight, outleakage of contaminated dust into occupied areas may occur during the shutdown periods.

High-hazard facilities often require standby exhaust systems that are operated only in the event of an emergency or when a parallel on-line system is shut down because of failure or maintenance. In designing standby systems the engineer must keep in mind the possibility of corrosion and filter deterioration, even though the system is not in use, and must make provision for periodic ventilation of the system, inspection, and testing. Operation of the system for 15 to 30 min each week is recommended. Routine testing of filters and adsorbers is fundamental to safe, reliable operation and is recommended at least once every 6 to 12 months. This requires that permanently installed injection and sampling ports be included in the original design (Chap. 7) and that adequate space be provided adjacent to the filter housing for testing equipment.

2.2.2 Filter Change Frequency

The principal costs in operation of an HEPA filter system are for the replacement filters and labor, and the principal factor affecting these costs is the frequency of changing HEPA filters. Replacement filter and labor costs may total as much as 70% of the total cost of owning a system (including capital costs) over a 20-year period.[1] Measures such as the use of high-efficiency building supply filters, the use of prefilters, operating the filter system below its rated capacity, and operation of filters to a high pressure drop before replacement, as discussed later in this chapter, all tend to decrease filter change frequency and thereby reduce cost.

2.2.3 Building Supply Filters

Atmospheric dust brought in with the building supply air constitutes a substantial fraction of the dirt load in most buildings. Since nuclear plant exhaust systems are, in most cases, once-through rather than recirculating, there is no cleanup of the air within the building, and atmospheric dust brought into the building is continuously transferred to the exhaust filters. Removal of this dust before it gets inside the building has the double advantage of protecting the exhaust filters from an avoidable dust load and of reducing janitorial and building maintenance costs. Where operations within the building do not generate heavy concentrations of smoke, dust, or lint, it may be possible, by providing

[1] M. W. First and L. Silverman, "Cost and Effectiveness of Air-Handling Systems," *Nucl. Safety* 4(1) (September 1962).

moderately efficient (50 to 80% NBS) supply filters, to dispense with prefilters in the exhaust system, thereby shifting the major burden of prefilter replacement from the "hot" (i.e., radioactive) exhaust system to the "cold" (i.e., noncontaminated) building supply system; the cost of replacing cold filters is a small fraction of that of replacing hot filters.

Noticeable decreases in janitorial costs have been observed in several AEC installations after changing to higher efficiency building supply filters. There is a definite trend toward using better filters in commercial buildings also. One building operator reported that the time interval between major cleaning and repainting operations had doubled after replacing his original low-efficiency panel filters with more efficient (60%) extended-medium filters.[2]

Louvers or moisture separators, or both, must be provided to protect supply filters from the weather. Rain, sleet, snow, and ice can damage the filters and increase operating costs. Heaters may be desirable even in ostensibly warm climates. Icing has caused severe supply filter damage at a number of AEC installations, even in the South. Screens should be provided over supply air inlets located close to the ground to protect the moisture separators and filters from grass clippings, leaves, and windblown trash.

2.2.4 Prefilters

HEPA filters are intended primarily for submicron particle removal and are not coarse dust collectors. They have low dust capacity and may plug rapidly when exposed to high concentrations of dust, smoke, or lint. The HEPA filter is also the most important element in the exhaust system from the standpoint of particle removal, and its failure will result in failure of the system. Prefilters, installed either locally at the entrances to the duct or in the central exhaust filter housing, extend the life of the HEPA filters and provide a measure of protection against damage. The theoretical increase in HEPA filter life by using prefilters is illustrated by Fig. 2.1. The actual increase, of course, depends on the quality of the prefilter selected and the nature and concentration of dust.

As a general rule, a prefilter should be provided when the dust loading to the exhaust system exceeds 10 grains per 1000 ft^3 and should be at least considered where the concentration exceeds 1 grain per 1000 ft^3.[3]

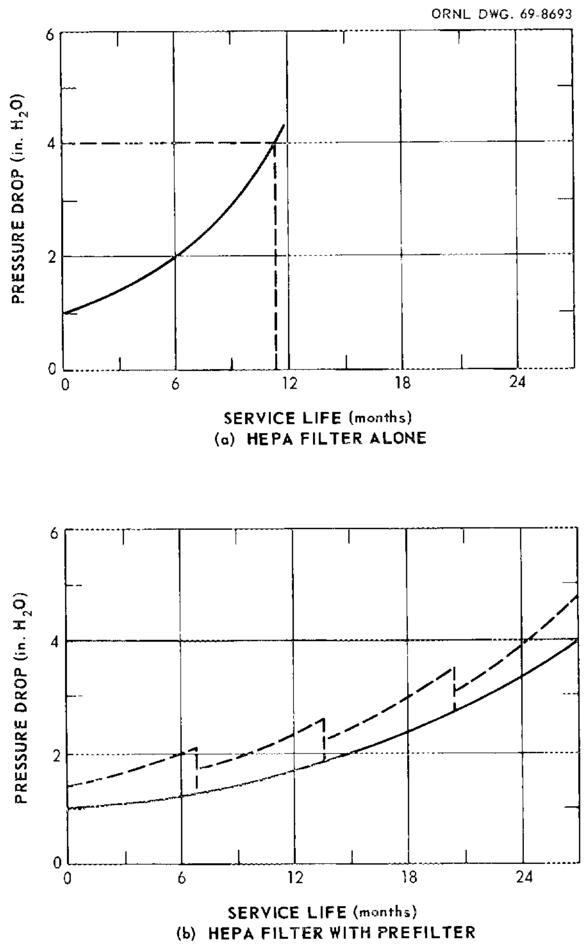

Fig. 2.1. Comparison of HEPA filter life with and without prefilter. HEPA filter replaced at 4 in. H_2O pressure drop, and prefilter replaced when pressure drop across it reaches 2 times the clean-filter pressure drop. From P. A. F. White and S. E. Smith, eds., *High Efficiency Air Filtration*, Butterworth & Co., London, England, 1964.

The decision to use prefilters must be based on providing the best balance between HEPA filter life, with its attendant decrease in change frequency, and procurement and maintenance costs for prefilters. The use of prefilters is not economical in some situations where, because of high radiation levels, the HEPA filters must be changed very frequently (even daily in some situations). Prefiltering increases the total frequency of system maintenance, as can be seen from Fig. 2.1. In systems with moderate to high levels of radiation, the labor costs for replacing prefilters may approach those for replacing HEPA filters, since the major part of this labor cost is in makeready and in cleanup following the change. On the other hand, since prefilters can in most

[2]News item, *Air Conditioning, Heating, and Refrigeration News*, July 31, 1967, p. 28.

[3]Personal communication, M. W. First to C. A. Burchsted.

cases be replaced without shutting down the fans, interruptions of activities in the occupied areas of the building would be reduced, resulting in a decrease in total building operating costs (this would not be a consideration where an alternate exhaust system, which can be brought on line during maintenance, is provided). Again, the necessity for consideration of all aspects of cost, not just the cost of furnishing the facility, can be seen.

Prefilters are located either locally, at the entrance to exhaust ducts leading from the controlled areas, or in the central exhaust filter housing. Local prefilters have the advantage that they can be changed without entering or interfering with the central exhaust system and also provide a measure of protection against corrosion of ducts, accidental high moisture loadings, and flaming trash or sparks that might be produced in a fire in the operating area. They also keep dirt out of the ducts and thereby reduce maintenance costs and the probability of duct fires. On the other hand, a number of local prefilter installations will probably cost from two to three times as much as the same prefilter capacity installed in the central exhaust filter housing.[1] Prefilters in the central exhaust system should not be attached directly to the HEPA filters but should be installed on a separate frame approximately 4 to 5 ft ahead of the HEPA filters. This involves higher space and investment costs but is justified by increased safety (dust fires are much more likely in the prefilter than in the protected HEPA filter – spacing the banks minimizes the likelihood of the fire or sparks getting to the more critical HEPA filters) and greater reliability of maintenance (a major cause of HEPA filter damage is puncturing during replacement of prefilters attached directly to them). A fine screen (e.g., insect screen) should be installed on the downstream side of the prefilter mounting in both local and central prefilter installations to stop flaming trash in the event of a prefilter fire. Where fire is a distinct possibility, a screen as fine as 40 mesh or a flame stop should be provided.

2.2.5 Operation to High Pressure Drop

The literature of most manufacturers suggests replacement of HEPA filters when the resistance reaches 2 in. H_2O. However, HEPA filters, by specification, are capable of withstanding pressure drops up to 10 in. H_2O without damage or decrease in performance, as discussed in Chap. 3, and replacement when resistance reaches only 2 in. H_2O results in underutilization. At many AEC installations, HEPA filters are operated routinely to resistances as high as 5 to 6 in. H_2O. The

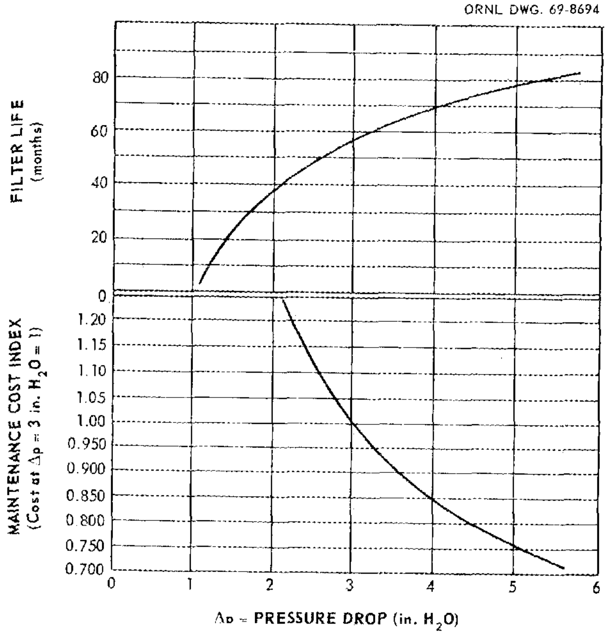

Fig. 2.2. Effect of operating HEPA filters to high pressure drop on filter life and maintenance cost (including replacement filters and labor). From W. V. Thompson, *High Efficiency Particulate Filter History and Activities as of August, 1964, 117-B, C, DR, F, H, KE, and KW Buildings,* USAEC report RL-REA-1000, Hanford Atomic Products Operation, Apr. 12, 1965.

results of such operation on filter life and maintenance costs at one AEC installation are shown in Fig. 2.2.

The advantages of operation to high pressure drop must be weighed against higher investment costs (higher-static-pressure fans, larger motors, and heavier ducting and housings) and higher power costs. The cost of both fans and motors is a function of the static pressure that must be developed. Fan size can be estimated from the formula:

$$hp_f = \frac{Q\,\Delta p}{63.56 E_f}, \tag{2.1}$$

where

hp_f = fan horsepower,

Q = system air flow, cfm,

Δp = average pressure drop across filters, in. H_2O, from installation to replacement,

E_f = fractional fan efficiency (0.60 usually assumed for estimating).

Motor size can be estimated from the formula:[4]

[4]Engineering data, American Air Filter Co.

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

where

hp_m = motor horsepower,

E_m = fractional motor efficiency (0.90 usually assumed for estimating).

Annual power cost can be estimated from:[4]

$$C = \frac{Q\,\Delta p\,hr}{852 E_f E_m}, \quad (2.3)$$

where

C = annual cost of power, dollars;

h = hours of operation per year;

r = cost of power, cents per kilowatt-hour.

Although investment costs are higher for a system operated to high pressure drop, the total annual cost will usually be lower than for the system in which filters are replaced at a pressure drop of 2 in. H_2O. The cost data in line 1 of Table 2.1 were taken from a survey of operating costs of HEPA filter systems by the Harvard Air Cleaning Laboratory.[1] Using these data, assuming a 50% higher capitalization for the larger equipment required, and using the filter life extension and replacement cost data of Fig. 2.2, the data in the second line of Table 2.1 show that the total cost of operating to high pressure drop is less than for replacing the filters at 2 in. H_2O pressure drop. What is not revealed by Table 2.1 or Fig. 2.2 is that interruptions to the facilities served by the exhaust system were halved and that total real savings were considerably higher than indicated.

Prefilters can also be operated to higher pressure drops than recommended by manufacturers in some cases. In Great Britain, prefilters are commonly operated to dirty-filter pressure drops of several inches of water.[5] This results in less frequent filter change than if the filters are replaced at a pressure drop of only two or three times the clean-filter resistance, as is usually done in the United States. However, care must be taken in the selection of filters. Because of the many types, efficiencies, and configurations available, the designer must determine the safe overpressure allowance for the particular model under consideration. The results of overpressuring prefilters can be seen from Fig. 2.3. In this case the problem was overcome by working with the manufacturer to reinforce the prefilters. Some benefit could also have been obtained by installing heavy screens or expanded metal against which the filter cores could bear; in any event, such screens would have prevented the damage which occurred when the pieces of prefilter struck the HEPA filters downstream.

Table 2.1. Operating Costs for a 10,000-cfm HEPA Filter System in AEC Operations (from ref. 1)

Δp when Filters Are Replaced (in. H_2O)	Annual Cost (dollars per 1000 cfm) for –				
	Capitalization (20-year Amortization)	Power	Replacement Filters	Labor	Total
2	20	34	107	15	176
5	30	77	51	6	164

Fig. 2.3. Result of overpressuring prefilters. Note damage to HEPA filters in rear. Courtesy Union Carbide Corporation, Nuclear Division, Y-12 Plant.

2.2.6 Underrating

The service life of both HEPA filters and the common air filters used for prefilters and building supply filters can be extended by underrating – that is, by installing more filter capacity than is required, based on the manufacturer's nominal ratings, for the system air flow.

[5] P. A. F. White and S. E. Smith, eds., *High Efficiency Air Filtration*, Butterworth & Co., London, England, 1964.

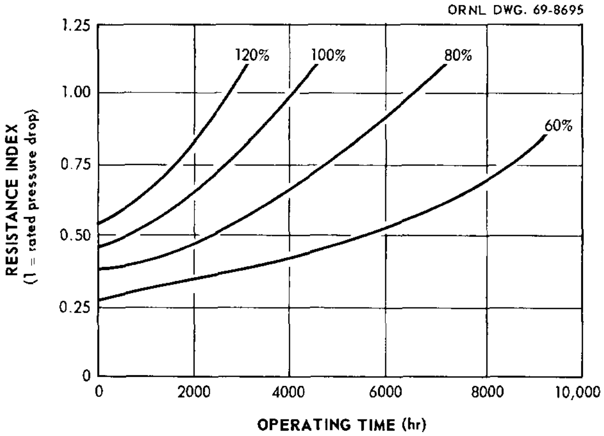

Fig. 2.4. Effect of underrating on service life of extended-medium filters, based on percentage of manufacturer's rated filter air flow capacity. From P. M. Engle and C. J. Bauder, "Characteristics and Application of High Performance Dry Filters," *ASHRAE Journal,* American Society of Heating, Refrigeration and Air Conditioning Engineers, May 1964, pp. 72–75.

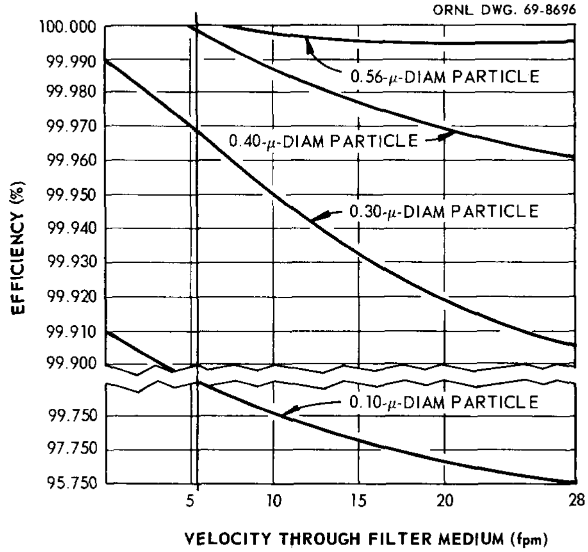

Fig. 2.5. Penetration of HEPA filter medium by submicron particles as function of flow rate through medium. Normal flow rate, at manufacturer's rated filter capacity, is approximately 5 fpm (vertical line). From MSA Ultra-Aire Filters, Bulletin No. 1505-20, Mine Safety Appliances Co.

Figure 2.4 shows that the increase in filter life is much greater than the corresponding degree of underrating. The Harvard Air Cleaning Laboratory study cited above suggests that the practical limit of underrating is about 20% (i.e., design air flow equal to 80% of nominal filter capacity).

Operation of filter systems above the rated capacity (i.e., overrating) is generally not recommended. When flow rates exceed rated capacity, filter life decreases more rapidly than the equivalent increase in flow rate, as can be seen from the 120% curve of Fig. 2.4. In actual systems, because of variations in the pattern of air flow across the filter bank, some of the filters may be subjected to higher flow rates than others, and their loading rates will be correspondingly higher (the flow and loading rates may or may not equalize over the life of the filters in the bank). If the system is operated above the rated capacity, the combined effect may be to compound the effect, to greatly overrate some filters in the bank and to greatly underrate others. Figure 2.5 shows that the penetration of HEPA filters by very small particles increases significantly with high flow rate. Conversely, the penetration by particles larger than 1 μ may increase significantly at very low flow, where impaction effects are minimized. If some filters are operating at much higher than rated capacity and some are operating at much less, it is possible that penetration could occur even though the filters are in good condition.

2.3 ENVIRONMENTAL FACTORS

The functions of a nuclear plant air cleaning system are to provide satisfactory working conditions for personnel and to prevent the release of radioactive or toxic substances to the atmosphere. The complexity of an air cleaning system design to meet these objectives depends on the nature of the contaminants to be removed (radioactivity, toxicity, corrosivity) and on heat, moisture, and other conditions that can affect the performance or life of system components.

2.3.1 Radiation and Airborne Radioactivity

Ventilation rates are based principally on cooling requirements and the inhalation hazard, or potential inhalation hazard, of substances present in the air of the controlled (i.e., ventilated) spaces. Concentrations of radioactive gases and aerosols in the air of operating areas should not exceed the maximum permissible concentrations (MPC) for occupationally exposed persons under any normal or abnormal condition, and concentrations at the point of release (or site boundary for nuclear reactors) must not exceed the permissible

Table 2.2. Hazard Classification of Radioisotopes

Hazard Class	Hazard	MPC in Air (curies/liter)	Amount of Radioactive Materials Permitted[a] (μc)
1	Very high	10^{-13} or less	0.1
2	High	10^{-13} to 10^{-11}	1.0
3	Moderate	10^{-11} to 10^{-9}	10.0
4	Low	10^{-9} or higher	100.0

[a]Amount of radioactive material that can be handled without special protection for personnel.

limits for nonoccupationally exposed persons.[6,7] As radioactive gases or aerosols or both may be accidentally released by an equipment failure, a spill, or rupture of a sealed container, the ventilating and air cleaning systems must be designed to control airborne activity within the prescribed limits in the event of the worst possible accident.

Radioactive materials may be grouped into four classes (Tables 2.2 and 2.3) with respect to inhalation hazard in the air of operating areas and with respect to the maximum quantity of radioactivity that can be handled open in operating areas. Quantities larger than those shown in Table 2.2 must be handled in special facilities such as hot cells or gloved boxes. A tabulation of radioactive materials (i.e., isotopes), with their MPC's in air, is given in the *Code of Federal Regulations,* 10-CFR-20.[6] Facilities can be separated into zones of varying degrees of hazard with respect to these hazard classes as shown in Table 2.4. The limits are guides and not absolute requirements. However, by introducing such indexes of hazard and limitations on materials that

[6]10-CFR-20, Standards for Protection Against Radiation, *Code of Federal Regulations,* Title 10, Part 20, U.S. Government Printing Office, 1965.

[7]10-CFR-100, Reactor Site Criteria, *Code of Federal Regulations,* Title 10, Part 100, U.S. Government Printing Office, 1966.

Table 2.3. Classification of Isotopes According to Relative Radiotoxicity Based on Inhalation Hazard[a]

Class 1: Very high radiotoxicity	Sr-90 + Y-90, Po-210, Po-210 + Bi-210, Ra-226, Th-228, U-232, Pu-238, Pu-239, Pu-240, Pu-241, Am-241, Cm-242
Class 2: High radiotoxicity	Na-22, P-32, Ca-45, Sc-46, V-48, Fe-59, Co-58, Co-60, Ni-63, Zn-65, Rb-86, Sr-89, Y-91, Zr-95 + Nb-95, Ru-103, Ru-106 + Rh-106, Ag-105, Ag-110, Cd-109 + Ag-109, Cd-115, In-114, Sn-113, Sb-122, Sb-124, I-131, Cs-134, Cs-137 + Ba-137, Ba-140 + La-140, Ce-144 + Pr-144, Pm-147, Sm-151, Eu-152, Eu-154, Tm-170, Hf-181, Ta-182, Ir-192, Hg-203, Tl-204, Bi-210, At-211, U-233, Th-234 + Pa-234, Np-237, Pu-242
Class 3: Moderate radiotoxicity	Be-7, Na-24, S-35, K-42, Ca-47, Sc-47, Sc-48, Mn-52, Mn-54, Fe-55, Mn-56, Cu-64, Ga-72, As-74, As-76, As-77, Se-75, Br-82, Sr-85, Y-90, Nb-95, Mo-99, Pd-103 + Rd-103, Rh-105, Pd-109, Ag-111, Cd-115, Sb-122, Te-127, Ba-131, La-140, Ce-141, Pr-142, Pr-143, Nb-147, Ho-166, Sm-153, Ho-170, Lu-177, W-181, W-185, W-187, Re-183, Re-186, Os-191, Ir-190, Ir-192, Ir-194, Pt-191, Pt-193, Au-196, Au-198, Au-199, Hg-197, Tl-200, Tl-201, Tl-202, Ac-227, pure U-233, U-234
Class 4: Slight radiotoxicity	H-3, C-14, F-18, Cl-36, A-37, Cr-51, Ni-59, Ge-71, Kr-85, Tc-98, Tc-99, Ru-97, Rh-103, Te-129, I-129, I-132, Xe-133, Pb-203, U-235, U-236, Th-natural, U-238, U-natural

[a]From C. E. Guthrie *et al., Operating Guide for Radiochemical Laboratories at Various Activity Levels,* USAEC report ORNL-TM-626, 1963.

Table 2.4. Zoning of Buildings Based on Radiotoxicity Hazard

Class	Hazard	Amount of Uncontained Materials Permitted			
		Zone I	Zone II	Zone III	Zone IV
1	Very High	>10 μc	0.1 μc–10 μc	0.01 μc–0.1 μc	<0.01 μc
2	High	>100 μc	1 μc–100 μc	0.1 μc–1 μc	<0.1 μc
3	Moderate	>1 mc	10 μc–1 mc	1 μc–10 μc	<1.0 μc
4	Low	>10 mc	100 μc–10 mc	10 μc–100 μc	<10.0 μc

can be handled in certain types of areas, it is possible to establish a basis for ventilation and air cleaning requirements for various parts of a facility. Not all of the zones will be present in all facilities, and some facilities may consist entirely of a single zone. The zones are defined as follows:

Zone I: A hot cell, gloved box, or other facility for handling high levels of radioactivity. Containment features must prevent spread of activity within or release from the facility. Complete isolation (physical separation) from neighboring facilities, laboratories, offices, shop areas, and operating areas necessary. *Entry forbidden* until area is cleaned up to zone II classification. Air inlet and exhaust ports fitted with HEPA filters, often two in series in exhaust.

Zone II: Hot cells or gloved boxes, service and maintenance areas, other facilities where high levels of radiation may be present. Operations carried on in fume hoods or gloved boxes require separate HEPA filtered exhaust. Opening to hoods, gloved boxes, or other containment must have inward air flow of 150 lin ft/min or higher and may be 200 fpm for hazardous operations or if hot plates, aspirators, or burners are operated inside the containment (e.g., fume hood). Air locks and personnel clothing-change facilities required at entry of facility to provide a degree of isolation from surrounding areas. Entry only with full-body protection and with full-face masks or respirators if needed. Continuous monitoring of airborne activity.

Zone III: Operating and general working areas. Generally inactive but sometimes mildly contaminated. Operating personnel should have protective clothing with respiratory gear immediately available for emergencies. Chemical operations carried on in fume hoods as for zone II. Routine radiation monitoring required.

Zone IV: Office and shop areas. No specific protective clothing required. Radiation monitoring may be required at exit points. Bench-top operations permissible in laboratory areas, but fume hoods should be considered for upper levels of activity.

Multizoned facilities are usually ventilated so that air flow is from the least contaminated zone to zones of increasing contamination. Air flow must be sufficient to provide the necessary degree of dilution and cooling and to maintain sufficient differential in pressure between any zone and any other zone or the atmosphere to ensure that there can be no backflow of air even under accident conditions. A pressure differential of at least 0.1 in. H_2O between zones is recommended. As an indication of the type of ventilation requirements needed for different activity levels, the following criteria are used at one AEC installation for the design of radiochemical and laboratory facilities and the buildings that contain them:[8]

1. Hot cells (caves)
   a) Vacuum equal to or greater than 1 in. H_2O relative to surrounding spaces shall be maintained in the cell at all times to ensure a positive flow of air into the cell.
   b) Cell exhaust capacity shall be at least 0.1 cell volume per minute[9] to minimize explosion hazards due to volatile solvents and also to ensure that, in the event of cell pressurization due to an explosion, the cell will be returned to the normal pressure of 1 in. H_2O in a minimum of time.
   c) Permissible leak rate of 0.01 cell volume per minute[9] at a pressure differential of 2 in. H_2O to ensure that the escape of radioactive material will be minimized in the event of cell pressurization.
   d) Seals and doors shall withstand a pressure differential of 10 in. H_2O[9] to ensure integrity of cell closures and penetrations under all operating and abnormal conditions.
   e) The cell shall withstand the pressure produced by the maximum credible accident.
   f) Operating procedures shall be designed to limit the presence of flammable materials and solvents within safe limits.
2. Gloved boxes
   a) Vacuum shall be at least 0.3 in. H_2O.
   b) Exhaust rate not specified, but must be adequate for heat load and dilution requirements of operations conducted in box.

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[8]W. D. Burch and T. A. Arehart, Safety Review Procedures for Hot-Cell and Radiochemical Processing Facilities at ORNL, *Proceedings of 15th Conference on Remote Systems Technology*, American Nuclear Society, 1967.

[9]These values may be relaxed depending on the requirements for the operating conditions and maximum credible accident.

c) Capacity of exhaust system shall be sufficient to provide at least 5 cfm for each box and to maintain a face velocity of at least 100 to 150 fpm through one open glove port on every five boxes to ensure adequate inflow in the event of glove rupture to prevent escape of contaminants to the room.

3. Containment building

a) The building shall be designed to prevent the dispersal of activity to the environment in the event of an accident.

b) Under emergency conditions, the building shall be capable of being maintained at a vacuum of at least 0.3 in. H_2O relative to the atmosphere. For increased reliability and simplicity, some buildings are normally held at this pressure. If this is not practical, then the ventilation system must be capable of reducing building pressure to 0.3 in. H_2O in 20 sec or less. All air must be exhausted through HEPA filters.

c) Air in the building must flow from areas of least contamination to areas of increasing contamination.

d) Recirculation of air within one zone or room is permitted, but recirculation from the central exhaust system is prohibited.

4. Air handling system

a) Ventilation and off-gas systems shall be backed up by emergency systems to maintain containment in the event of fan breakdown, filter failure, or power outage.

b) Air discharged from contained systems shall be exhausted through prefilters and HEPA filters. Contaminated air (vessel, gloved box, or hot cell exhaust) from work areas shall be exhausted through two individually testable HEPA filter banks in series. Air which is normally clean (secondary containment exhaust) but which has the potential of becoming contaminated in the event of an accident and air from only mildly contaminated areas (zone III) require only one HEPA filter.

c) Corrodents or moisture in the exhaust air that is capable of damaging the filters shall be removed or neutralized prior to discharge to the filters.

d) HEPA filter systems shall be tested in place at a prescribed frequency (usually twice a year), using dioctyl phthalate (DOP) aerosol, and shall have a minimum test efficiency of 99.95% (see Chap. 7).

e) Maximum chronic release of radioiodine (^{131}I) shall be within the limits established by the Federal Radiation Council and the code of Federal Regulations.

f) The adsorber system of any facility or experiment capable of releasing more than 0.2 curie per week under accident conditions shall be tested in place as specified in Chap. 7.

The hazard and zoning classifications are used throughout the remainder of this handbook to define relative hazards in various applications. The inside of a duct or filter housing is considered to have the same hazard classification as the space that is being ventilated. Recommended ventilation rates for occupied areas are:

Hazard Class	Room Air Changes per Hour
1	12 to 60
2	Not less than 12
3	8 to 12
4	4

2.3.2 Nature, Size, and Distribution of Particulates

Although process-generated particles are usually the primary consideration, atmospheric dust and particulates are also important because of their effect on the exhaust filters with respect to loading and because they can of themselves become radioactive when exposed to some operating environments (e.g., by adsorption of radioactive vapors or gases). Particles in the range of 0.05 to 5 μ, because they tend to be retained by the lungs when inhaled, are of primary concern in operations involving radioactivity.[10] As can be seen from Table 2.5, over 99% of the particles in atmospheric air fall in this size range. On the other hand, particles in this size range probably account for less than 20% of the weight of dust in the air.

Reports of dust concentrations are generally based on weight. As shown in Table 2.5, weight accounts for only a small portion of the number of particles actually present – that is, 99% of the dust on a weight basis includes no more than 0.00006% of the particles. This is an important factor in filter testing because filters

[10] Report of IAEA symposium on airborne radioactivity, *Nucleonics Week* 8(29), 7 (July 20, 1967).

Table 2.5. Distribution of Particles in Typical Urban Air Sample

Engineering data, American Air Filter Co.

Mean Particle Size[a] (μ)	Particle Size Range (μ)	Approximate Particle Count per Cubic Foot of Air	Percent by Weight
20	50–10	12.5×10^3	28
7.5	10–5	10×10^4	52
4	5–3	12.4×10^6	11
2	3–1	10×10^7	6
0.75	1–0.5	10×10^7	2
0.25	0.5 and smaller	12×10^{15}	1

[a]Based on light scattering.

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

Fig. 2.6. Distribution of particles by shape in atmospheric air. Courtesy K. T. Whitby (see ref. 11).

having a high efficiency based on weight-percent testing actually have a very low efficiency on a count basis. Dust concentrations vary widely from place to place and from season to season. Concentrations of particles in the atmosphere may vary from as low as 0.01 grain per 1000 ft^3 in rural areas to more than 10 grains per 1000 ft^3 in heavily industrialized areas. Dust-producing operations may generate concentrations as great as several thousand grains per 1000 ft^3. Since weight-percent determinations account for only a small fraction of the total particles present, the true count of particles smaller than 5 μ may number in the billions per 1000 ft^3. Dust concentrations are usually lowest during the summer months (June 1 to August 1) – as much as 30% lower during that period than during the remainder of the year.[11]

Figure 2.6 shows the distribution of particles in atmospheric air by shape.[11] This distribution also varies widely from place to place and season to season. Variations in particle shape, mean size, size range and distribution, and concentration have an important bearing on the life, costs, and operational effectiveness of high-efficiency air cleaning systems. The size range of various particles, the technical nomenclature of various types of aerosols, and the applicability of different types of air cleaning devices, as a function of aerosol size range, are shown in Fig. 2.7.

Atmospheric particles can be introduced into operating areas with the supply air, by infiltration through cracks in walls and around windows and doors (where the areas are at a pressure lower than atmospheric), with air pumped into the area by opening and closing of doors, and on personnel and materials entering the area. Particles and droplets may be generated within the operating area by a process or by personnel moving about. Even at rest, the average person gives off more than 2,500,000 particles, 0.3 μ and larger, per minute.[12] A major source of the lint often found on filters is abrasion of clothing by workmen in the area.

Process-generated contaminants in nuclear operations can be grouped in three classes: noble gases, halogen gases (of which the most abundant, with respect to activity, is iodine), and particulates. Because of their chemical inertness, their limited reactivity with available sorbents, and their relatively short half-life, the noble gases are usually treated by storage for sufficient time for radioactivity to decay to safe levels or by controlled release from high stacks. The halogen gases can be removed by adsorption on activated charcoal. Particulates are removed by filtration.

2.3.3 Moisture

Moisture is a major hazard to both HEPA filters and prefilters and can reduce the effectiveness of activated charcoal. Where heavy concentrations of water, mist, or steam can be expected under either normal or accident conditions, impingers, moisture separators, or other means of reducing entrained moisture to tolerable levels must be provided upstream to prevent plugging, deterioration, or reduced performance of filters and adsorbers.

[11]K. T. Whitby *et al.*, "The ASHAE Air-Borne Dust Survey," *Heating, Piping and Air Conditioning*, November 1957, pp. 185–92.

[12]P. R. Austin, "Personnel Emissions in Laminar-Flow Clean Rooms," *Contamination Control*, July 1966.

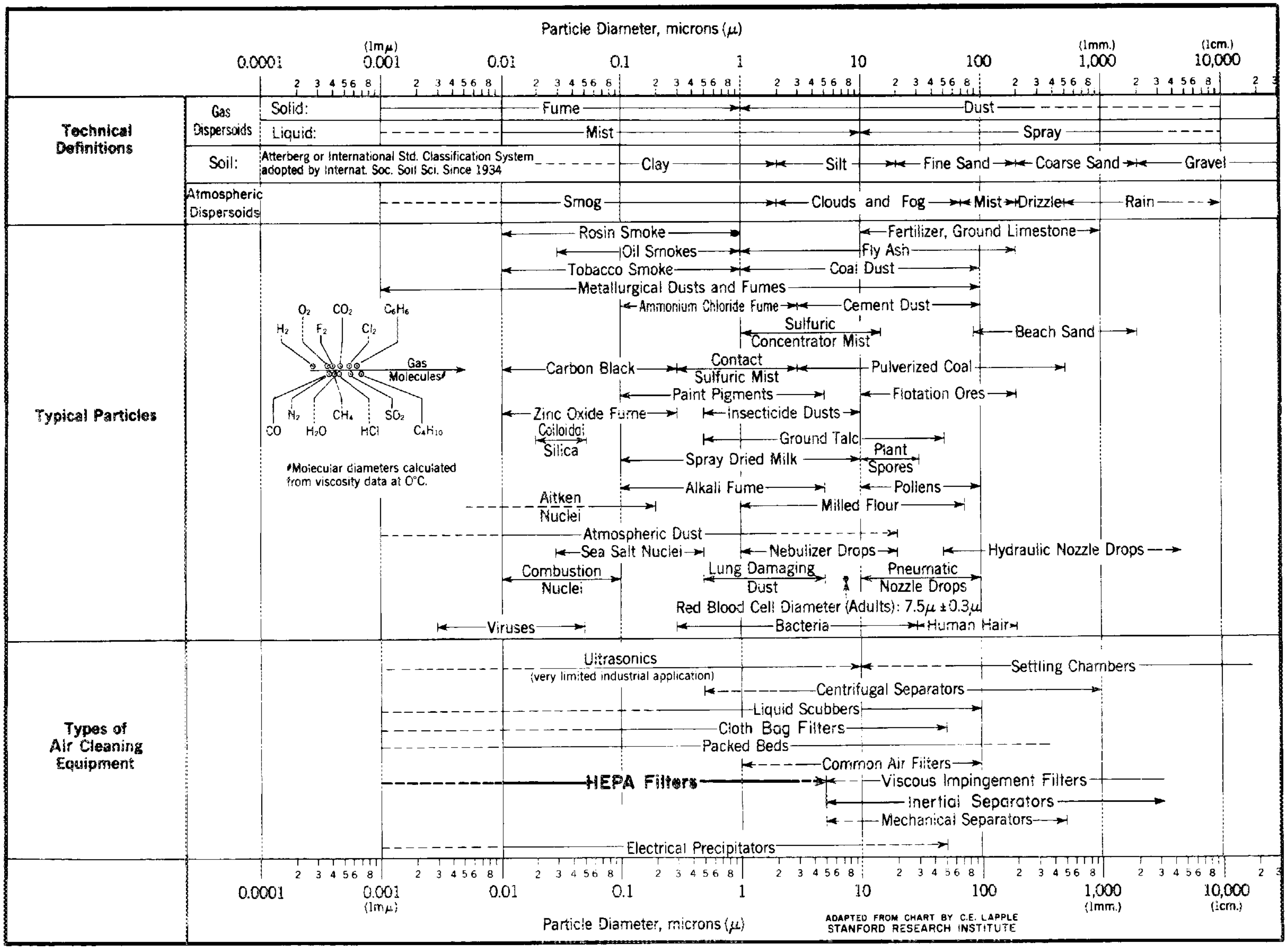

Fig. 2.7. Characteristics of atmospheric and process-generated particulates, fumes, and mists and effective ranges of typical air cleaning equipment. Courtesy C. E. Lapple, Stanford Research Institute.

Condensation and carry-over from air washers and scrubbers are common sources of moisture. When sprinklers are provided in operating areas, ducts, or filter housings, moisture can be drawn into the filters in the event of activation during a fire. In nuclear reactor systems, large volumes of steam and moisture may be generated following a loss-of-coolant or heat-exchanger accident.

Condensation is particularly troublesome when filters are installed in underground pits and in housings located outdoors or in unheated sections of the building. Even when air passing into the filters is above the dew point, dampers, ducts, or the filter units themselves may be cold enough to cause condensation. Condensation can also take place in standby systems, particularly when groundwater can evaporate into the filter housing to condense on the walls, mounting frames, and filters. Salt from groundwater and salts that leach from the fire-retardant-treated filter cases can deteriorate the filters in time. In one instance the aluminum separators of a bank of filters installed in a pit were destroyed by this action in a three-month period. Regular ventilation of standby filter systems, as recommended in Sect. 2.2.1, is essential for reliability.

2.3.4 Dry Air

Dry air is generally not a problem. However, extremely dry air (20 ppm water or less) is damaging to wood and wood-particle-board filter cases.

2.3.5 Heat

Continuous operation at high temperature is detrimental to filters and charcoal adsorbers. At high temperatures the shear strength of adhesives used in the manufacture of HEPA filters and some prefilter types diminishes, limiting the safe pressure drop to which the filters can be subjected.[13] The limiting temperature varies with the specific adhesive used and should be checked with the filter manufacturer. Steel-cased filters with glass-fiber seal between the case and filter core are suitable for higher temperatures, although they often are unable to meet the efficiency requirements for HEPA filters (i.e., 99.97% for 0.3 μ particles). Because the binder of the glass-fiber media used in HEPA filters (and in some prefilter types) burns out at about 400 to 425°F, sharply reducing the tensile strength of the media, even high-temperature units must be used with caution at temperatures above 400°F.[13] Most commercially available prefilters are not resistant to heat, and special construction requirements must be specified if continuous operating temperatures exceed 150°F.

The limiting temperature of activated charcoal which has been impregnated to enhance its ability to trap radioactive organic iodine compounds is the temperature at which the impregnant begins to desorb, about 300 to 350°F for charcoals presently available. For nonimpregnated charcoals, the ignition temperature is the limiting temperature, approximately 550 to 650°F for the charcoals now available.

Ceramic filters having efficiencies as high as 80% for 0.3-μ particles at room temperature are suitable for service at temperatures as high as 2000°F (as with any high-efficiency filter, however, the performance tests are made at room temperature, and the actual efficiency at operating temperature is unknown). Ceramic filters are expensive and extremely fragile and must be handled and installed with great care.

Where temperatures higher than the operating limits of the filter system components are encountered, heat sinks, long runs of duct, dilution with cooler air, or some other means of cooling must be provided to reduce temperatures to tolerable levels. Consideration must be given to problems of thermal expansion and heat resistance of materials of construction in the ducts, dampers, filter housing, filter mounting frames, and fans. Consideration must also be given to the effect of heat on materials located close to the ducts or filter housing.

2.3.6 Corrosion

Many radiochemical operations generate acid or caustic fumes that can damage or destroy filters or ducts. High levels of performance and reliability cannot be assured when filters are exposed, even only occasionally, to corrosive fumes. Corrosion-resistant HEPA filters, having specially treated media and separators and wood cases, and stainless steel ducts, housings, and mounting frames are recommended in areas of probable attack. Stainless steel may not be adequate under some circumstances, and coated (e.g., vinyl, epoxy) stainless steel or plastics may have to be resorted to. The latter must be used with caution, however, because of fire or possible collapse at high temperature.

Scrubbers or air washers may be employed to remove corrosive fumes before they get to the filters, but consideration must be given to the moisture carry-over problems they create if not properly designed and

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[13] C. A. Burchsted, "Environmental Properties and Installation Requirements for HEPA Filters," *Treatment of Airborne Radioactive Wastes*, International Atomic Energy Agency, Vienna, 1968.

operated. Mist eliminators should be provided between scrubbers or air washers and the filter system. Hydrogen fluoride (HF) fumes are unavoidable in certain nuclear fuel processing operations. Because HF rapidly attacks and destroys the glass fiber media of HEPA filters, either scrubbers or air washers to protect the filters, or special filters with cellulose-asbestos media, which is more resistant to HF, must be employed. However, the fire hazard created by the latter will require additional protective measures.

The possibility of corrosion is not always obvious. In charcoal adsorbers, even trace amounts of NO_2 or SO_2, so small as not to be detectable except with a very sensitive gas chromatograph, can accumulate in the charcoal over a long period of time and mix with adsorbed moisture to form acid solutions which can corrode the adsorber cases or mounting frames. In one instance the resulting corrosion necessitated replacement of several hundred carbon-steel-cased adsorbers with stainless-steel-cased units, at great cost.

2.4 EMERGENCY CONSIDERATIONS

A particular danger in nuclear plant exhaust systems is damage to the filters and resultant leakage of contaminated air to the atmosphere or occupied spaces of a building in the event of a system malfunction, fire, or explosion. The hazard is particularly severe in nuclear reactors because of the potential for large energy release, steam, water, heat, liquid slugging, radiation, and chemical attack.

The probability of accidents and fires which could affect the air cleaning system can be minimized but cannot be completely eliminated. Consideration must be given to the possibility of such occurrences and their possible consequences. The designer must give consideration to damage of the filter system from shock, vibration, or fire; to design and arrangement of ducts and housings to alleviate these conditions; to the possibility of a power outage and means of switching to an alternate power system; and to methods of controlling the exhaust system during failure conditions. To provide the necessary protection to the plant and to the public, air cleaning devices on which containment leakage control depends must remain essentially intact and serviceable under accident conditions. Components must be capable of withstanding the differential-pressure forces, heat, moisture, and stress of the maximum predictable accident with minimum damage and loss of integrity and must remain operable long enough to satisfy system objectives.

2.4.1 Shock and Vibration

Vibration can be produced by turbulence generated in poorly designed ducts, transitions, dampers, or fan inlets and by improperly installed fans and motors. Apart from discomfort to personnel, excessive vibration or pulsation can result in mechanical damage to ducts and filters when cyclic forces become high or when accelerative forces coincide with the resonant frequency of the filter housing, mounting frame, or other components. Weld cracks can be produced even by low-level local vibrations, and vibrations or pulsations that produce no apparent short-term effects can cause serious damage after long duration.

Mechanical shock can be produced by explosion and by rapid compression or decompression of the system from sudden opening or closing of a damper. When pressure transients last for periods measurable in seconds, static pressure is primarily responsible for the destructive effect. For shocks having a duration of only a few milliseconds, with nearly instantaneous pressure rise, such as occurs in most chemical explosions, destructiveness depends on the momentum of the shock wave. Nuclear accidents, including the blast effects of a "design basis accident," usually fall between these two extremes. The duration of a nuclear shock is generally considered to be about 50 msec.

Protection against vibration and shock may be accomplished in two ways: by isolation of critical components, such as filters and fans, to minimize the transmission of forces to them and by increasing the shock resistance of critical components. Mechanical resistance can be improved by using extra-high-strength construction in ducts, filter housings, and filter mounting frames; by providing several sharp turns or cushion chambers in the duct leading to the filters; and by the use of face guards on the HEPA filters. Although dampers, moisture separators, and prefilters may be damaged by a shock wave, they serve to attenuate shock pressures and thereby protect the more critical HEPA filter.

2.4.2 Fire

The possibility of filter fires has generally been overlooked, and adequate provision for detection and control of fires has been the exception rather than the rule. It is often thought that, with all-steel or all-concrete ducts and filter housings and with fire-resistant filters, there is nothing to burn. This is not true. The dust collected on the filters is often highly flammable, and even a fire-resistant filter can be destroyed by sparks, flaming trash carried into the filter housing, or burning dust. In contaminated exhaust systems, the release to the atmosphere of contaminated dust or smoke from a burning filter may be a more serious hazard than the fire itself.

The first defense against fire is to plan safe operating procedures in the building. This includes control of solvents and other flammables, good housekeeping, and damage control planning by personnel in the event of a fire or other accident. The most likely hazard arises from a fire in an operating or maintenance area. Hot gases from a fire can degrade the filters or ignite dirt collected in the duct or on the filters. Flaming trash or incandescent particles from the primary fire can start secondary fires in the exhaust system. Duct or filter fires may also be started from heat transmission from fires in surrounding areas or adjacent equipment, from welding and burning operations carried out in the vicinity (particularly near intakes to exhaust ducts), and from static discharges within the duct system or filter housing.

Solvent fires present the worst hazard. Duct temperatures can build rapidly to 1000°F or higher, particularly where the fire occurs in chemical fume hoods or gloved boxes, where the fire is likely to be located right at the entrance to the intake to the exhaust duct. When fire is caused by ignition of gases that are already at a temperature of 1000°F or higher, the resultant temperature of the gas is likely to exceed 2000°F. Pyrophoric dust fires in machine tool hoods or gloved boxes may give rise to temperatures as high as 3000°F or higher, in addition to producing burning metal fragments that can be carried into the exhaust system.[14]

Because loss of the filters may be the most serious consequence of a fire, the first design decision must be to use fire-resistant filters. The fire-resistant filter, both wood-cased and steel-cased, can withstand temperatures of 700 to 750°F for at least 5 min without loss of filtration efficiency and may retain a significant degree of effectiveness even longer. Above 800°F the fine fibers of the medium break or "pill," producing pinholes in the medium. Rapid deterioration can be expected at temperatures above 1000°F.

It is essential that HEPA filters be located where they are exposed to the least hostile environment in case of a fire in the operating area or in the duct leading to the filters. Protection against burning trash and sparks from the operating area or from burning prefilters should be provided. Experiments at the Atomic Weapons Research Establishment (AWRE) in Great Britain showed that the installation of glass-fiber panel filters at the entrances of exhaust ducts appreciably reduced the temperature in the central filter housing during a fire in the operating area.[14] The proper installation of prefilters at exhaust grilles, fume hoods, machine tool enclosures, and gloved boxes is covered in Chaps. 5 and 6.

Flame arresters and gas coolers are of limited value when located close to the upstream face of an HEPA filter. Tests by the AEC showed that no commercially available flame arrester prevented failure of the HEPA filter when installed in this manner. To be effective, a flame arrester or gas cooler must have considerable heat capacity and be located at least 10 to 20 ft ahead of the HEPA filter. For protection of a main filter bank, more reliance should be placed on dilution with cool air from

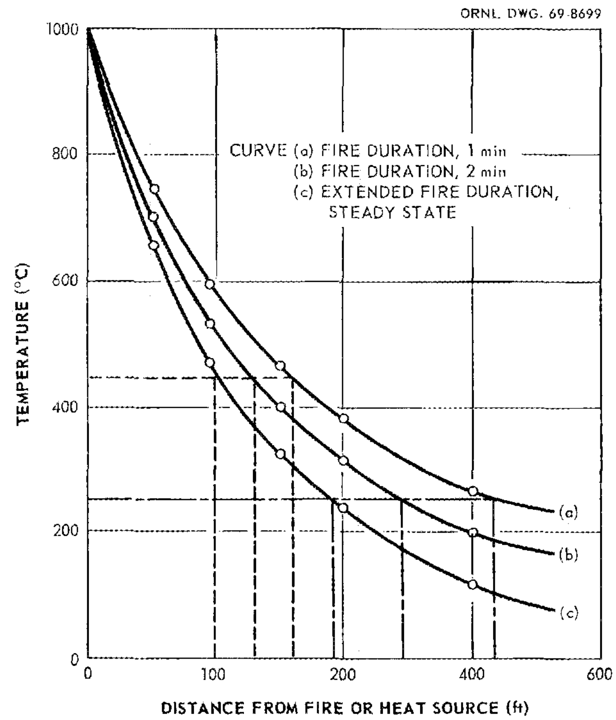

Fig. 2.8. Cooling rate of air in a 12-in.-diam uninsulated duct carrying 1000 cfm of air. Dashed lines show the length required to cool air from initial temperature of 1000°C (1832°F) to 450°C (842°F) and 250°C (482°F) for various fire conditions. From S. E. Smith *et al., Protection Against Fire Hazards in the Design of Filtered Ventilation Systems of Radioactive and Toxic Gas Process Buildings,* UKAEA report AWRE 0-24/65, Atomic Weapons Research Establishment, Great Britain, July 1965.

[14] S. E. Smith *et al., Protection Against Fire Hazards in the Design of Filtered Ventilation Systems of Radioactive and Toxic Gas Process Buildings,* UKAEA Report AWRE 0-24/65, Atomic Weapons Research Establishment, Great Britain (July 1965).

side ducts and from very long runs of air ducting ahead of the bank. It has been estimated that the maximum temperature that can be expected in the event of a fire at the entrance to a 12-in.-diam uninsulated steel duct carrying 1000 cfm of air is about 1800°F.[14] The cooling rate of air in such a duct is shown in Fig. 2.8.

2.4.3 Fire Control

The first requisite for effective control of filter fires is a sensitive detection system. If protective action is started soon enough, a filter fire can be extinguished with only a small quantity of water. If the fire gets a good start, however, it can be difficult to put out. The second requisite is an effective fire-fighting method. There are three basic fire-fighting methods: manual hose lines, personnel-controlled sprinklers, and automatic sprinklers. Automatic sprinklers are recommended. Hoses and nonautomatic sprinklers suffer from the inherent delays of any personnel-response system, and the filters may be severely damaged before effective action can be taken. Fog nozzles should be used for either hose or sprinkler systems; the blast effect of an ordinary nozzle or sprinkler head may do more damage to the filters than the fire. Although the rate of water application with a fog-type sprinkler or nozzle is only about a tenth of that of a spray-type sprinkler or nozzle, it is more effective because it blankets and cools the fire and the small droplets can be drawn into the pleats of the filter where they can be most effective.[15] Automatic sprinklers should also be installed inside and above ducts made of plastic or other material that can burn or collapse when exposed to fire or hot air.

In addition to cost considerations, there is a prejudice among plant operators against sprinklers because of the presumed possibility of water damage to the filters resulting from a false alarm or sprinkler system failure. Although it cannot be made infallible, an automatic sprinkler can be designed to make the probability of a false alarm remote. The slight possibility of a false alarm must be weighed against the certain dangers from fire, smoke, and release of contamination to the environment in the event of a fire. Experience at the AEC's Rocky Flats plant indicates that, with fog-type sprinklers and moisture-resistant filters, little significant damage is likely to result from an accidental sprinkler release.[16] Further discussion of alarm and sprinkler systems appears in Chaps. 5 and 6.

Charcoal fires are particularly difficult to extinguish. Charcoal in an adsorber can be ignited from external heat or flame or can spontaneously ignite from the decay heat of fission products collected in the charcoal when air flow is discontinued. The ignition temperature of new activated charcoal is between 550 and 650°F. The ignition temperature of installed charcoal may be less due to adsorbed impurities. With impregnated charcoals there is the additional problem of iodine desorption at high temperature. Fog-type sprinklers are recommended for charcoal cooling also. Carbon dioxide cannot be used unless it is released at a temperature above the freezing point of water, else ice and CO_2 "snow" will collect on the surface of the charcoal and prevent penetration of the gaseous CO_2. Fog-type sprinklers also have the advantage that they reduce the danger of explosion of the carbon monoxide evolved during a charcoal fire.

2.4.4 Power and Equipment Outage

Design for emergency must consider the possibility of power and equipment outages. Outages are costly and in some operations could result in a contamination hazard to personnel or the community. The speed with which alternate or emergency facilities must pick up the load to avoid spread of contamination in the event of an outage must be estimated and will determine the degree of sophistication required.

Possible emergency measures include dual fans, dual motors, alternate power supplies to the fan motors from separate and independent switchyards, emergency motor-generator sets, steam turbines, batteries, and automatic gravity-operated fail-safe dampers. Where continuous ventilation must be maintained, rapid automatic switching to an alternate fan, power supply, or standby exhaust system is essential. However, if brief interruptions of air flow can be tolerated, manual switching to alternate equipment may be permissible, at less expense. In any event, visible and audible alarms must be provided, both at the equipment itself and at a central control panel, showing the operating status of the equipment. The designer must consider the failure sequence in a power outage. This may be quite complicated in some systems. In one radiochemical plant, for example, this involves first a shift to an alternate power supply; should this fail, another shift to an emergency steam turbine; and, should the turbine fail, a third shift to a diesel-electric emergency power unit. In addition, dual fans and motors and an alternate filter system are provided. In all cases the consequences of failure in terms of hazard to plant, personnel, and the public and the economics of interruptions to the

[15] Personal communication, D. J. Keigher, fire protection engineer, Richland Operations Office, USAEC, to C. A. Burchsted.

[16] Personal communication, F. J. Linck, Dow Chemical Co., Rocky Flats Operations, Denver, Colo., to C. A. Burchsted.

facility will dictate the complexity of the emergency system that is needed.

2.4.5 System Control During an Outage or Equipment Failure

The containment philosophy during an accident or other emergency will vary according to the conditions that must be maintained in the controlled (zone I) area. In systems where exhaust is provided by a number of individual filter-blower systems, it may, for example, be possible to shut down only a single fan to isolate a fire. In buildings with zone ventilation, on the other hand, where ventilation is provided by a central exhaust system, it may be imperative to maintain air flow during an emergency to maintain the pressure gradients between zones to prevent backflow of contaminated air to occupied areas of the building. Pressurization of a gloved box (zone I area) could, for example, rupture a glove or blow out a window of the gloved box, permitting contaminants to escape to the personnel (zone III) area.

Provision must be made for both manual and automatic control of dampers and fans in both supply air and exhaust systems in the event of a fire. Fire dampers must be provided in ducts to prevent the spread of fire from one area of a building to another. Where close control of pressure gradients from one zone to another is required, pressure-relief devices may be required to limit abnormal pressure surges. In large systems, separate air handling facilities for controlled (zone I) and occupied (zones III and II) areas may be desirable, which would be interlocked for proper operation in the event of an emergency.

2.4.6 Compartmentation

A higher degree of control is possible in the event of fire or other emergency if the filter can be compartmented. Compartmentation of large filter banks may be accomplished by partitioning the filter housing or by splitting the air flow between separate parallel housings. Compartmentation provides isolation in the event of fire, and a fire in one compartment can be fought without endangering the filters in the other. For systems that require continuous ventilation during emergency conditions, air flow can be continued through other compartments while the one affected is dampered off. Series compartmentation may also be desirable in high-risk systems to isolate prefilters from the HEPA filters. The series-parallel compartmentation of the central exhaust filter system of a laboratory handling large quantities (i.e., with respect to inhalation

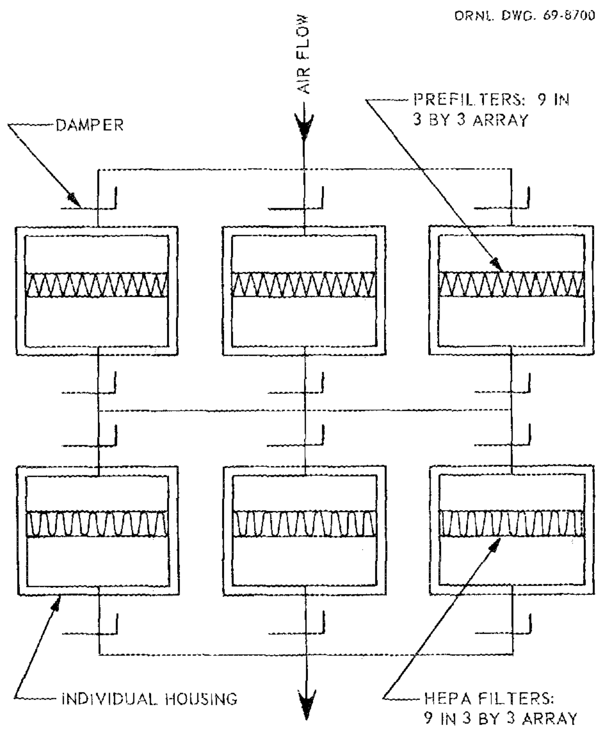

Fig. 2.9. Series-parallel arrangement of central exhaust filter system for a high-hazard radiochemical laboratory.

hazard) of high-specific-activity alpha-emitting materials is shown schematically in Fig. 2.9. In the event of fire in any one of the housings, that housing can be isolated and the remaining filters kept in service. Any one of the filter housings can be isolated for filter change without interruption of activities in the laboratory. This is an expensive arrangement but was justified by the high risk potential.

2.4.7 Standby Filter Systems

High-hazard facilities such as nuclear reactors and radiochemical plants often require standby or alternate filter systems to ensure continuous ventilation during service and in the event of failure of the on-line system. Figure 2.10 shows the normal off-gas and building exhaust filter systems for one nuclear reactor. Each complete filter system consists of three parallel subsystems in separate housings (underground pits). Two subsystems are normally on line, with the third in standby. Any one of the pits can be isolated by means of the diversion dampers, and any one subsystem can provide sufficient air for emergency ventilation and cooling.

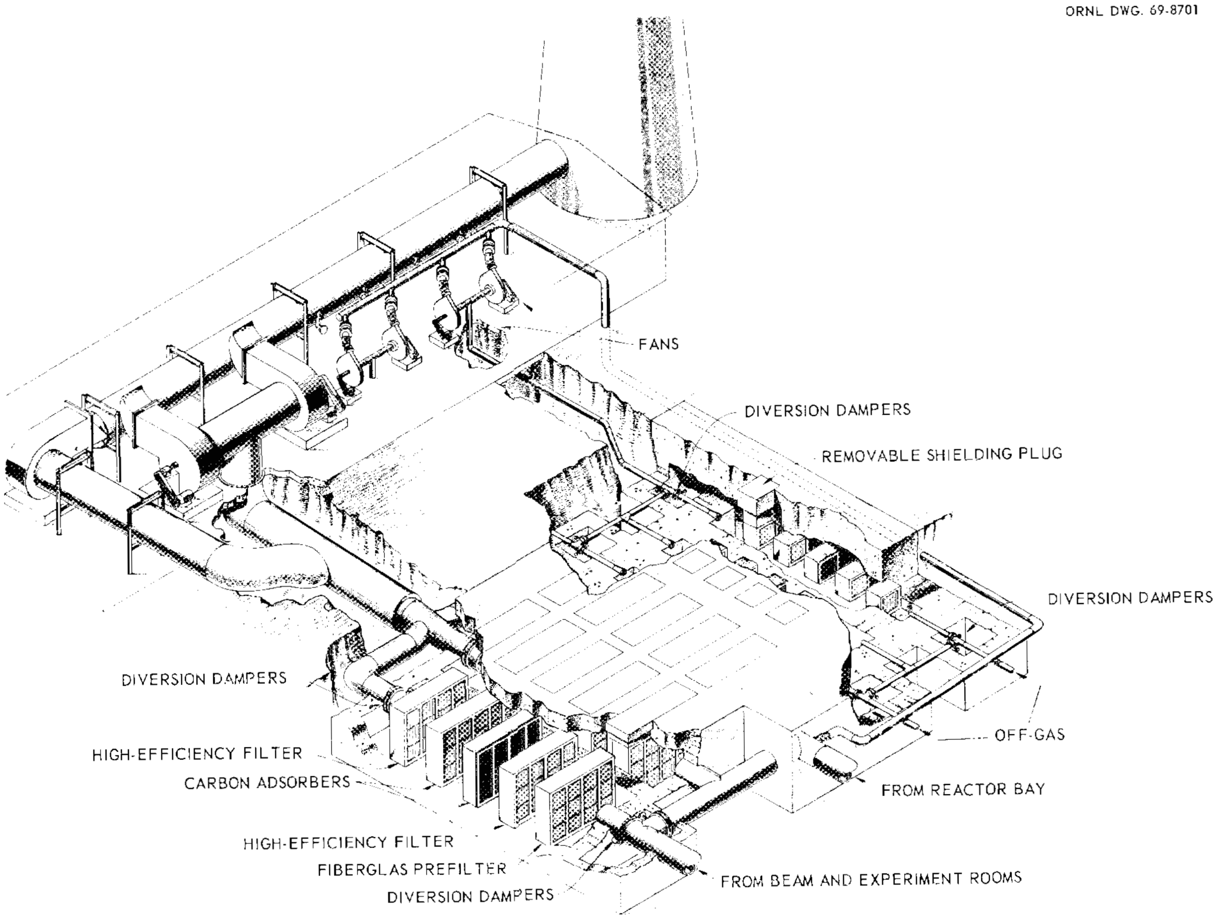

Fig. 2.10. Compartmented filter system for a nuclear reactor. Continuous off-gas system at right, continuous building exhaust system at left. Each system consists of three independent, interconnected subsystems, two of which are normally on line. Courtesy Oak Ridge National Laboratory.

Reactors having exhaust filter systems which are operated only in an emergency may also require parallel systems to avoid shutdown of the reactor during servicing of the filters (one filter system must always be ready for operation while the reactor is running) and to provide for continuous ventilation during an emergency should the filters in the on-line system fail.

2.4.8 Location of Filters

The location of filters in an exhaust air cleaning system plays a large part in minimizing filter damage and spread of contamination in the event of fire or accident. A not uncommon practice has been to install filters at random in unused building or attic spaces. The typical filter installation at too many sites is a non-fire-resistant open-face filter clamped between two duct transitions. Filters are too often located behind ducts, pipe, conduit, or other obstructions to easy access. All of these conditions are illustrated in the filter installation shown in Fig. 2.11.

Installations such as this are hazardous from several standpoints. First, the obstructions and lack of a floor or catwalk make service and inspection difficult and dangerous. Second, being located in an open attic, dropping of a used filter during a filter change could result in spreading contamination throughout the attic, which would be difficult, if not impossible, to clean up. Should there be a fire in the attic, the wood case could be breached, releasing contaminated dust to the attic and permitting smoke, flame, and contamination to get to the occupied areas below. Conversely, should fire

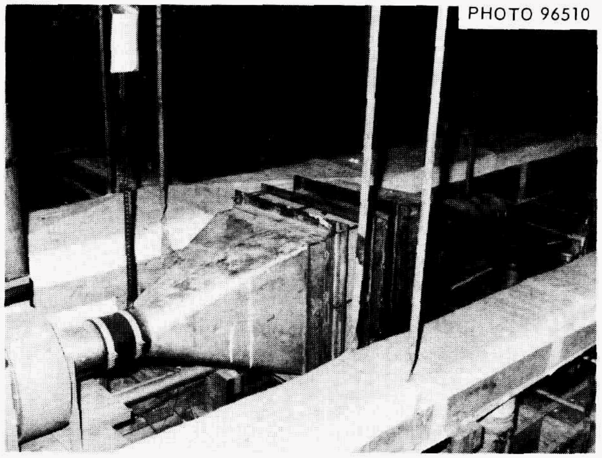

Fig. 2.11. An illustration of poor filter-installation practice. Note unprotected wood-cased filter simply clamped between two transitions; difficult access for service; location in open attic; lack of floor or catwalk. Courtesy Oak Ridge National Laboratory.

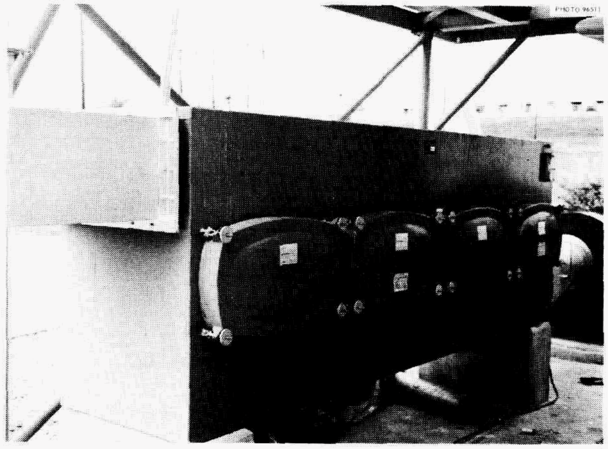

Fig. 2.12. Filter enclosure designed for "bag-in, bag-out" filter change. Courtesy Oak Ridge National Laboratory.

from the operating area reach the filter and should the fan fail at the same time, the wood case could be breached and spread smoke, fire, and contaminated dust to the attic. In-duct installations of this type, where the wood case of the filter actually becomes a continuation of the duct walls, do not conform with a strict interpretation of NFPA Standard 90-A[17,18] and are not recommended for nuclear applications. If such installation practices must be used, the filters should be installed in a windowless room that meets zone II criteria or better.

Another common practice is to install filter housings on the roof of a building with access only over the roof. This also presents the possibility of contamination spread should a used filter be dropped during maintenance, not only to a surface which would be very difficult to decontaminate but to the atmosphere as well. Wherever possible, exhaust filters and filter housings should be installed indoors in heated and easily accessible areas. Preferably, these should have floors and walls that can be easily decontaminated in the event of a spill and should be controlled areas (zone II) that can be cordoned off or closed off from surrounding building spaces so they can be managed as contamination zones. Restrictions on location of filters can be relaxed somewhat where they are installed in steel enclosures such as the Caisson[19] shown in Fig. 2.12. This enclosure (and also the HGS and Vokes, Ltd., enclosures) is designed so that filters are inserted and withdrawn in plastic bags (the "bag-in, bag-out" procedure is discussed in more detail in Chap. 6). Even with such enclosures, installation inside the building, with surrounding areas manageable as contamination zones, is recommended.

2.5 MAINTENANCE

Maintenance is one of the largest cost factors that can be controlled during the design of an air handling system. Inadequate attention to maintenance requirements and procedures can result in operating costs many times as high as they should be. Two factors that largely influence the cost of maintenance are the frequency and ease of replacing filters. In exhaust systems handling radioactive contaminants the frequency of filter change and the time to accomplish the change can be especially critical, as the total integrated radiation dose a workman can be permitted to receive in a given calendar period is limited. When all personnel have received their maximum dose for the period, the supervisor faces the prospect of no personnel to carry out a needed filter change. Maintenance of nuclear plant exhaust filters is much more costly than that of noncontaminated filter systems because of the time required for personnel to change in and out of protective clothing and to decontaminate and clean up

[17]NFPA Standard 90-A, *Air Conditioning*, National Fire Protection Association, Boston, 1967.

[18]Personal communication, R. E. Stevens, National Fire Protection Association, to C. A. Burchsted.

[19]Copyright, Nuclear Safety Systems, Inc.

the area, decontaminate tools and equipment, dispose of used filters, and bathe and be surveyed by health physics monitors after the filter change. The fact that personnel have to work in clumsy protective clothing, including respirators or full-face gas masks, also adds to the time required for radioactive filter replacement. Aside from cost, proper maintenance is a primary factor in assuring the reliability of the filter system, and it cannot be done properly if the facility has been improperly designed and built.

2.5.1 Frequency of Maintenance

All measures that reduce filter replacment frequency (both HEPA filters and prefilters) reduce maintenance cost and system downtime. Several of the factors discussed previously – operation to high pressure drop, underrating, efficient building supply air filters, and prefilters – serve to extend filter life and to reduce the frequency and costs of maintenance.

2.5.2 Ease of Maintenance

Ease of maintenance consists of two factors: accessibility and simplicity of maintenance procedures. Simplicity of maintenance is a primary factor in minimizing the time required for personnel to be inside contaminated filter housings or contamination zones, and therefore a primary factor in reducing personnel exposure to radiation.

2.5.3 Accessibility

In laying out filter systems the designer must consider the location of the filters, working space adjacent to and inside the filter housing, spacing of banks, height of banks, finger space between filter elements, and methods to be used for moving new and used filters between storage, installation, and disposal areas. Management, design, and engineering personnel who are not aware of the real costs and problems of maintenance often find it difficult to understand the need for allowing ample room for filter systems and mechanical equipment and are often unwilling to provide such space in view of the high cost of buildings. Failure to provide adequate access and adequate space in and around filter systems and mechanical equipment results in high maintenance costs, inhibits proper care and attention, and thereby reduces the reliability of the system, creates safety hazards, and increases the chance for accidental spread of contamination during maintenance operations. Recommendations for arranging and spacing filter systems and components for adequate access are given in Chaps. 4, 5, and 6.

2.5.4 Simplicity of Maintenance Procedures

Simplicity of maintenance is achieved by:

1. A layout that minimizes reaching, stooping, and the use of ladders or temporary scaffolding for gaining access to filters. Reaching and stooping are unavoidable in bank systems; in single-filter installations, however, it should not be necessary for workmen to go through physical contortions or climb ladders to remove and replace filters.
2. Adequate finger space (2 in. recommended) between filter elements.
3. Provision for aligning and supporting filter elements during filter change. See par. 4.3.5.
4. Simple filter clamping devices. A properly designed bolt-and-nut clamping system has proven most satisfactory. Although toggle clamps, cam-operated devices, and other more sophisticated devices may be more quickly operated with fewer tools, they tend to jam or become difficult to operate after extended exposure to the environment of a contaminated exhaust system. See par. 4.3.4.
5. Elimination of ledges and sharp corners over which the workman might stumble or which might snag and tear his protective clothes.
6. Adequate lighting and ventilation in the filter housing.
7. Communication ports or portable talker systems to permit personnel inside and outside of the housing to converse easily and clearly.
8. Floor drains within the housing and in the adjacent working area to facilitate easy removal of water after cleanup of the area following a filter change.
9. Electrical, water, and compressed air services nearby, but not inside the filter housing.
10. Provision of materials-handling facilities, including dollies for moving new and used filters to and from the installation site, and elevators for moving loaded dollies up and down within the building.
11. Rigid, hinged doors on filter housings, large enough for an erect man carrying a loaded filter carton (26 X 26 X 12 in. X 40 lb) to pass through without stooping or twisting, and with vacuum breaks to aid in opening when the fan is operating. Sliding doors are not suitable since they may jam with any distortion of the housing. Bolted closures are too time consuming, and nuts often jam to the extent that the bolt must be cut off to open the hatch.

12. Nearby decontamination and clothing-change facilities (including showers).
13. Well-planned maintenance procedures.

2.5.5 Construction

Design for maintenance requires careful attention to construction, tolerances, surface finishes, and the location of adjacent equipment and service lines. Ducts and housings should be laid out with a minimum of ledges, protrusions, and crevices that can collect dust and moisture, or which can impede personnel or create a hazard in performance of their work. Easily openable inspection ports and hatches must be provided at strategic and accessible locations in the ducts. Duct runs should have enough mechanical joints to permit easy erection and dismantling -- replacement of radioactively contaminated ducts can be very expensive because of the special procedures necessary to prevent radiation hazards to personnel and the cost of shipping the contaminated materials to an approved burial ground for disposal.

Housing, filter mounting frames, and ducts must be able to withstand anticipated system pressures without distortion, fatigue, or yielding of such magnitude that inleakage or bypassing of the filters results. Ability to meet an air pressure test of ±12 in. H_2O for 1 hr without excessive distortion or leakage is often specified for filter housings to be used in contaminated exhaust systems.

The quality of interior surfaces and finishes warrants special attention. When coatings are permissible, various finishes can be used, depending on the nature of the environment. Regardless of the formulation of the coating, a primary factor in long and dependable service is proper preparation of the surface to be coated. All coated (i.e., painted) metal surfaces exposed to exhaust air and gases should be sand blasted to white metal (see Chap. 4), and the first primer coat should be applied within 4 hr of blasting. In no case should the blasted surface be permitted to stand overnight before being primed. Ducts should be thoroughly purged before installation of charcoal adsorbers.

2.6 THE VENTILATING SYSTEM

A filter system cannot be designed without considering the ventilation system of which it is a part, nor can the ventilation system be designed independently of the filter system. Filters often constitute the largest single source of resistance and are usually the most demanding components from the standpoint of maintenance. Inadequacies in the filter installation will impair performance of the ventilating system, and deficiencies in the ventilating system will result in lower performance, reduced reliability, or higher costs of filters. In addition to the filters, important parts of the ventilating system are the fans, ducts, dampers, and instruments. Location of building air intakes and stacks and noise are important design considerations.

2.7 FANS

Air flow rate (air changes per hour in the operating areas of the building) is often a primary operating requirement for exhaust systems. The filter change interval, however, is usually determined by the maximum permissible pressure drop across the filters (i.e., the dirty-filter pressure drop). Centrifugal fans (blowers) are generally used in exhaust systems. Because the variable resistance of the filters from time of installation to time of replacement is a major factor influencing the pressure-flow requirements of the system (i.e., the system characteristic, curve 1 in Fig. 2.13), a fan with a steeply rising pressure-flow characteristic is desirable to maintain reasonably constant air flow over the entire life of the filters. The volume of air delivered by the fan is determined by the intersection of its characteristic curve with the curve representing the resistance of the system. The flow represented by this point of intersection is the only flow that can be delivered under those operating conditions. As system resistance increases with dirt loading of the filters, the volume of air that can be delivered by the fan decreases as shown in Fig. 2.13. If a fan with a broad, flat characteristic is selected – as is sometimes done – the fan will not be capable of delivering the required air flow when the filters become loaded, and so filter life may be sacrificed in order to maintain the required air flow in operating areas of the building.

If, in the system having the broad characteristic in Fig. 2.13, the filters were kept until the maximum dirty-filter pressure drop were reached, the fan would be operating on a very unstable portion of its curve, and even a slight variation in the resistance of the system – which can be caused by opening or closing a damper in the ducts leading to the fan, by opening or closing a filter housing door, by a variation in operation of the building supply-air fans, or by variable wind conditions outside of the building – might push operation of the fan to the left of the peak of its characteristic, or perhaps cause operation to "hunt" back and forth from one side of the characteristic peak to the other. This instability of operation can cause excessive and even destructive pulsation.

Fans must be sized to deliver the required air flow against the total resistance of the duct system plus the maximum resistance of the dust-loaded filters. Because some duct-system losses cannot be accurately calculated or may be overlooked, some extra capacity (at least 5%) must be provided when sizing the fans required for a specific application. Experience has shown that fans are too often undersized to meet the actual demands of the duct system as installed, and sacrifices in performance or efficiency must be made. In push-pull systems (i.e., systems containing both building supply and exhaust fans) the exhaust fan capacity should be at least 10% greater than the supply fan capacity to compensate for infiltration, pressure surges, and temperature effects and to remove any possibility of overpressurizing the building by the supply fans. However, sizing of fans must be approached with caution. A fan that is too greatly oversized may adversely affect total ventilating system performance as much as one that is too small. Fan operation must be stable during all conditions of system operation (see above); this means that the fan must operate well beyond, on the high-pressure side, of the peak of its characteristic. Improper fan operation can be avoided only by carefully evaluating the system pressure drops under all operating conditions and by specifying a type and size of fan that matches the demands of the duct system as installed. Allowance must be made for the fact that the true characteristic curve of the fan, after installation in the exhaust system, may differ greatly from the idealized curves published by the fan manufacturer, which are often exaggerated for even the ideal conditions. Selection must be based on total fan pressure, not on static pressure alone, and on a careful summation of system resistances, including fan inlet and outlet losses. Selection on the basis of static pressure often results in a fan that is grossly undersized for the service conditions.

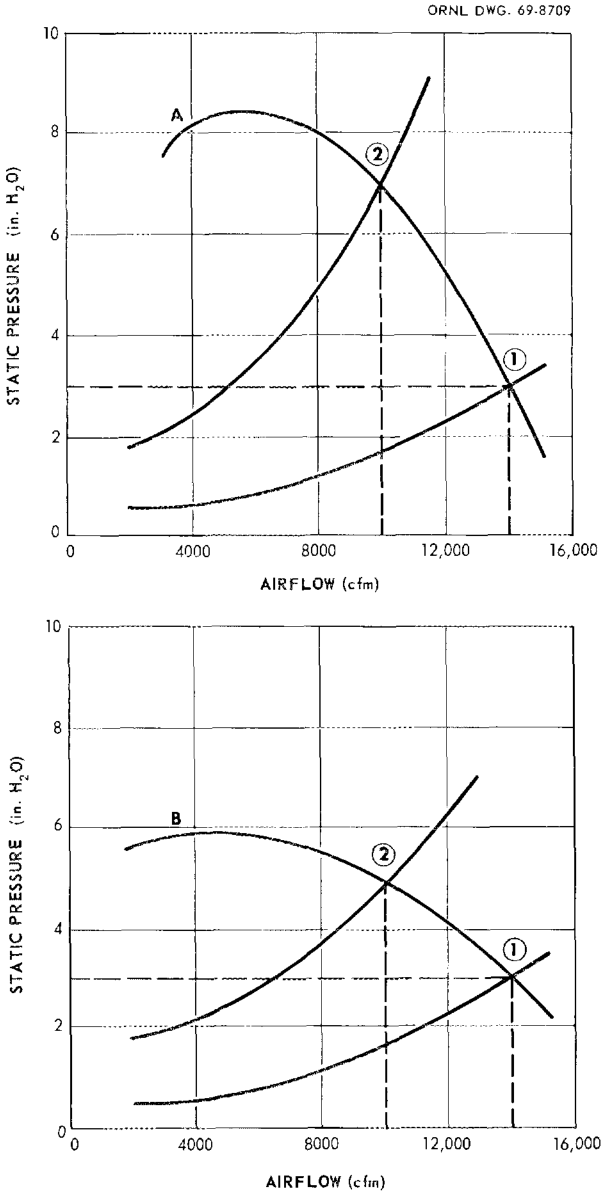

Fig. 2.13. Effect of fan performance on filter system performance. System air flow can vary from 14,000 cfm to a minimum of 10,000 cfm. Constant-speed fans, no dampers or speed control. Initial system resistance with new filters is 3 in. H_2O gage, including 1 in. H_2O pressure drop across filters. Fan A, with backward-inclined airfoil blades, has a steeply rising characteristic that permits operation of filter system to economical pressure drop (5 in. H_2O across filters). With fan B, having a broad, flat characteristic, filters must be replaced at 2 in. H_2O pressure drop in order to maintain minimum system air flow of 10,000 cfm. If filter resistance goes higher, fan B will be operating in unstable region near peak of curve.

Fans for nuclear reactor postaccident cleanup systems present special problems. When the fan and motor are located within the primary containment (e.g., recirculating system) they must be able to operate continuously for long periods of time both at normal containment conditions (negative pressure with respect to atmosphere, temperatures of 100 to 120°F) and at postaccident containment conditions, which may, in some reactors, be as high as 50 psig, 280°F, and air density as much as three times normal. Water cooling must be provided for the motor, with an alternate supply in event of failure of the first. An alternate filter system, an alternate motor, an alternate fan, or all three may have to be provided to ensure continuous operation in the event of failure. Since motors and fans to meet these conditions require special design, the owner must obtain documented proof of their ability to perform under such conditions, including calculations and actual test data pertaining to the items furnished. Acceptance tests are essential. In addition, regular performance tests should be made during containment pressure tests to check the continued reliability of the system.

Dependability of operation is an important consideration in fan selection. Seldom is a fan installed and operated under the ideal conditions used for rating the fan.[20] Even when the system is planned for part-time or intermittent operation, continuous operation may be required after it goes into service and should be considered as the norm in the original design. Savings in capital costs by specifying light-duty equipment are offset quickly by high maintenance costs after the system is in operation for a brief period. Roller bearings are preferred for fans over sleeve bearings because of their superior operating characteristics, lower maintenance, and the greater availability of replacement parts. Direct drive is more reliable than V-belt drive, although it is not as flexible for adjustable flow rates with changing system requirements. When V-belt drive is specified, one should provide at least 25% extra belts in addition to what is required to carry the starting load of the motor. This gives better wear characteristics and ensures continued operation in the event of belt failure. AMCA drive arrangement No. 4 or No. 8 is recommended.[21]

2.7.1 Fan Mounting

Proper mounting of a fan will minimize noise and vibration and reduce maintenance costs. Noise is objectionable in supply and exhaust systems and is very difficult and costly to eliminate after installation. Excessive noise may be accompanied by vibration or pulsation that may be harmful to filters and other equipment. Flutter or "reeding" of the separators is a common cause of HEPA filter failures. Vibration of charcoal adsorbers can cause settling and crushing of the granules and, eventually, carbon loss and leakage of contaminated air.

When possible, fan and motor should be mounted on a common base designed for vibration isolation. A typical base for large fans is shown in Fig. 2.14. The fan and motor are mounted on a concrete pad that acts as an inertial mat to limit the amplitude of vibration and to dissipate vibrational energy. The pad is mounted on spring isolators that afford a high degree (99% or more) of vibrational damping.

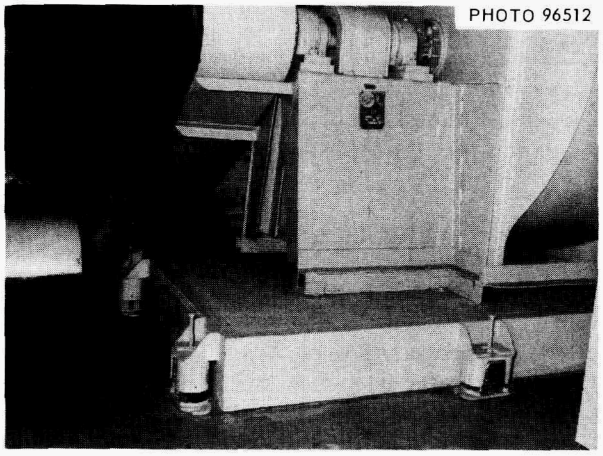

Fig. 2.14. Typical vibration isolation mounting for fans. Courtesy Oak Ridge National Laboratory.

Floors and walls adjacent to the fan and filter housing should be designed for minimum resonance. This can be done for simple structures by first determining floor deflection through the use of standard beam formulas[22] and then determining the vibrational frequency of the structure by the formula:[23]

$$f = \frac{187.7}{(y)^{1/2}}, \quad (2.4)$$

where

f = frequency of vibration of the structure in hertz,

y = deflection of supporting beams or floor under normal load, as determined from beam formulas, in inches.

For minimum vibration, the speed of the motor and fan should be at least 25% less than the frequency of vibration of the structure (i.e., beam or floor). Walls and ceilings of plenums can be checked by a similar method, using the deflection due to static pressure in the plenum for finding the frequency of vibration.

[20] *AMCA Standard Test Code for Air Moving Devices,* Bulletin 210, Air Moving and Conditioning Association, Inc., New York, April 1962.

[21] AMCA Standard AS-2404, *Fans – Arrangement of Drives,* Air Moving and Conditioning Association, Inc., New York, December 1965.

[22] *Manual of Steel Construction,* 6th ed., pp. 2-118–2-135, American Iron & Steel Institute, New York, 1965.

[23] C. J. Trickler, "Cause and Prevention of Fan Vibration," *NYB Engineering Letter,* No. E-9-r, New York Blower Co., Chicago.

Whenever possible, the fan should be mounted directly over a column to obtain maximum rigidity. A fan that is to develop a total static pressure of 3.75 in. H_2O or more should be test run at the factory and checked for vibration at the bearings and fan-housing extremities.[23]

2.7.2 Location of Fans

Fan location has a direct bearing on ventilating system performance. Fans in contaminated exhaust systems are normally located downstream of the filters and as close to the stack as possible. This places the fan in the most favorable location with respect to cleanliness and protection of personnel from contamination during maintenance and provides negative pressure in as much of the duct system as possible so that any leakage will be inleakage of clean air rather than outleakage of contaminated air to occupied areas of the building. There is evidence that some backleakage of particles from areas of low pressure to areas of high pressure can occur, however,[24] and the designer cannot depend on negative pressure alone for containment; attention to leak-tightness of ducts, filter housings, and fan casings is imperative, especially in high-activity systems. Locating a fan within the filter housing reduces duct transmission of noise and vibration, eliminates some ducting, and makes a flexible connection between fan and filter housing unnecessary; however, this may be a poor location from the standpoint of access and fan-entrant pressure losses.

2.7.3 Duct Connections

Many of the ills of fan operation stem from poorly designed duct connections. Close coupling, large-angle tapered transitions, square-to-round connections, elbow connections, and poorly designed inlet boxes create spinning or eccentric flow into the fan wheel and result in noise, vibration, and low efficiency. A 45° spin in the opposite direction to fan rotation may reduce fan delivery by as much as 25% and require an increase in fan static pressure of 50 to 55% to compensate. The effect of various types of inlet connections on fan efficiency and the increase in fan static pressure required to offset them are shown in Table 2.6. Too often these effects are not taken into account when calculating fan requirements, with the result that neither the fan nor the filters can perform to the intended design levels. When possible, a straight round duct at least three diameters in length or a 5%-maximum-taper round transition at least three major diameters in length is desirable. When large-taper inlets or inlet boxes must be used, they should be equipped with turning vanes.

Outlet connections also affect fan performance. A properly tapered outlet, for example, may produce a several-percent increase in static pressure, while a poorly designed outlet may substantially reduce the capacity of the fan. The effects of typical fan outlet designs on static pressure are shown in Fig. 2.15.

Rigid flange-and-bolt connections between fan casing and the duct or filter housing are not desirable because they permit direct transmission of fan noise and vibration to the duct system. Flexible connections are recommended. A frequent problem in flexible connections is tearing and pulling out of the fabric at the connector clamp. The connection shown in Fig. 2.16 overcomes these problems. The fabric consists of two layers of 32-lb neoprene-impregnated glass-fiber cloth, lapped so the ends are displaced from one another, and glued.

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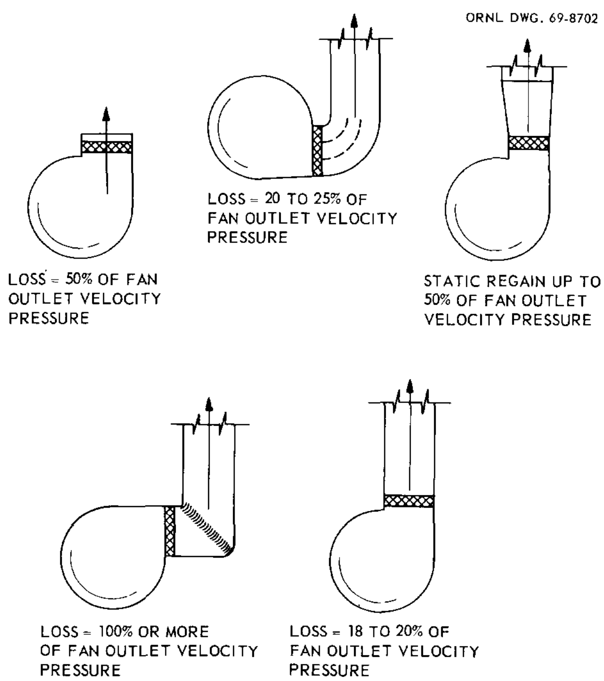
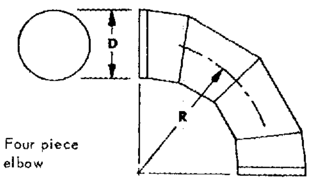
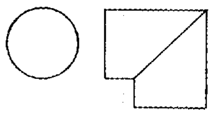
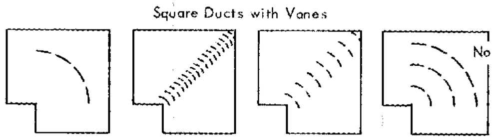
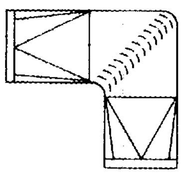
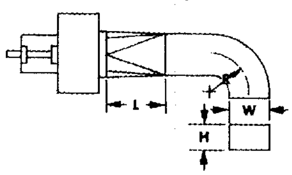
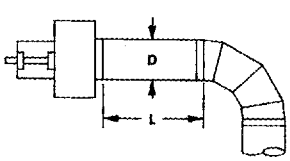


Fig. 2.15. Effect of fan outlet on fan performance.

[24]Personal communication, W. J. Soules, Eastman Kodak Co., to C. A. Burchsted.

Table 2.6. Effect of Fan Inlet on Fan Performance[a]

DESCRIPTION	PERCENT LOSS IN CFM IF NOT CORRECTED	PERCENT INCREASE NEEDED IN FAN SP TO COMPENSATE
 Four piece elbow		
Three piece elbow $R/D = 0.5$	12	30
1.0	6	13
2.0	5	11
6.0	5	11
Four piece elbow $R/D = 1.0$	6	13
2.0	4	9
8.0	4	9
Five piece elbow $R/D = 1.0$	5	11
2.0	4	9
8.0	4	9
 Mitered elbow	16	42
Square Ducts with Vanes  A B C D		
No Vanes	17	45
A	8	18
B	6	13
C	5	11
D	4	9
 Round to Square to Round	8	18
Rectangular Elbows without Vanes*  *In all cases use of three long, equally spaced vanes will reduce loss and needed sp increase to 1/3 the values for unvaned elbows. The maximum included angle of any element of the transition should never exceed. 30°. If it does, additional losses will occur. If angle is less than 30° and L is not longer than the fan inlet diameter, the effect of the transition may be ignored. If it is longer, it will be beneficial because the elbow will be farther from the fan.		
$\frac{H}{W} = 0.25$, and $\frac{R}{W} = 0.5$	7	15
1.0	4	9
2.0	4	9
$\frac{H}{W} = 1.00$, and $\frac{R}{W} = 0.5$	12	30
1.0	5	11
2.0	4	9
$\frac{H}{W} = 4.00$, and $\frac{R}{W} = 0.6$	15	39
1.0	8	18
2.0	4	9



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

No duct	Loss = 10%	SP needed = 23%
$L/D = 2\frac{1}{2}$	Loss = 8%	SP needed = 19%
5	Loss = 6%	SP needed = 13%
$7\frac{1}{2}$	Loss = 4%	SP needed = 9%
10	Loss = 2%	SP needed = 4%

[a]From C. J. Trickler, "Is the System Correctly Designed," p. 87 in *Air Conditioning, Heating, and Ventilating,* May 1960.

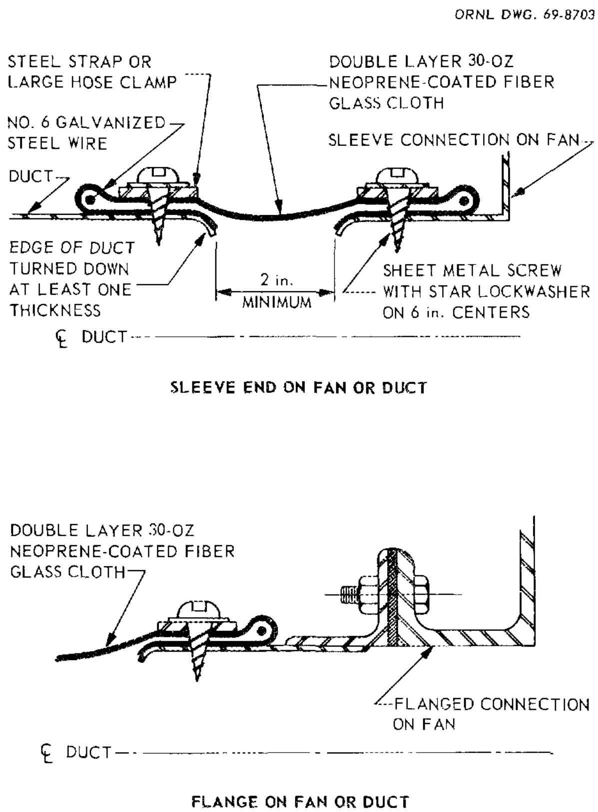


Fig. 2.16. Recommended flexible connection design.

2.8 DUCTS

The least expensive first-cost duct arrangement is often not the most economical when total annual operating costs are considered. Duct cost is influenced by the sizes and quantities of duct, materials of construction, the presence and types of coatings used for protection against corrosion, joint construction, the sequence of erection and installation, including a consideration of space limitations, posterection cleaning requirements, and the number and type of field connections and supports required. Consideration should also be given to future dismantling and disposal of the contaminated duct.

When space permits, round duct is preferred to rectangular duct because it is stronger and less likely to collapse under external pressure, is more economical of materials, provides more uniform air flow velocities, is easier to fabricate and erect, is easier to join and seal than rectangular duct, and is usually cheaper. The principal disadvantages of round duct are that it makes less efficient use of building space and that there is difficulty in making satisfactory side connections.

Guides to the functional design of duct systems are given in the *ASHRAE Guide and Data Book*,[25] USA Standard Z9.2,[26] and *Industrial Ventilation*.[27]

2.8.1 Duct Construction

Structural and mechanical design of duct for positive-pressure systems and negative-pressure systems that operate at static pressures of 2 in. H_2O or less can be in accordance with the SMACCNA high-velocity-duct design manual.[28] That manual is not suitable for the structural design of duct for systems which operate at static pressures of more than 2 in. H_2O.

Recommended structural requirements (sheet-metal thickness and size and spacing of reinforcements) for negative-pressure metal ductwork are given in Tables 2.7 through 2.10. Sheet-metal thicknesses of elbows and transitions should be one or two gage numbers thicker than straight runs; the sheet-metal thickness of transitions should be based on the major diameter. The sheet-metal thicknesses for round ducts are based on commercially available rolled sheets and include allowances for eccentricity (unavoidable in rolled-sheet construction) and corrosion. When drawn or extruded tubing is used, permissible wall thicknesses can be considerably less than those shown in Table 2.7; however, sched 5 or 10 pipe is recommended in most applications because of its ease of welding and availability. Sheet-metal thicknesses less than 24 gage (U.S.) are not recommended for rolled-sheet construction because of welding difficulties and the possibility of damage should workmen climb on to the erected duct. Spiral-welded duct can be used in considerably thinner wall thicknesses than rolled-sheet duct or tubing because the spiral weld acts as a reinforcement; however, it is not recommended where moisture or corrosive fumes may be present because the spirals act as condensation collectors.

Flanges at the end of duct sections for mechanical joints and reinforcement should be joined by a continuous seal weld at the duct entrance and reinforced with intermittent welds at the back of the flange, as

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[25] *ASHRAE Guide and Data Book – Applications*, American Society for Heating, Refrigeration, and Air Conditioning Engineers, New York, 1968.

[26] U.S. Standard Z9.2-1960, *The Design and Operation of Local Exhaust Systems*, U. S.A. Standards Institute, New York, 1960.

[27] *Industrial Ventilation*, American Conference of Governmental Industrial Hygienists, Ann Arbor, Mich., 8th ed., 1964.

[28] *High Pressure Duct System Design*, sect. 2, Standard of the Sheet Metal and Air Conditioning Contractors Association, Chicago, current edition.

Table 2.7. Recommended Sheet-Metal Thicknesses for Round Duct Under Negative Pressure

Factor of safety = 3 for ducts with diameters up to 24 in. and 5 for ducts with diameters over 24 in. based on paragraph UG-28 in Sect. VIII of the *ASME Boiler and Pressure Vessel Code.*

Negative Pressure in Duct	Reinforcement Spacing (in.)	Sheet-Metal Thickness (U.S. Gage No.) for Duct Diameter of —								
		4 in.	8 in.	12 in.	16 in.	20 in.	24 in.	36 in.	48 in.	60 in.
4 in. H_2O	∞[a]	24	24	20	18	16	14	10	8	4
	96	24	24	24	22	20	18	16	14	14
	48	24	24	24	24	24	22	20	18	16
	24	24	24	24	24	24	24	22	20	18
8 in. H_2O	∞	24	22	18	16	14	12	8	4	
	96	24	22	22	18	18	18	14	12	12
	48	24	24	24	22	20	20	16	14	14
	24	24	24	24	24	22	22	18	16	16
12 in. H_2O	∞	24	20	16	4	12	12	6	2	
	96	24	22	18	18	16	16	12	11	11
	48	24	22	22	20	18	18	14	14	12
	24	24	24	24	22	22	22	16	16	16
20 in. H_2O	∞	24	18	14	12	11	8	4		
	96	24	20	16	16	14	14	11	11	8
	48	24	22	20	18	16	16	14	12	11
	24	24	24	22	20	18	18	16	14	12
	12								20	16
1 psi	∞	20	14	12	10	8	6			
	96	24	18	16	14	12	12	10	8	6
	48	24	20	18	18	16	16	12	11	11
	24	24	24	22	20	18	18	14	12	12
	12								16	14
2 psi	∞	18	12	11	8	4	2			
	96	22	16	14	12	12	11	6	6	4
	48	24	18	16	14	14	12	10	8	6
	24	24	20	18	18	16	16	11	11	11
	12							14	12	12
4 psi	∞	16	12	8	4	2				
	96	20	14	12	11	10	8	4	2	
	48	20	16	14	14	12	12	8	6	4
	24	22	18	16	14	14	14	11	10	8
	12				16	16	16	12	12	11

[a]Where ∞ is shown, no reinforcement is required.

shown in Fig. 2.17. Intermediate reinforcements should have intermittent welds on opposite sides of the angle, as shown in Fig. 2.17, to avoid heat distortion of the duct. The total length of the intermittent welds should be somewhat greater than the total circumference of the duct.

Glass-fiber-reinforced epoxy or polyester plastic ducts are sometimes used in corrosive applications where fire and safety requirements permit, and they may be less expensive than stainless steel, lined carbon steel, or epoxy- or vinyl-coated carbon steel. Glass-fiber-reinforced plastic duct has been approved under National Fire Protection Association Standard 90-A for

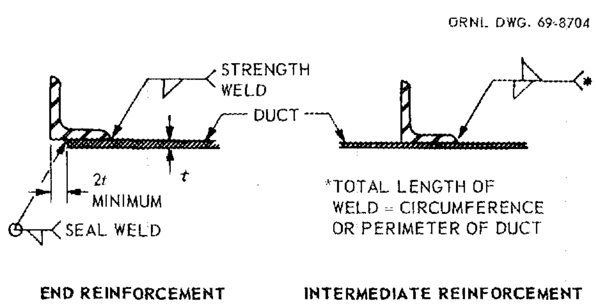

Fig. 2.17. Recommended welding for attaching reinforcements to ducts.

Table 2.8. Recommended ASTM A36 Angle Reinforcement for Round Duct Under Negative Pressure

Based on R. J. Roark, Formula 12, Table XV in *Formulas for Stress and Strain,* 4th ed., McGraw-Hill, 1965.

Negative Pressure in Duct	Angle Size[a] for Duct Diameter of –								
	4 in.	8 in.	12 in.	16 in.	20 in.	24 in.	36 in.	48 in.	60 in.
4 in. H_2O	A	A	A	B	B	B	B	C	C
8 in. H_2O	A	A	A	B	B	B	B	C	C
12 in. H_2O	A	A	A	B	B	B	B	C	C
20 in. H_2O	A	A	A	B	B	B	B	C	C
1 psi	A	A	A	B	B	C	C	C	C
2 psi	A	A	A	B	B	C	C	D	D
4 psi	A	A	A	B	B	C	C	D	D

[a]Symbol Angle Size (in.)

A = 1 × 1 × 3/16 B = 1½ × 1½ × ¼ C = 2 × 2 × ¼ D = 2½ × 2½ × ¼

Table 2.9. Recommended Sheet-Metal Thicknesses for Rectangular Duct Under Negative Pressure

Based on R. J. Roark, p. 246 in *Formulas for Stress and Strain,* Flat Plate Formula for Edges Held but Not Fixed, 4th ed., McGraw-Hill, 1965.

Negative Pressure in Duct (in. H_2O)	Reinforcement Spacing (in.)	Sheet-Metal Thickness[a] (U.S. Gage No.) for Longest Side of Length –				
		12 in.	24 in.	36 in.	48 in.	60 in.
4	48	24	20	16	14	
4	24	24	22	18	20	20
4	12	24	24	24	24	24
8	48	22	14	12	12	
8	24	22	16	16	14	14
8	12	24	22	22	22	22
12	48	18	12	8	11	
12	24	18	16	12	12	12
12	12	22	18	18	18	18
20	48	14	11	6	6	
20	24	14	14	11	11	11
20	12	20	14	14	14	14

[a]For maximum deflection of 1/16 in. per foot in the shortest dimension.

Table 2.10. Recommended ASTM A36 Angle Reinforcement for Rectangular Ducts Under Negative Pressure

Based on uniformly loaded beam with 50% simple support, 50% fixed ends, and deflection of ⅛ in. per foot.

Negative Pressure in Duct (in. H_2O)	Angle Size[a] for Ducts With Maximum Panel Size of –											
	12 in. by –					24 in. by –				48 in. by –		
	12 in.	24 in.	36 in.	48 in.	60 in.	24 in.	36 in.	48 in.	60 in.	36 in.	48 in.	60 in.
4	E	E	E	F	F	E	G	G	G	H	H	H
8	E	E	E	F	F	E	G	G	G	H	H	H
12	E	E	E	F	F	E	G	G	G	H	H	H

[a]Symbol Angle Size (in.)

E = 1 × 1 × 3/16 F = 1¼ × 1¼ × 3/16 G = 1½ × 1½ × 3/16 H = 2 × 2 × 3/16 both class 1 and class 2 ducting;[29] however, even high-temperature resins soften at 350 to 450°F and are destroyed at temperatures above 200°F under continuous exposure.[30] Because softening could lead to collapse and release of contamination, the use of plastic duct is not generally recommended for nuclear exhaust applications. Where it is used, sprinklers should be both inside and above the duct so as to protect against both internal and external fires. The actual cost of making satisfactory joints in plastic duct often far exceeds the duct manufacturer's advertising claim, often resulting in such high installation costs that the installed cost exceeds that of an equivalent stainless steel or lined pipe system.

Ductwork must be pressure tested under negative pressures of at least 1.5 times the maximum fan static pressure and at the normal operating temperature. Proof pressure must be held at least 12 hr. After the negative-pressure test the ductwork should be pressurized to about 3 in. H_2O positive and leak tested with a soap-bubble solution or a halogen leak detector. A good soap-bubble solution consists of equal parts of water, glycerin, and any domestic liquid dishwashing detergent. The test pressure must be maintained until every joint has been inspected.

2.8.2 Joints in Ductwork

Welded joints are preferred to mechanical joints in contaminated exhaust ductwork, although sufficient mechanical joints must be provided at strategic points for flexibility of erection and dismantling. Longitudinal seams should always be welded – lock seams are not sufficiently leak-tight. Soft-solder joints are not permitted because the solder will melt under high-temperature conditions, permitting the escape of contaminated air. The inert-gas-shielded metal-arc process (MIG) process is recommended for welding because it is fast, produces good-quality welds when made by a qualified welder, produces a minimum heat-affected zone, and can be easily performed in both shop and field.

When locating mechanical joints, the designer must give consideration to problems of dismantling and disposal of highly contaminated ducts. The length of duct sections between mechanical joints should be based on the lengths and weights that can be taken down and disposed of easily, keeping in mind that final disposal may entail shipment to an AEC authorized burial site by common carrier. Bolted and gasketed joints provide the most reliable mechanical joints. Flange faces should be from 1½ to 2 in. wide; no significant improvement in leakage integrity is gained by using wider flanges. Bolt holes should be spaced a maximum of 5 in. on center and, for uniformity, should straddle the vertical axis of round ducts. Bolt holes of adjoining sections should be match drilled and marked to facilitate erection in the field. Quarter-inch-thick neoprene gaskets (40 to 60 Shore A durometer) are usually suitable. Large ducts should be constructed with the necessary strength to resist not only operating pressures but also external loads imposed by snow (if installed outdoors), thermal expansion, and personnel walking or climbing on them.

2.8.3 Duct Coatings

Coating and painting requirements must be consistent with the corrosion expected in the application and with the size of the duct. Unless special spray heads are used, spray coating of the interior of ducts smaller than about 12 in. in diameter is often unreliable, as it is not possible to obtain a perfect coating and inspection is difficult. Since ducts 8 in. in diameter and smaller cannot be properly brush painted, dip coating is recommended. The length of ducts that are brush painted should be no longer than 4 ft to ensure proper coverage. When special coatings (high-build vinyls or epoxies) are specified, the designer should keep in mind that difficulties in application and special inspections may increase costs of coated carbon steel duct to the point that stainless steel may be economically competitive, as well as perhaps being more satisfactory. It is important to note that protective coatings may be damaged during shipping, handling, and erection. Under service conditions, corrosion then occurs under the coating. Where plastic-lined duct is specified, static testing for defects and "holidays" must be required.

2.9 VENTILATING SYSTEM CONTROL AND INSTRUMENTATION

Air flow in operating areas can be controlled by the use of dampers, inlet vanes on the fan, or fan-speed variation. The simplest, often most effective, but least economical method is by the use of dampers. Throttling of flow by the damper introduces an additional system resistance which alters the characteristic of the system (see Fig. 2.13) and requires additional power. The use

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[29] Personal communication, R. E. Stevens, National Fire Protection Association, to C. A. Burchsted.

[30] Personal communication, M. W. First, Harvard Air Cleaning Laboratory, to C. A. Burchsted.

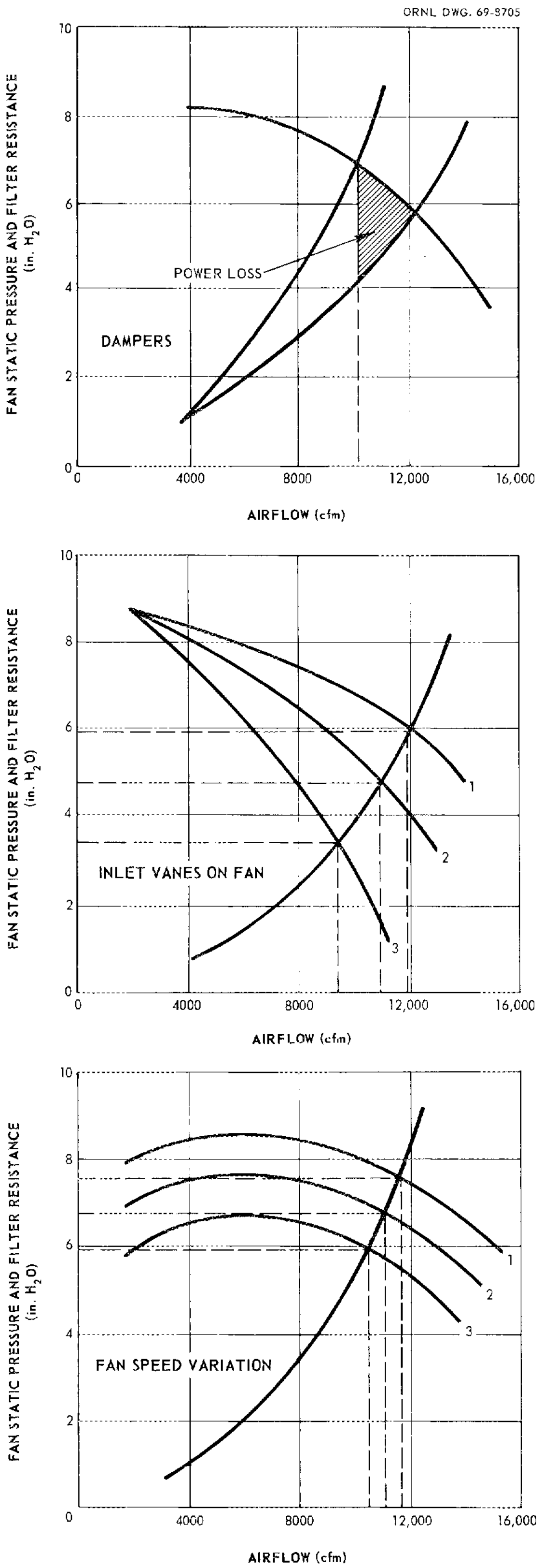

Fig. 2.18. Comparison of fan and system operating characteristics with different methods of controlling air flow.

of inlet vanes on the fan alters the shape of the fan characteristic by varying the size of the inlet, and control is effected without power loss in overcoming an additional system resistance. Some loss of power does result from reduced efficiency of the fan as the vanes are closed. The most economical method (from the standpoint of operating costs) is by speed control, which shifts the operating point of the fan, as shown in Fig. 2.18. The cost of effective speed control equipment is high but is coming down with new developments in the electric motor and control industry. Throttling dampers are required in most systems for branch-line control, apart from any requirement for total system air flow control, and the effect of these dampers on the system must be considered in duct design and motor and fan selection.

2.9.1 Automatic Control

Automatic control of nuclear plant exhaust systems is recommended only where system response must be more rapid than is possible with personnel-response control. Automatic control systems are costly to buy, install, and maintain and often do not give satisfactory operation in contaminated exhaust systems. Malfunction at the time of an emergency or power failure could jeopardize the safety of the ventilated area. Upkeep of a system where high reliability is needed involves recurring high maintenance and testing costs throughout the life of the system and requires the services of highly skilled instrument technicians, who may not always be available. Experience in several AEC facilities indicates that automatic control should be approached with great caution, no matter how attractive it appears from the standpoint of operational efficiency. The present trend is away from automatic control, even in low-confidence systems.

It should not be construed that there is a trend away from specific-purpose automatic safety devices and controls, however. Systems that detect and warn of unsafe conditions are a necessity, but in many instances the necessary corrective action can be accomplished more reliably, and at less expense, by the usual personnel-response methods than by an infrequently used automatic device.

2.9.2 Dampers

Clear, concise specifications must be established for mechanical strength, leakage rate at maximum operating and emergency conditions, and ability to perform under required operating and emergency conditions. Operability must be guaranteed by specification of minimum torque requirements under full load, and static water testing should be specified to prove the strength of the damper. All features important to proper operation should be specified in detail, including materials of construction, permissible lubricants, bearings, blade design, blade edgings (if permitted), locking quadrant, supports, and accessibility of linkages, blades, and bearings for maintenance.

When large dampers are required, the multiblade louver type is generally used; however, the availability of large low-leakage multibladed dampers that are suitable for contaminated exhaust service at static pressures less than 5 in. H_2O is limited. Large dampers, both louver and butterfly types, that are commercially available at reasonable cost usually leak at these pressures, and it is necessary to resort to liquid-service pipeline butterfly valves. Metal-to-metal seating is preferred for louvered dampers, as edge coverings may deteriorate rapidly when exposed to corrosive environments and are very difficult to replace without removing the entire damper from the duct, a serious drawback in a contaminated exhaust system. Carefully aligned metal-to-metal-seat blades with airfoil cross sections offer the best louver-type damper design for reliable operation. Butterfly valves for pipeline service have many times the structural strength required for air handling service, and the designer is forced to pay a penalty in cost, weight, and space to use them. Nevertheless, very low leak-rate and high reliability requirements often justify their use. Butterfly valves should have resilient elastomer seats that are compatible with the corrodents carried in the exhaust system. Since these seats form dams that can trap dust, moisture, and corrosive condensates, the valves should be installed in vertical or steeply sloping runs of duct wherever possible.

Motor-operated, manually controlled dampers are desirable where remote operation from a central control panel is required. Motorized dampers permit rapid adjustment and save time of operating personnel when located in inaccessible areas; for areas where it is necessary to exclude personnel, motorized dampers may be the only alternative. All dampers must be arranged to fail in a safe condition.

2.9.3 Instrumentation

Safe and reliable operation of a ventilating system requires instrumentation to monitor critical conditions. These include air flow resistance (pressure drop) across each bank of filters (not across the total filter system!) and air flow rate at critical points in the duct system such as entrances to fume hoods, machine-tool hoods, and gloved-box loading ports. Quality instruments with accurately engraved, legible scales and settings, rugged enough to withstand continuous operation under less-than-ideal conditions, and durable enough to last for the life of the installation are essential. Interconnecting tubing, preferably of stainless steel, must be attached securely to the filter housing or surrounding structure.

The principal requisite for locating instruments is accessibility. An instrument that is beyond easy reach or out of sight will not be maintained or used. Instruments should be located at eye level or only slightly below. Panel mounts should be provided for fragile items or those which require back access for service or adjustment. Instruments are adversely affected by vibration, particularly those with delicate electrical contacts or springs, and should be installed on vibration isolators or panels that are mounted on vibration isolators. Where stable support is not available, the panel should be mounted on its own standard. Instruments with related functions should be grouped on a single panel, as shown in Fig. 2.19, so that operators can correlate related readings such as pressure drop across filters and velocity-pressure readings (which indicate air flow rate) without going to several locations.

The installation of instruments outdoors should be avoided whenever possible, but not at the expense of greatly extended sensing lines that would decrease

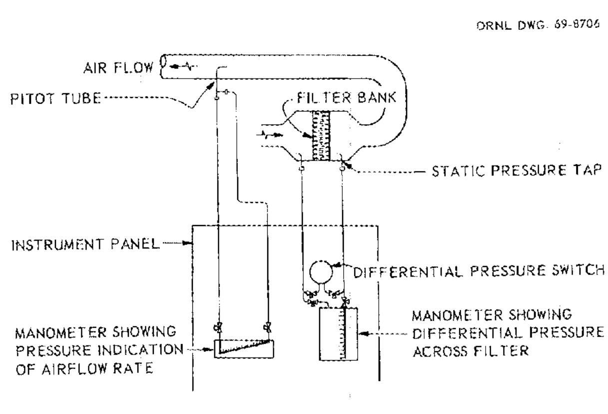

Fig. 2.19. Grouping of instruments with related functions.

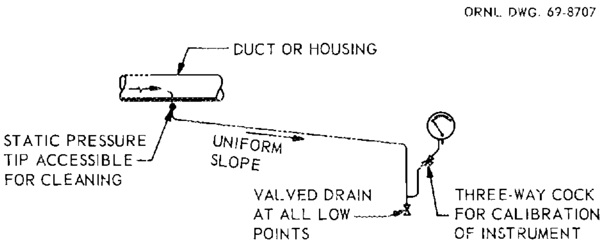

Fig. 2.20. Proper installation of sensing lines.

sensitivity and reliability, or at the expense of inaccessibility. When located outdoors, the instruments must be protected from the weather. Low temperatures can freeze or congeal the indicating liquid in manometers and can cause condensation and freezing of water in sensing lines. Outdoor instrument lines must have provision for bleeding, and they should be heat traced. Liquid manometers, particularly the plastic types, must be shielded from direct sunlight because the dyes used for coloring the graduations and the indicating liquid will discolor or fade. Raintight electrical cabinets, NEMA Class 3,[31] are recommended for outdoor instrument enclosures.

In low-hazard areas of the building and where easy access is possible, the requirements for pressure drop readings may be met by providing a sealable connection to which portable instruments can be connected; a length of tubing that penetrates, and is welded to, the housing or duct is satisfactory. For critical locations (e.g., the central exhaust filter system), permanently installed pressure drop instruments, either liquid-filled manometers or aneroid type, should be provided in an accessible location close to the monitoring point and also at a central control panel. The location, number, and size of all pressure taps must be specified in the original design.

Air flow measurements (velocity) are essential for surveillance and control of the ventilation system, especially where velocity is the major system characteristic (as in fume hoods), where pressure differentials between sections of a zoned facility are low, or when the rate of air change is a determining characteristic of normal system operation.

Pressure transmission lines must be kept as short as possible to minimize the time response of indications. Sensing lines for small signals, such as velocity pressure (total pressure minus static pressure) lines from a Pitot-static tube, must have a minimum of bends and flow restrictions so that displacement of air through them can take place within a reasonable response time. Sensing lines should be rigid to prevent expansion under pressure that would give false readings or multiply short-term variations. Figure 2.20 illustrates the proper installation of pressure transmission lines.

2.10 AIR SAMPLING

Air samples are often taken from the stack or other locations downstream of the filters to monitor the amount of radioactivity in the air being released to the atmosphere. If the sampling system is not properly designed, false readings and underestimation of the true amount of escaping radioactivity may result. The element often at fault is the sampling line itself. If too long or too small in diameter (relative to flow velocity in the line), it may act as a diffusion tube to remove small particles or as an inertial separator to capture large particles before they can reach the counting and recording equipment. Sharp-angle bends, valves, and other flow restrictions must be minimized to avoid losses due to inertia, impaction, and impingement. Horizontal runs must be minimized to avoid gravitational settling. Conduit diameter must be large enough, consistent with flow velocity, to minimize diffusion losses and turbulence that can cause migration of particles to the conduit walls, where they may be captured (turbulence in sampling lines can take place at a Reynolds number of 1200 or lower).[32] The optimum sampling line diameter, considering both line losses and practical limitations on line size, can be found from the formula:[33]

$$d = \frac{Q}{150}, \tag{2.5}$$

where

d = diameter of sampling conduit, cm,

Q = sampling rate, cc/sec.

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[31] *Enclosures for Electrical Control,* National Electrical Manufacturer's Association, NEMA Standard IC-4-1958, New York, 1958.

[32] Personal communication, J. W. Thomas, USAEC Health and Safety Laboratory, to C. A. Burchsted.

[33] J. W. Thomas, "Particle Loss in Sampling Conduits," *Proceedings of the Annual Conference of the International Atomic Energy Agency,* Vienna, 1967.

Sampling nozzles should be sized for isokinetic sampling, and lines should be as short as possible between the nozzle and the counting instruments, which should be located as close to the sample point as possible (some stack sampling installations are installed on the stack, at the same level as the sampling point). Sample lines should be metal, preferably stainless steel; they must be clean and smooth on the inside and should be detachable to permit field cleaning. Oil and moisture on the inner surfaces of sample lines will trap particles and give false readings. Instrumentation and counting equipment must be located in a low-radiation background area or be shielded.

2.11 AIR INTAKES AND STACKS

The location of building air intakes and discharge stacks is often inadequately treated during the design of the ventilation system. If air intakes are too close to the ground, blowing sand, dust, and other particulate matter will be drawn into the building, plugging or reducing the life of supply air filters (or exhaust filters if supply air filters are not provided or if only low-efficiency supply air filters are provided). Exhaust fumes from nearby streets or from vehicles standing close to the intakes may also be drawn into the building supply air system and discharged to occupied areas. Grass clippings and leaves may cover the screens of intakes located too close to the ground, causing unnecessarily high system resistances. Intakes must be sited to protect them from snow, ice, and freezing rain during the winter months, and baffles must be provided to give protection from driving rain and to minimize the effect of wind. Wind pressure can have an appreciable effect on flow rates in a low-head system and can cause pulsations that may disrupt differential pressures between control zones.

The average wind direction and weather conditions that are likely to cause stack discharges to come close to the ground (the phenomena known as looping and fumigation) close to the point of emission must be analyzed in establishing the location of both stacks and intakes. Intakes located downwind of an exhaust stack may result in drawing contaminants directly back into the supply air system. Intakes located downwind of shipping docks will draw noxious vehicle exhaust fumes into the building. Intakes located close to a roof may have the same problems as those located too close to the ground.

Low exhaust stacks should be avoided because of the possibility of drawing fumes into open windows or intake systems of adjacent buildings or into the same building from which they were exhausted. Buildings and unevenness of the ground nearby may cause eddies, whirls, or stagnant air pockets (the presence of a hill with a slope steeper than 15° is sufficient to create a stagnant zone adjacent to it, for example). A stack height of not less than 12 ft above the highest point of the building or of any adjacent building within 500 ft, whichever is higher, is recommended. Deflectors or rain caps should not be installed on stacks from air cleaning systems serving radioactive exhaust systems. Either of the vertical discharge caps shown in Fig. 2.21 provides excellent rain protection for the stack with no pressure loss.

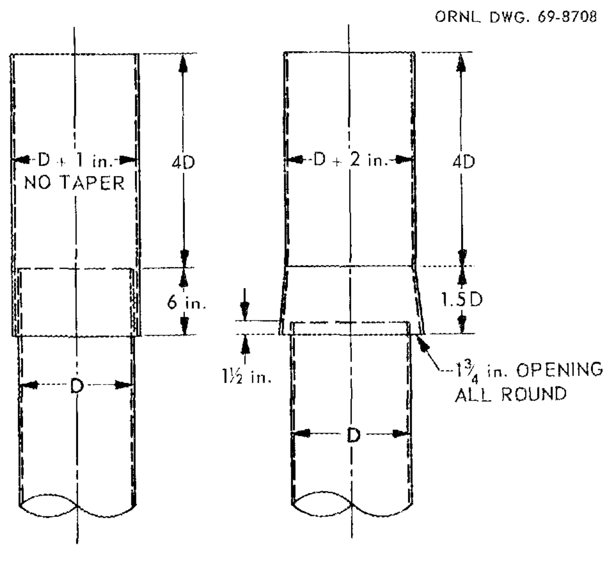

Fig. 2.21. Recommended discharge cap for stacks of radioactive exhaust systems. The rain protection afforded by these caps is superior to that provided by a conical cap located at 0.75D from the top of the stack. From *Industrial Ventilation*, American Conference of Governmental Industrial Hygienists, Ann Arbor, Mich., 8th ed., 1964.

3. Components

3.1 INTRODUCTION

The primary component of a nuclear plant exhaust system is the high-efficiency particulate air (HEPA) or "absolute" filter. Most systems also include a prefilter, and some reactor and radiochemical plant systems will also include activated charcoal adsorbers for trapping radioactive gases, moisture separators, or both. This chapter reviews characteristics, construction, and limitations of these components. Other types of air cleaning equipment such as scrubbers, cyclones, settling chambers, bag filters, and electrostatic precipitators are not commonly used in these applications and are beyond the scope of this manual.

3.2 HEPA FILTERS

HEPA filters (also known as absolute, super-interception, very-high-efficiency, extreme efficiency, AEC, and CWS [for Chemical Warfare Service] filters) are by far the most satisfactory and economical devices for removing submicron particles from air and gas streams at extremely high collection efficiency. By definition,[1] an HEPA filter is a throwaway, extended-medium, dry-type filter having (1) a minimum particle removal efficiency of no less than 99.97% for 0.3-μ particles, (2) a maximum resistance when clean of 1.0 in. H_2O when operated at rated air flow capacity, and (3) a rigid casing extending the full depth of the medium. A sample procurement specification for HEPA filters is given in Appendix A.

3.2.1 Performance

Efficiency and Resistance. – The efficiency and resistance of each HEPA filter are determined by the manufacturer before it is shipped from the factory, using procedures developed by the Army[2] and the USAEC.[3] Most AEC contractors require a confirming test by one of the two AEC Quality Assurance Stations (Oak Ridge, Tennessee, and Richland, Washington)[4] before accepting the filters. This confirming test is an important factor in quality control and is recommended also for nongovernment operators. The service is available from the AEC at cost.[5] Both manufacturer's and Quality Assurance Station efficiency tests employ a monodisperse, thermally generated dioctyl phthalate (DOP) aerosol.

The American Association for Contamination Control (AACC) standard[1] for HEPA filters lists three classes with respect to performance: type A filters, which are tested for overall penetration (i.e., 100 minus efficiency) at rated flow only; type B filters, which are tested for overall penetration at rated flow and also at 20% of rated flow, with the filter encapsulated to disclose casing leaks; and type C, or scanned filters. "Scanning" is a special leak test for filters used in clean benches and other clean-air devices and is not applicable for contaminated exhaust filters. Type A filters are primarily for applications where air is recirculated through the filters (e.g., clean rooms and recirculating cleanup systems). Type B two-flow-tested filters are recommended for contaminated exhaust applications. The AEC Quality Assurance Stations make either the single-flow or two-flow test, as specified by the user.

The measured efficiency of most HEPA filters passing through the Quality Assurance Stations at this time is

[1]AACC Standard CS-1T, *HEPA Filter Units*, American Association for Contamination Control, Boston, 1968.

[2]Military Standard MIL-STD-282, *Filter Units, Protective Clothing, Gas-Mask Components, and Related Products: Performance Test Methods*, U.S. Army, Edgewood Arsenal, 1956.

[3]"Minimal Requirements for High Efficiency Air Filter Units," *Health and Safety*, issue No. 120, U.S. Atomic Energy Commission.

[4]Filter Unit Testing and Inspection Service, *Health and Safety* (bulletin issued annually), U.S. Atomic Energy Commission.

[5]Six dollars for a 1000-cfm filter in 1969, with minimum charge of $60.00.

Table 3.1. Standard HEPA Filter Sizes

Capacity at Clean-Filter Resistance of 1.0 in. H_2O (scfm)	Filter Face Dimensions (in.)	Filter Depth less Gaskets (in.)
25	8 × 8	$3\frac{1}{16}$
50	8 × 8	$5\frac{7}{8}$
125	12 × 12	$5\frac{7}{8}$
500	24 × 24	$5\frac{7}{8}$
1000	24 × 24	$11\frac{1}{2}$

close to 99.99% (i.e., a penetration of one particle in 10,000). The resistance and air flow capacity of the filters are determined at the same time as the efficiency, and all three values are stamped on the filter casing.[6]

Air Flow Capacity. – The five sizes of HEPA filters listed in Table 3.1 are standard for contaminated exhaust service. The 1000-cfm size is recommended for bank systems. Although some manufacturers rate their filters differently, the capacities shown are recommended for design purposes. The use of sizes not shown in Table 3.1 or of filters with handles, cleats, or other special attachments is not recommended because, as experience has shown, it nearly always results in procurement problems and higher costs.

Dust-Holding Capacity. – Dust-holding capacity in an actual situation is a function of the type and concentration of dust. For HEPA filters it is generaly not an important factor since the filter will be protected by a prefilter in high-dust-concentration applications. HEPA filters are particularly susceptible to plugging by fibrous and flakelike particles, which comprise a substantial part of atmospheric and personnel-generated dust. Dust-holding capacity does have a bearing on filter life and is generally considered as 4 lb per 1000 cfm of rated capacity. Actual life can only be determined from simulation tests under comparable operating conditions.

3.2.2 Construction

Typical construction of wood-cased and steel-cased open-face HEPA filters is shown in Fig. 3.1. The core (i.e., filter pack) is made by pleating a continuous web of fiber glass or cellulose-asbestos paper (the medium)

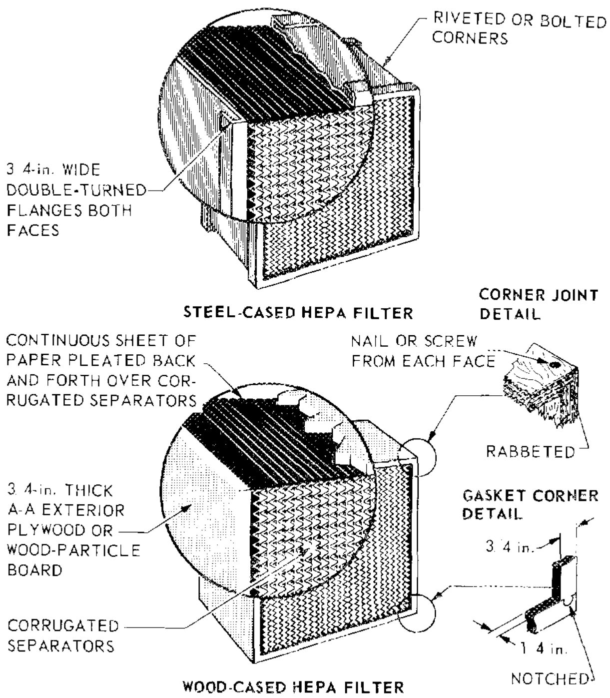

Fig. 3.1. Construction of open-face HEPA filter units.

back and forth over corrugated separators[7] which add strength to the core and form air passages between the folds. The core is sealed into a full-depth wood or steel casing (frame), usually with an elastomeric adhesive.

Media (Filter Papers). – The filter papers consist of very fine (submicron) fibers in a matrix of larger (1 to 4 μ) fibers. An organic binder (5% maximum, by weight) is added to hold the fibers during the papermaking process. Fire-resistant papers are made from glass fibers. Combustible papers required for certain special applications are made from cellulose and asbestos fibers. A minimum thickness of 0.015 in. and a minimum basis weight of 48 lb per 3000 ft^2 are sometimes specified to ensure adequate abrasion resistance. The filter paper is extremely weak and fragile, and the filters must be handled with care to avoid damage. Tensile strength is sharply reduced (about 50%) at temperatures above 400°F,[8] probably due to burnoff of the binder.

[6]Percent penetration, rather than percent efficiency, is actually reported. Percent penetration equals 100 minus percent efficiency. For very low "leak" rates, percent penetration is a more meaningful number. The 99.97% efficient filter has a minimum penetration of 3 parts in 10,000.

[7]Filters made without separators that are now available do not have sufficient strength for contaminated exhaust applications.

[8]C. A. Burchsted, "Environmental Properties and Installation Requirements of HEPA Filters," *Treatment of Airborne Radioactive Wastes*, International Atomic Energy Agency, Vienna, 1968.

Separators. – Separator materials commonly used are aluminum foil and asbestos paper. Kraft paper and various plastics are also used in some filters but are not recommended for nuclear applications because of poor heat and fire resistance.

Sealant. – The sealant usually used to seal the core into the case is a heat- and moisture-resistant elastomeric adhesive. One manufacturer uses a chemically expanded heat-resistant urethane foam. Filters that will be operated continuously at high temperature (above 400°F) are sealed with compressed glass-fiber matting or high-temperature silicone or refractory adhesives. The sealant (1) must be moisture resistant, (2) must not deteriorate excessively or lose its resiliency under alternating exposure to heat and cold or dry and humid air, (3) must not crack or delaminate from the frame at high temperature (5 min at up to 750°F), and (4) must maintain a reliable seal between the filter core and casing under continuous operation under service conditions. The high-temperature sealants do not meet all of these criteria, and their use, except in very special circumstances, is not recommended. Glass-fiber matting may not maintain a reliable seal at high temperature, silicone sealants delaminate quickly at only 10 or 20° above their rated temperatures, and refractory sealants are extremely brittle after heating. Rubber-base adhesives are generally used for gluing the gaskets to the filter. Since the gasket is completely constrained after the filter has been installed, the only requirement on these adhesives is that they firmly hold the gasket until the filter has been installed.

Casing (Frame). – The usual casing materials are fire-retardant exterior-grade plywood or wood-particle board and cadmium-plated carbon steel. Thicknesses of ¾ in. for wood and 0.061 in. (No. 16 U.S. gage) for steel are required for rigidity and to resist the compressive loads imposed when the filter is clamped to a mounting frame (axial compressive loads as high as 400 psi, or higher, may be encountered in service). Grade A-A plywood is specified to avoid manufacturing errors. Exterior grade for plywood and wood-particle board, and cadmium plating* for steel are required for moisture resistance. For wood-particle board, a minimum density of 45 lb/ft^3 is required to ensure adequate impermeability and strength.

Gaskets. – Gaskets are critical items. Tests have shown that excessive variation in gasket thickness, poorly formed gasket corners, and improperly glued gaskets result in air leakage exceeding the acceptance level of the filter.[9] When the gasket material is too hard, excessive bolt loading may be required to properly seal the filter to the mounting frame, resulting in possible filter damage; when the gasket material is too soft, excessive compression set may take place, resulting in air leakage as clamping bolts and casing materials relax or expand under service conditions. Tests of various shapes, materials, and hardnesses are continuing. The best information at this time suggests the use of ASTM D1056 grade SCE 43 closed-cell neoprene sponge, with cut surfaces on both faces. Gaskets are usually made in strips (¾ X ¼ in.) with notched or dovetailed corners.

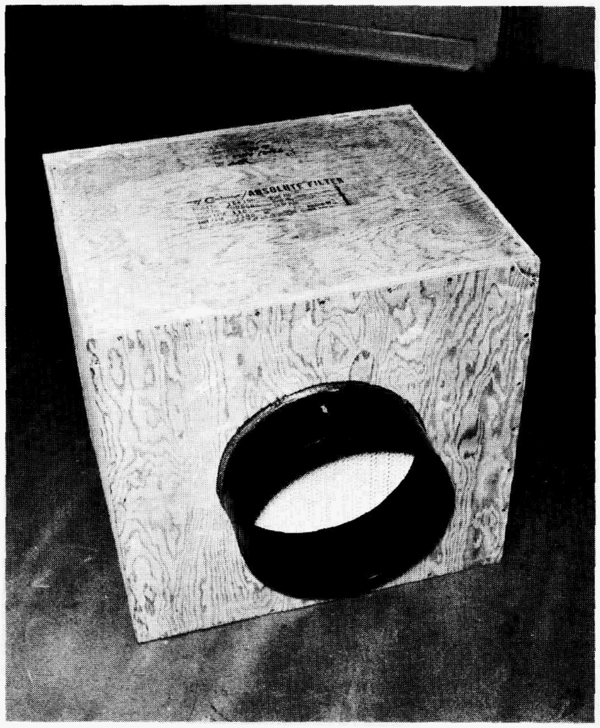

Fig. 3.2. 1000-cfm wood-cased enclosed HEPA filter. Courtesy Cambridge Filter Co.

Configuration. – Rectangular and cylindrical HEPA filters are available in open-face and enclosed configurations. Open-face construction is shown in Fig. 3.1. The enclosed filter (Fig. 3.2) is similar except that the case

*Chromized steel (titanium-stabilized carbon steel with a diffusion-bonded chromium coating) has been found superior to cadmium plated steel; cost of finished frame assemblies of both materials are about the same.

[9] F. E. Adley, "Progress Report, Factors Influencing High Efficiency Gasket Leakage," *Proceedings, 9th AEC Air Cleaning Conference,* USAEC Report CONF-660904, Harvard Air Cleaning Laboratory, 1966.

is longer and closed, with nipples for attachment of the filter as an integral part of the duct. Currently available enclosed filter units cannot qualify for fire resistance under Underwriters' Laboratories Standard UL-586.[10] Wood-cased enclosed filter units do not meet the requirements of National Fire Protection Association (NFPA) Standard 90-A.[11] Steel-cased enclosed filters, because of their bolted or riveted corners, may leak under service conditions; acceptance tests of steel-cased units should specify encapsulation to ensure freedom from corner leaks. Cylindrical filters often provide an apparently ideal solution to some design problems. However, because experience with them has not always been satisfactory and because they cannot be qualified for fire resistance under UL-586, they are not generally recommended for hazardous applications.

3.2.3 Weight of HEPA Filters

The weight of filter elements is an important factor in the design and maintenance of filter installations. Clean-filter weights of open-face and enclosed rectangular models are given in Table 3.2. Dirty-filter weights are approximately 4 lb more per 1000 cfm of rated capacity.

[10] Standard UL-586, *High Efficiency Air Filter Units*, Underwriters' Laboratories, Chicago, 2d ed., 1964.

[11] NFPA Standard 90-A, *Standard for the Installation of Air Conditioning and Ventilation Systems Other than Residence Types*, National Fire Protection Association, Boston, 1968.

3.2.4 Mechanical Properties

Other factors (heat, moisture) being equal, wood-cased filters are preferred to steel-cased filters because of their greater rigidity, superior vibration-damping characteristics, and greater corner strength. Common practice in nuclear plant exhaust systems is to compress filter gaskets by 80% or more. This amount of gasket compression requires a clamping force of at least 18 lb per square inch of gasket surface, or a total load of 1250 lb or more on the frame of a 1000-cfm filter unit. Because its moment of inertia is nearly 20 times that of a steel case, the wood case is better able to withstand high axial loads. The wood case with properly constructed (rabbeted) corners has about two times the corner strength of a steel case of the same size and is therefore better able to withstand "racking" or skewing when subjected to a force couple. Racking, which frequently occurs during handling, shipping, and installation, can damage either the filter medium or the seal between the core and case, or both.

Resistance to shock pressures is important in an HEPA filter because it is often the final barrier between the contaminated zone and the atmosphere. The shock-overpressure resistance of open-face rectangular filters, based on tests by the U.S. Navy,[12] is given in Table 3.3.

[12] W. L. Anderson and T. Anderson, "Effect of Shock Overpressure on High Efficiency Filter Units," *Proceedings, 9th AEC Air Cleaning Conference*, USAEC Report CONF-660904, Harvard Air Cleaning Laboratory, 1966.

Table 3.2. Weight of HEPA Filters

Filter Size (in.)	Nominal Flow at 1 in. H_2O (cfm)	Approximate Weight (lb) of Filters with –	
		Wood Case	Steel Case
	Open-Face		
8 × 8 × 3$\frac{1}{16}$	25	2	3
8 × 8 × 5$\frac{7}{8}$	50	3.6	5.8
12 × 12 × 5$\frac{7}{8}$	125	4.8	7.3
24 × 24 × 5$\frac{7}{8}$	500	17	22
24 × 24 × 11$\frac{1}{2}$	1000	32	40
	Enclosed		
8 × 8 with 2-in. Nipples	25	5	9
8 × 8 with 3-in. Nipples	50	7	10.5
12 × 12	125	17	20
24 × 24	500	64	72
24 × 24	1000	78	95

Table 3.3. Shock Overpressure Resistance of Open-Face HEPA Filters[a]

Filter Dimensions (in.)		Overpressure (psig)		
		Test Value[b]	Recommended Design Limit[c]	
Face	Depth		With Face Guards	Without Face Guards
8 by 8	$3\frac{1}{16}$	3.6	3.1	2.0
8 by 8	$5\frac{7}{8}$	4.5	3.8	2.5
12 by 12	$5\frac{7}{8}$	3.6	3.1	2.0
24 by 24	$5\frac{7}{8}$	2.2	1.9	1.2
24 by 24	$11\frac{1}{2}$	3.2	2.7	1.8

[a]C. A. Burchsted, "Basic Requirements for HEPA Filters," *Proceedings, 9th AEC Air Cleaning Conference,* USAEC Report CONF-660904, Harvard Air Cleaning Laboratory, 1966.
[b]Clean filter with 4 by 4 mesh face guards on both faces.
[c]Dirty filters.

The values given are the maximum shock overpressure that the filters will withstand without visible damage or loss in filtration efficiency when exposed to a shock of approximately 50-msec duration. Filters with hardware-cloth face guards on both faces have about 40% greater shock resistance than those without. Dirt-loaded filters in the Navy tests had about 15% less shock resistance than clean filters. At overpressures about 0.5 to 1.0 psi greater than the test value, sections of the filter medium burst on the downstream sides of the pleats, and at overpressures 2 psi greater than the test value, extensive damage and even complete blowout of the filter core occurred.[12] The greater shock resistance of filters with 4 × 4 mesh face guards is significant. The AEC has long advocated face guards to minimize personnel-incurred damage during handling and installation. The additional factor of higher shock resistance gives added importance to this recommendation. The shock-overpressure resistance of enclosed filters is probably less than the values shown because the shock load will be concentrated at the center of the core of this type of unit; however, actual tests have not been conducted.

3.2.5 Fire Resistance

The AACC Standard for HEPA filters[1] lists three grades with respect to fire resistance. These are: "fire resistant," made of fire-resistant materials throughout and able, when new, to meet requirements of UL-586; "semicombustible," made with fire-resistant medium but may have combustible separators and case; and "combustible," having combustible medium and either combustible or fire-resistant separators and case. Use of the latter is permissible only in applications where the filters will be incinerated in order to recover valuable product (e.g., uranium) trapped in the filter, or where chemical fumes would destroy the fire-resistant glass-fiber media. Only fire-resistant filters should be used in nuclear exhaust applications except under the two conditions noted.

Fire-resistant filters are qualified and labeled by Underwriters' Laboratories.[10] The test requires the filter to withstand 700 to 750°F air for 5 min at rated capacity with no significant reduction of filtration efficiency, plus a spot-flame test, in which a Bunsen burner flame is played on the filter, with no afterburning when the flame is removed. For sizes not specifically covered by the UL standard, the buyer should specify filters of the same materials of construction as filters that have been qualified. It should be noted that both wood-cased and steel-cased filters can meet the requirements of UL-586.

3.2.6 Environmental Properties

Hot Air Resistance. — Limiting continuous service temperatures for steel-cased and wood-cased HEPA filters, based on commonly used sealants used for sealing the core to the case, are given in Tables 3.4 and 3.5.[8] Filters with both types of case are designed to withstand temperatures to 750°F for periods of 5 to 10 min. Continuous operation at high temperature is limited primarily by the sealant. At temperatures well below the char or "checkering" point, adhesives lose their shear strength (from about 850 psi at room temperature to as low as 15 psi at 300°F). The buyer should determine the limiting continuous service temperature from the manufacturer if continuous operation at high temperature is necessary (see discussion of sealants).

Moisture and Corrosion Resistance. — The HEPA filter has limited resistance to corrosion. The separators, which must retain their shape to prevent collapse of the filter core, are most subject to attack. Of the common separator materials, asbestos has the best corrosion resistance but has almost no moisture resistance unless specially treated; and aluminum has excellent moisture resistance but poor corrosion resistance. Plastic separators (polystyrene, polyvinyl chloride) are not suitable for nuclear applications because of their poor heat and fire resistance. If treated asbestos is specified, it must be

Table 3.4. Recommended Limiting Service Temperatures for Steel-Framed Fire-Resistant HEPA Filter Units Sealed with Elastomeric Adhesives

Sealant Used	Temperature to Which Filter Was Exposed (°F)				
	Up to 10 min[a]	Up to 2 hr	Up to 48 hr	Up to 10 Days	Indefinitely
HT-30-FR[b]	750	350	325	300	260
Z-743[c]	750	325	300	275	200
EC-2155[d]	750	250	220	200	200
Polyurethane[e]	750	325	300	275	230

[a]Some reduction in efficiency may occur after 5 min of exposure.
[b]Goodyear.
[c]Pittsburgh Plate Glass.
[d]Minnesota Mining and Manufacturing (3M).
[e]Proprietary formulation of Flanders Filters, Inc.

Table 3.5. Recommended Limiting Service Temperatures for Wood-Framed Fire-Resistant HEPA Filter Units[a]

Frame Material	Temperature to Which Filter Was Exposed (°F)				
	Up to 10 min	Up to 2 hr	Up to 48 hr	Up to 10 Days[b]	Indefinitely[b]
¾-in.-thick plywood[c]	750	300	275	200	180
¾-in. wood particle board[c,d]	750	300	250	180	180

[a]Subject to sealant limitations given in Table 3.4.
[b]Maximum temperature of 120°F where relative humidity is 75% or higher.
[c]Exterior grade fire-retardant treated.
[d]Minium density = 45 lb/ft^3.

qualified for exposure to the corrodents expected in service, because, if the coating is destroyed, the separator will collapse if exposed to moisture. A standard qualification test for moisture and corrosion-resistant separators has been developed.[13]

Wood casings are more resistant to chemical attack than casings made of cadmium-plated steel. However, wood is not suitable for extended operation (seven days or more) in very-high-humidity (95 to 100%) environments at temperatures higher than 130°F, particularly when periods at temperature will alternate with system operation or shutdown at room temperature. Under these conditions, condensation at the casing surface may enter the wood, softening and releasing the fibers beneath the sealant, and may result in failure of the seal or even complete release of the filter core. When steel frames are used, cadmium plating is recommended for corrosion resistance; experience has shown that zinc (galvanized) platings do not give adequate protection in a contaminated exhaust environment. Stainless steel casings and separators have been used by some operators, but they are very costly. Wood-cased filters are not recommended in extremely dry environments (1 or 2% relative humidity or less) in either air or inert gas because the wood will deteriorate.

3.2.7 Costs

Relative costs of various open-face HEPA filter constructions are given in Table 3.6. Unit costs of

[13]C. A. Burchsted, *Qualification Test for Moisture and Corrosion Resistant Separators for Air Filters,* Oak Ridge National Laboratory, 1965.

Table 3.6. Relative Costs of Various HEPA Filter Constructions

Casing Material	Separator Material				
	Untreated Asbestos	Aluminum Foil	Treated Asbestos[a]	Plastic	Stainless Steel
Wood	1.00	1.02	1.08	1.71	7.73
Carbon steel	1.13	1.16	1.22	1.89	
Stainless steel	1.96	1.99	2.04	2.69	8.69

[a]Qualified for moisture and corrosion resistance in accordance with procedures established by the USAEC.

1000-cfm filters, at the time this manual is published, are about $60.00 to $80.00, depending on discounts and quantity purchased.

3.3 PREFILTERS AND BUILDING SUPPLY AIR FILTERS

The common air filters used as prefilters for HEPA filters and as building ventilation air supply filters are classified as indicated in Table 3.7.

By comparison, an HEPA filter, which is classed as "extreme efficiency," has an NBS atmospheric dust-spot efficiency of 100%. Because the dust-spot test is based on the staining capacity of the dust that penetrates the filter and is not a true measure of particle removal efficiency for any given particle size range, a more meaningful comparison is given in Table 3.8.

3.3.1 Performance

The performance of air filters is defined by particle removal efficiency, resistance to air flow (i.e., pressure drop), air flow capacity, and dust-holding capacity. To understand manufacturer's rated efficiencies, it is important for the buyer to know what test method was used, what the reported efficiency means, what test dust was used, and whether clean-filter efficiency or average efficiency is reported. Three test methods are used for rating group I, II, and III filters, the Air Filter Institute (AFI) weight method,[14] the AFI dust-spot method,[15] and the National Bureau of Standards (NBS) dust-spot method.[16]

The AFI weight test determines the percent of a synthetic dust (Arizona road dust plus carbon black and lint) that penetrates the filter. The efficiency or "arrestance" determined by this method represents the amount by weight of dust that the filter is able to remove during an accelerated test. As was shown in Table 2.5, on a weight basis more than 97% of the particles in a typical air sample are larger than 1 μ, whereas on a count basis over 99.99% are smaller. It is obvious, therefore, that a filter having high weight efficiency may actually be quite inefficient for removal of small particles.

The dust-spot tests are made by comparing the opacities of stains made on filter papers by air samples withdrawn from the test duct upstream and downstream of the filter. Because particles in the 1-μ and submicron range, which represent only a fraction of the total weight of dust charged to the filters, are chiefly responsible for staining the samples, the test essentially measures the efficiency of the filter for small particles. The AFI dust-spot test uses atmospheric air and determines clean-filter efficiency. The NBS dust-spot test uses dust from a Cottrell precipitator for filters up to 70% efficiency, and atmospheric dust for higher-efficiency filters, and reports average efficiency during an accelerated test. Since both the AFI test and the NBS atmospheric dust-spot test use ambient air, results depend on the atmospheric conditions in the location where the tests are being made.

Obviously the results of the various tests are not comparable, and an efficient filter by one test may be inefficient by another. ASHRAE is presently working on a testing standard that, hopefully, will bring some order out of the air filter testing confusion. In the meantime, the user should examine filter efficiency data very carefully to make sure that he understands what it means. The General Services Administration specifies use of the NBS dust-spot method for filters furnished for government buildings. Efficiency tests for

[14]"Unit or Panel Type Air Filtering Devices," *Code for Testing Air Cleaning Devices Used in General Ventilation,* Air Filter Institute, Louisville, Ky., 1956.

[15]*AFI Dust Spot Test Code,* Air Filter Institute, Louisville, Ky., 1960.

[16]R. S. Dill, *A Test Method for Air Filters,* National Bureau of Standards, 1938.

Table 3.7. Classification of Common Air Filters

Group	Efficiency	Filter Type	NBS Efficiency[a] (%)
I	Low	Viscous impingement, panel type	5–35[b]
II	Moderate	Extended medium, dry type	40–75[b]
III	High	Extended medium, dry type	80–98[c]

[a]National Bureau of Standards, Dill Dust-Spot Method [R. S. Dill, *A Test Method for Air Filters*, National Bureau of Standards (1938)].
[b]Test using synthetic dust.
[c]Test using atmospheric dust.

Table 3.8. Comparison of Air Filters by Percent Removal Efficiency for Various Size Particles

Group	Efficiency	Removal Efficiency (%) for Particle Size of –			
		0.3 μ	1.0 μ	5.0 μ	10.0 μ
I	Low	0–2	10–30	40–70	90–98
II	Moderate	10–40	40–70	85–95	98–99
III	High	45–85	75–99	99–99.9	99.9
HEPA	Extreme	99.97 min	99.99	100	100

group I, II, and III filters are made on prototypes only, and the results are extrapolated to the various size filters of similar design made by the same manufacturer. Testing of each filter unit would be costly and not too informative and is not recommended. Comparative NBS efficiencies of group I, II, and III filters (average over the life of filter to manufacturer's recommended maximum pressure drop) are given in Table 3.1.

Air Flow, Resistance, and Dust-Holding Capacity. – Representative values for air flow capacity, resistance, and dust-holding capacity of common air filters are given in Table 3.9. The values for dust-holding capacity are based on NBS testing with Cottrell precipitator dust (a weight test is included as part of the NBS test). Because dust-holding capacity varies with the nature and composition of the dust, the dust-holding capacity under service conditions cannot be accurately predicted on the basis of laboratory tests or manufacturer's catalog data. The data given in Table 3.9 are presented only for comparative purposes.

3.3.2 Construction

Panel Filters. – Panel (group I) filters (viscous impingement filters) are shallow, traylike assemblies of coarse fibers or metal mesh enclosed in a steel or cardboard casing. The filter medium may be glass, wool, vegetable, or plastic fibers or crimped metal mesh. The medium is coated with a tacky oil or "adhesive" to improve particle retention. Throwaway, replaceable-medium, and cleanable-medium types are available. The latter have metal mesh and are generally not used in contaminated exhaust service because of the difficulties associated with cleaning. Typical throwaway and replaceable-medium types are shown in Fig. 3.3. Panel filters have high dust-holding capacity, high air flow capacity with low resistance, and high removal efficiency for large particles. They are particularly effective against heavy concentrations of coarse particles (10 μ and larger). Except when large particles are present from a production operation such as grinding, panel filters are of limited value as prefilters for nuclear exhaust applications because of their limited effectiveness against small particles (5 μ and less) and because they are rapidly plugged by lint and other fibrous materials. Panel filters of the type shown in Fig. 3.3 have low initial cost and low operating cost, but when total operating cost is considered, noting the limited protection provided to the HEPA filters, they may be more expensive than an initially more expensive group II or III filter.

Group II and III Filters. – Group II (moderate efficiency) and group III (high efficiency) filters are extended-medium dry-type units. That is, the medium is pleated or formed as bags or "socks" to give large surface area with minimum frontal area and is not coated with an oil or "adhesive." Throwaway cartridge (Fig. 3.4), replaceable-medium (Figs. 3.5 and 3.6), and cleanable-medium types are available. The particle removal efficiency of group II filters is moderate to poor for submicron particles but often approaches 100% for particles larger than 2 or 3 μ. In most cases the pressure drop of extended-medium filters varies directly with efficiency. Group II filters are recommended for high lint and fiber loading applications. The

Table 3.9. Air Flow Capacity, Resistance, and Dust-Holding Capacity of Air Filters

Group	Efficiency	Air Flow Capacity (cfm per square foot of frontal area)	Resistance (in. H_2O)		Dust-Holding Capacity (lb per 1000 cfm of air flow capacity)
			Clean Filter	Used Filter	
I	Low	300–500	0.05–0.1	0.4–0.3	1–3
II	Moderate	250–750	0.1–0.5	0.2–0.5	1–5
III	High	250–750	0.20–0.5	0.6–1.4	1–5

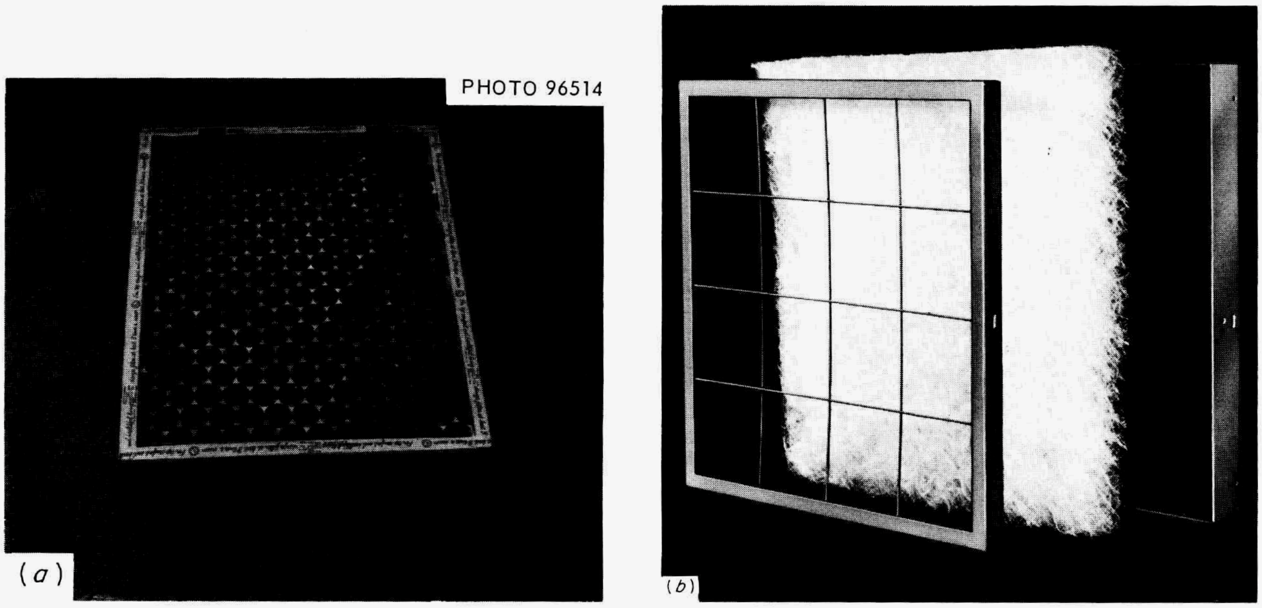

Fig. 3.3. Panel (viscous impingement) filters. (*a*) Courtesy Oak Ridge National Laboratory. (*b*) Courtesy American Air Filter Co.

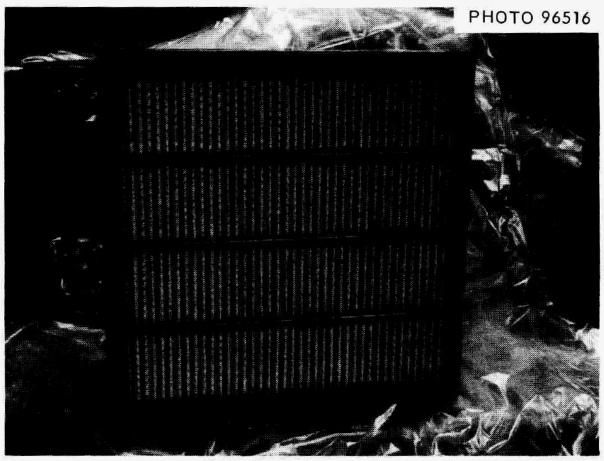

Fig. 3.4. Throwaway group III (high efficiency) filter with fiber glass medium, aluminum separators, and mineral board case. Courtesy Oak Ridge National Laboratory.

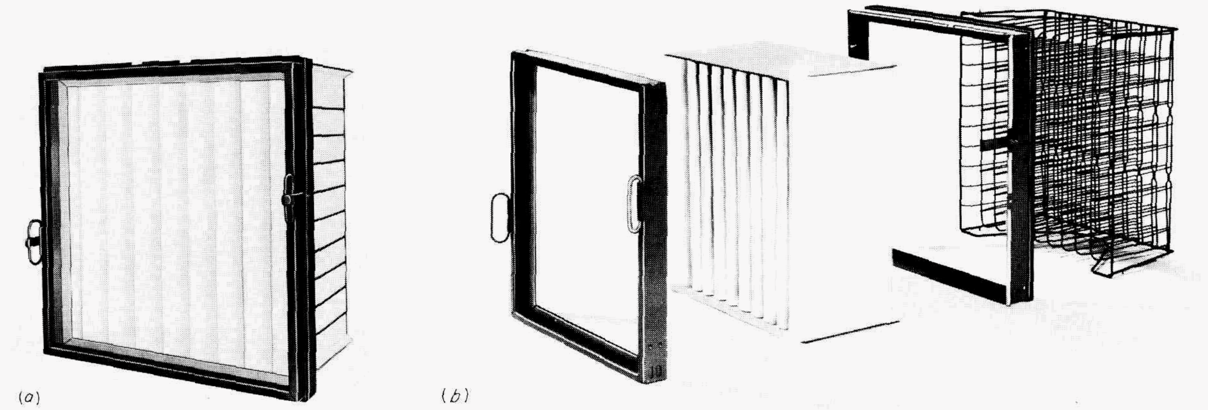

Fig. 3.5. Replaceable-medium group II (moderate efficiency) filter with preformed medium with wire support, and steel case. (*a*) Assembled view; (*b*) exploded view. Courtesy The Farr Co.

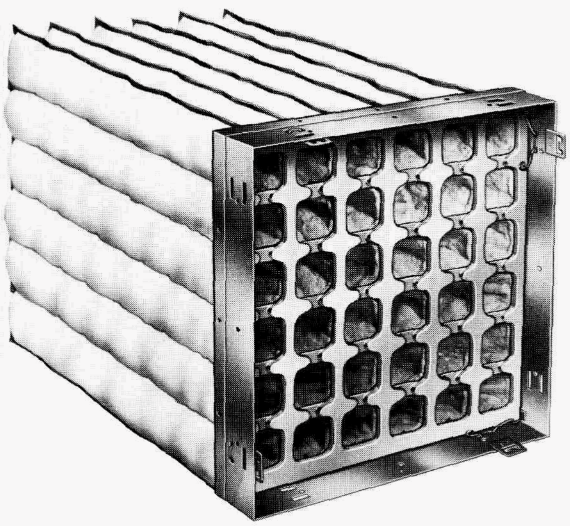

Fig. 3.6. Bag-type replaceable-medium group III (high efficiency) filter. Courtesy American Air Filter Co.

large area of the medium relative to frontal area permits the use of extended-medium filters at duct velocities equal to or higher than those permissible with panel filters.

3.3.3 Fire Resistance

Underwriters' Laboratories classifies common air filters in two categories with respect to fire resistance.[17] When clean, UL class 1 filters do not contribute fuel when attacked by flame and emit only negligible amount of smoke. UL class 2 filters may contain some combustible material but cannot contribute significantly to a fire. Dust collected on either a UL class 1 or class 2 filter may burn quite vigorously and create a fire which is difficult to extinguish, and the use of UL-rated filters should not lead to an unwarranted sense of security on the part of the user. Filters that meet the UL requirements are listed in the current UL *Building Materials List.*[18] NFPA Standard 90-A makes the use of either UL class 1 or UL class 2 filters mandatory.[11] Non-UL-rated filters should not be used in nuclear exhaust service.

3.3.4 Hot Air Resistance

Most types of common air filters are suitable for continuous operation at temperatures no higher than 150 to 250°F. Certain types with glass-fiber media in steel or mineral board casings may be used at temperatures as high as 400°F. With any high-temperature filter, the user should take a conservative view of performance claims, particularly for efficiency at

[17] Standard UL-900, *Air Filter Units,* Underwriters' Laboratories, Chicago, 1965.

[18] *Building Materials List* (current edition), Underwriters' Laboratories, Chicago, issued annually.

operating temperature. The user should examine his application closely to determine if the filters will actually be exposed to continuous high temperature, or if the high-temperature exposure will only be under intermittent or emergency conditions.

3.3.5 Maintenance Considerations

Air filters may be classified by the method of medium renewal – throwaway cartridge, replaceable medium, or cleanable medium. The first choice for nuclear exhaust applications is the throwaway cartridge. The filters shown in Figs. 3.3 (left) and 3.4 are typical of this class. Replaceable-medium filters offer the advantage over throwaways that the bulk of material to be disposed of is smaller, which may reduce handling and burial costs (radioactively contaminated filters are usually buried at an AEC-authorized burial ground); however, they present the possibility of reentraining contaminated dust as the medium is removed from the holding frame and crumpled up as it is stuffed into a bag for disposal. Replaceable-medium designs are not, therefore, recommended for nuclear exhaust applications. Cleanable filters are not satisfactory because they require long downtime of the facility and introduce the necessity of decontamination facilities adjacent to the filter house. Cleaning of filters merely transfers the radioactivity problem from the filter to the contaminated waste system, which may cause a more difficult problem than the disposal of throwaway units.

Corrosion and Moisture. – The choice of filter may be limited by corrodents and moisture in the air stream in which it is to operate. Many filter media will not withstand acid or caustic fumes; fiber glass will withstand exposure to most reagents except hydrofluoric acid or gaseous hydrogen fluoride. Aluminum parts (e.g., separators) may deteriorate in sea air or when caustic substances are deposited on them. Plastics have poor heat resistance and generally will not meet UL requirements. Heavy concentrations of water droplets or condensate may plug or deteriorate filters, resulting in frequent replacement.

Change Frequency. – Dust-holding capacity has a direct bearing on life and change frequency, and therefore on maintenance costs. Panel filters will plug rapidly under heavy lint loads, whereas some lint, by breaking up the uniformity of the dust deposit, may be beneficial to extended-medium filters. Extended-medium filters will plug rapidly in heavy concentrations of soot or smoke, whereas panel filters can handle these relatively effectively. Operation at levels below the manufacturer's rated capacity extends filter life and reduces filter change frequency (see discussion of underrating, Chap. 2). On the other hand, when air flow exceeds manufacturer's recommendations by more than about 15 to 20%, dust-loading rate, and therefore filter replacement costs, begins to increase geometrically with arithmetic increases in flow.

3.3.6 Operational Considerations

The decision to use prefilters must be determined for each application on the basis of total air-cleaning system costs and the consequences of exposing the HEPA filters to the environment without protection. In some cases, prefilters may double or triple the life of HEPA filters; in other cases, the increase may be insignificant. In general, HEPA filters should be protected from (1) particles larger than 1 or 2 μ in size, (2) lint, and (3) dust concentrations greater than 10 grains per 1000 ft^3. When radioactivity levels of the collected dust are so high that HEPA filters would have to be changed frequently (weekly or monthly) anyway, the extra cost of prefilters may not be justifiable. Resistance (and, correspondingly, power costs), system installation costs, and filter element replacement costs all increase with increasing prefilter efficiency. On the other hand, filter-change frequency and therefore maintenance costs of both the prefilter system and the HEPA filter system generally decrease. The price ranges of filters usually used for prefiltering are shown in Table 3.10.

Table 3.10. Prices of Common Air Filters per 1000 CFM Capacity

Group	Efficiency	Type	Price Range per 1000 CFM (dollars)
I	Low	Panel, viscous impingement	1–20
II	Moderate	Extended medium	25–40
III	High	Extended medium	30–65

3.4 ACTIVATED-CARBON ADSORBERS

Activated-carbon adsorbers, often referred to as gas filters, are the most satisfactory devices presently available for trapping of fission product gases from nuclear reactors and radiochemical operations. These adsorbers are tightly packed beds of adsorbent carbon granules through which air and gases are passed before being released to the atmosphere. The carbon is "activated" by controlled heating under a steam atmosphere, which drives off organic matter and generates large internal surfaces or "sites" on which adsorption can take place. The internal area of activated carbon varies from 700 to 1800 m^2/g. The carbon is often impregnated with chemicals to increase its affinity for certain gases.

The gas of primary concern in the design of adsorber systems for nuclear applications is elemental radioiodine, which is the most abundant (from the standpoint of radioactivity) sorbable gas released in a reactor accident or in operations with nuclear fuel. Under some conditions, organic radioiodine compounds, principally methyl iodide, may also be formed. Although the quantity is small relative to the amount of elemental radioiodine present, it represents a possible health hazard, and it is usually necessary to design the system to remove it. Carbons impregnated with potassium iodide (KI), triethylenediamine (TEDA), or other compounds are necessary for trapping organic radioiodine compounds in humid air. Future mention of impregnated carbons will mean those impregnated for trapping of methyl iodide and other organic iodine compounds.

3.4.1 Performance

The important properties of an adsorber are trapping (i.e., adsorption) efficiency, holding capacity or "activity," retentivity or the ability to prevent desorption of the sorbed iodine, ignition temperature, air flow capacity, and resistance to air flow.

Adsorption Efficiency. – The efficiency of a carbon adsorber is a function of (1) the degree of activation, ash and moisture content, and impurities in the charcoal; (2) the type and quantity of impregnant (for impregnated carbons); (3) granule size (the separation factor varies inversely with granule size); (4) the contact time between the gas and the carbon (i.e., the residence time in the carbon bed, which is a function of bed depth and velocity); and (5) the temperature and humidity of the gas stream. Special high-purity low-ash grades of carbon are required for the high levels of performance required of nuclear plant exhaust applications. The efficiencies of nuclear-grade charcoals, based on 1-in. bed depth for elemental iodine efficiency and 2-in. bed depth for methyl iodide efficiency, can be summarized as follows:

Table 3.11. Recommended Design Values for Single-Pass Methyl Iodide Efficiency of Full-Scale Adsorbers Containing Impregnated Activated Carbon[a]

2 in. bed depth, 0.2 sec residence time, 3 mg radioiodine as methyl iodide per gram of carbon

Relative Humidity (%)	Percent Efficiency for Radioiodine as Methyl Iodide	
	70°F	270°F
85 or less	95	98
90	90	90
95	80	70
98	70	30

[a]R. E. Adams, Oak Ridge National Laboratory, personal communication to C. A. Burchsted.

(1) Nonimpregnated charcoals: Efficiency for elemental iodine is satisfactory (over 99%) even after extended operation in high-temperature (260 to 280°F) environment containing steam and water droplets.[19] Efficiency for methyl iodide is satisfactory at relative humidities less than 70% but nil at high (over 80%) humidity.

(2) Impregnated charcoals: Efficiency for elemental iodine is satisfactory (over 99%) under all temperature and humidity conditions, up to 270°F and 100% relative humidity. Single-pass efficiency with 0.2 sec residence time is given in Table 3.11. Flooding of the carbon due to condensation or impingement of free water may reduce efficiency to as low as 20%.[20]

The efficiency of both impregnated and nonimpregnated carbons, for both elemental iodine and methyl iodide, is reduced somewhat when the iodine loading in the gas stream is less than about 0.01 mg/m^3. This phenomenon is still under investigation, but preliminary

[19]W. S. Durant, "Performance of Airborne Activity Confinement Systems in Savannah River Plant Reactor Buildings," *Proceedings, 9th AEC Air Cleaning Conference*, USAEC Report CONF-660904, Harvard Air Cleaning Laboratory, 1966.

[20]R. E. Adams, Oak Ridge National Laboratory, personal communication to C. A. Burchsted.

reports indicate that efficiencies are still within the ranges given above.[21]

Experimenters have found substantial differences in the methyl iodide removal efficiencies of various carbons and impregnants, and the user should ask for efficiency data under the service conditions of his application. It is recommended that a bid sample of the proposed carbon, plus representative samples from each batch of carbon used for filling the adsorbers furnished, be required for testing by the user.

Holding Capacity. – When the quantity of iodine charged to a charcoal adsorber exceeds its holding capacity, breakthrough occurs and efficiency drops accordingly. Holding capacity is a function of the amount of charcoal in the system, the number of remaining active sites on which adsorption can take place, and, for impregnated charcoals, the nature, quantity, and condition of the impregnant. The mechanism for capture of elemental iodine is physical condensation (i.e., adsorption) of iodine molecules on the active surfaces of the charcoal. The mechanism for capture of organic radioiodine is apparently a combination of chemical reaction and isotopic exchange, in which the stable iodine of the impregnant substitutes for the radioactive iodine of the methyl iodide; the nonradioactive methyl iodide goes on through the adsorber.

Holding capacity for both iodine and methyl iodide decreases with time because of physical or chemical "poisoning" of the carbon by impurities, particularly by hydrocarbons and water, that occupy active sites on the surface or react with the impregnant. The holding capacity of impregnated carbon may also decrease with gradual loss of the impregnant by volatilization. Tests with KI and TEDA-impregnated coke-base carbons indicated a loss of 50% of the initial holding capacity for methyl iodide during 18 months exposure to flowing air, a 50% loss in three years when the beds were exposed to static air (as would be the case in a standby system), and a loss of 50% in five years when the beds were sealed in closed containers.[22] Experience with coconut-shell carbons used in the United States shows a more gradual, but still significant, loss of holding capacity.[23]

The loss in holding capacity for elemental iodine is much slower than that for methyl iodide. Beds exposed continuously to flowing air at one installation showed adequate remaining capacity for elemental iodine after four years of service.[24] It should be noted that the loss in holding capacity is not accompanied by a corresponding loss in efficiency as long as the quantity of iodine or methyl iodide charged to the bed is less than the holding capacity of the carbon. The loss in holding capacity does indicate (1) the need for routine analytical tests on samples taken from the beds to determine remaining holding capacity; (2) the need for conservative adsorber design; and (3) the necessity of protecting the adsorbers from unnecessary exposure to moisture, hydrocarbons, and other poisons. When poisoning is caused by moisture or short-chain hydrocarbons, some degree of rejuvenation can be accomplished by periodic heating of the adsorbers with warm (90 to 100°F) air. Long-chain hydrocarbons are nearly impossible to drive off in this manner. Exposure to paint and solvent fumes can reduce holding capacity to the point that efficiency is reduced in only a few months.[25] The adsorbers must be protected during construction and maintenance operations.

Holding capacity can be severely limited when the carbon is wet, as would be the case in some types of reactors if adequate moisture separators were not provided.

Retentivity. – Because adsorbers may have to be operated for several days or weeks following a reactor accident, consideration must be given to retention of the trapped gases. The retentivity for a sorbed chemical is usually about 35 to 45% of the holding capacity.[26] As long as the integrated quantity of iodine or methyl iodide charged to the bed is less than the retentivity limit, desorption is not a significant problem at temperatures below 250 to 300°F. Some iodine loss will take place at higher temperatures, particularly from impregnated carbons, which will also desorb the impregnant

[21] R. E. Adams *et al.*, "Application of Impregnated Charcoals for Removing Radioiodine from Flowing Air at High Relative Humidity," *Treatment of Airborne Radioactive Wastes*, International Atomic Energy Agency, Vienna, 1968.

[22] D. A. Collins *et al.*, *The Development of Impregnated Charcoals for Trapping Methyl Iodide at High Humidity*, TRG Report 1300(W), United Kingdom Atomic Energy Authority, London, 1967.

[23] R. E. Ackley, *Trapping of Radioactive Iodine and Methyl Iodide by Iodized Charcoals*, paper at Nuclear Safety Information Meeting, Oak Ridge National Laboratory, Feb. 6, 1968.

[24] A. H. Peters, Savannah River Laboratory, personal communication to C. A. Burchsted.

[25] Letter, R. E. Adams to R. Herzel, Phillips Petroleum Co., reporting results of tests on charcoal samples removed from adsorbers of Carolina-Virginia Tube Reactor, Aug. 7, 1967.

[26] L. Kovach, North American Carbon Co., personal communication to C. A. Burchsted.

and further reduce the capacity for radioactive methyl iodide. The extent of loss is still under investigation. The retentivity factor further emphasizes the need for conservative adsorber design.

Ignition Temperature. – Adsorption systems must be designed so that the decay heat of collected fission products will not cause ignition of the carbon or overheating to the point that collected fission products (and impregnant of impregnated charcoals) are desorbed. As fission products are deposited in the charcoal, the spot or bulk temperature of the carbon can increase to the ignition point unless adequate air flow or other means of cooling is maintained.

The ignition temperature of new charcoal is a function of the ash content, impurities, internal surface area, granule size and hardness, and the flammability of chemical impregnants. Adsorbed substances may alter the ignition temperature. Ignition temperature varies directly with the degree of activation and inversely with granule size and hardness. The lowest ignition of new impregnated coconut-base carbons is about 500°F.[27] The ignition temperature of nonimpregnated coconut-base carbons ranges from about 640 to 900°F, depending upon ash and impurity content. With conservative bed design, that is, a bed that contains a large volume of charcoal relative to the air flow capacity of the system and the amount of iodine to which it can be exposed, the specific loading of fission products will be low, reducing the possibility of spontaneous combustion.

Air Flow Capacity and Resistance. – Air flow capacity is a function of bed configuration and resistance. Resistance is a function of the size of carbon granules (mesh size), packing density, bed thickness, free area of the granule retaining screens, and air flow velocity. For a given bed design (configuration), resistance varies directly with air flow velocity. Efficiency, at least for methyl iodide, varies inversely with velocity because it is dependent on the contact time between the gas and the charcoal. Operation above the rated capacity of the adsorber is therefore not recommended because of the possible reduction in efficiency, as well as the more obvious penalties of higher pressure drop and operating costs. Assuming no change in air flow velocity and that particulate filters are provided upstream to intercept dust that might otherwise collect on the screens or in the charcoal itself, pressure drop will remain constant over the life of the adsorber.

[27]R. E. Adams and R. P. Shields, "Ignition of Charcoal Adsorbers by Fission Product Decay Heat," *ORNL Nuclear Safety Research and Development Program Bimonthly Progress Report for November–December 1967*, USAEC Report ORNL-TM-2095, February 1968.

3.4.2 Adsorber Design

The mechanisms involved in trapping radioiodine, particularly methyl iodide, are not fully understood, and research is still continuing. Mass transfer, physical condensation, chemical reaction, and isotopic exchange all take place in varying degrees. Because of these uncertainties and because of the known loss in holding capacity with time, a good deal of conservatism should be exercised in the design of adsorber systems.

In the event of a major accident in a nuclear reactor, the concentration of iodine in the air flowing to the adsorbers may range from as low as 10 ppm to as high as 500 ppm, according to the size of the reactor and the nature of the accident. Of this, from 5 to 10% may exist as methyl or other organic iodide and the remainder as elemental iodine vapor. It is believed that there would be no organic iodides for certain types of reactors.[28] Where it can be shown that elemental iodine is the only consideration, the adsorber system should contain enough charcoal so that the maximum amount of iodine that could be charged to the adsorber units (beds) under the worst accident conditions will not exceed 5 mg per gram of charcoal.[29] When methyl iodide must also be considered, the system should contain enough charcoal so that the maximum amount of iodine charged to the units will not exceed 2.5 mg per gram of charcoal,[20] that is, double the amount required for elemental iodine alone. These loading rates are probably much higher than would be experienced in the large adsorber systems used in most power reactors.

To determine the amount of charcoal required for a specific system, the quantity of radioiodine that may exist in the containment following an accident must be estimated. It is generally assumed that one-half of the potential iodine inventory in the fuel can escape to the containment space and that one-half of this amount will plate out on the walls and floor. On this basis, 25% of the inventory could theoretically get to the adsorbers. Using these assumptions, the amount of charcoal required can be estimated from the following formula:

$$C = 0.22Q \, , \qquad (3.1)$$

[28]A. H. Peters, *Application of Moisture Separators and Particulate Filters in Reactor Confinement*, USAEC Report DP-812, Savannah River Laboratory, 1962.

[29]R. E. Adams and R. D. Ackley, *Removal of Elemental Radioiodine from Flowing Humid Air by Iodized Charcoals*, USAEC Report ORNL-TM-2040, Oak Ridge National Laboratory, 1967.

where

C = pounds of charcoal required in the adsorber system,

Q = potential iodine inventory that could be released (grams).

Using this formula, a 1000 Mw (electrical) power reactor, having a potential iodine inventory of 15,000 g, would require a minimum of 3300 lb of carbon to provide protection against both elemental iodine and methyl iodide. Half of this amount is required if it can be shown that only elemental iodine would be present.

3.4.3 Construction

Adsorbers are available in a variety of bed and cartridge designs, of which the bed types are of primary interest for large systems. A bed-type adsorber consists of a layer of carbon granules tightly compressed between perforated metal screens which are enclosed with a metal casing. Figure 3.7 is a cutaway of a typical pleated-bed adsorber and shows its parts. Because thin beds are subject to channeling of the charcoal, a minimum bed thickness of 1 in. ($+\frac{1}{8}$, -0) and a maximum velocity of 60 fpm through the bed (i.e., perpendicular to the screen face) are recommended.

When it is necessary to consider only elemental iodine, a single 1-in. bed is sufficient. When methyl (i.e., organic) iodide must also be considered, a bed thickness of 2 in. or two 1-in. beds in series are required to keep space requirements of the system to a minimum (a residence of the gases in the carbon of 0.2 sec is necessary to develop the required methyl iodide efficiency). The use of two 1-in. bed units in series is recommended over a single 2-in. bed unit, for two reasons. First, the upstream unit will take the brunt of moisture, impurity, and iodine loading, leaving the downstream unit relatively clean (which may reduce total system maintenance costs); and second, should a leak develop in one unit (leaks can result from settling of the charcoal, faulty gaskets, cracked welds, etc.), the second provides full protection against elemental iodine and a substantial measure of protection against organic iodides. The latter is in keeping with the "double containment" philosophy practiced at many AEC installations. The cost of two 1-in.-bed units is not greatly more than that of a single 2-in.-bed unit.[26] Installation costs, on the other hand, are substantially higher because two mounting frames and considerably more housing space are required. Lower replacement and maintenance costs, since the upstream unit alone may usually need replacement, may result in lower total costs over a given period of time (20 years).

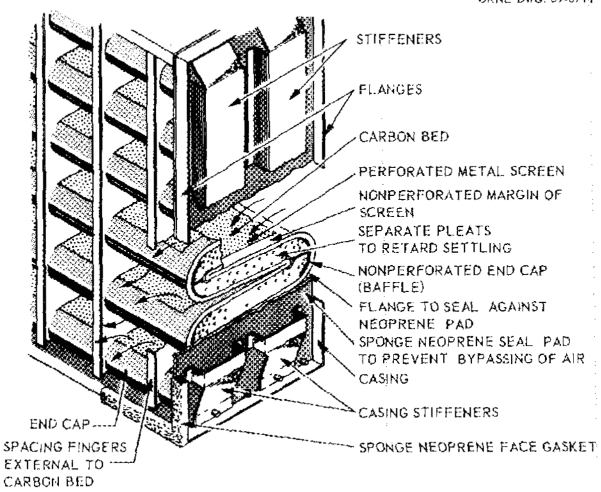

Fig. 3.7. Cutaway of 1-in.-pleated-bed adsorber.

Carbon. – Detailed requirements for carbon are given in the sample specification in Appendix A. Fracturing and crushing of carbon granules under service conditions can result in "dusting" and subsequent escape of contaminated carbon, or in channeling through the bed, with subsequent leakage of contaminated air or gas. Very hard carbons are necessary to resist fracturing and crushing. A minimum hardness of 97% is recommended for nonimpregnated carbons. Impregnated carbons are inherently softer because of the greater degree of activation of the base carbon; a minimum hardness of 94% is recommended. To minimize fracturing, vibration and pulsation in the air-handling system must be minimized, and adsorber units should be installed with beds horizontal so that there is a minimum pressure head on the carbon granules.

Carbon must be packed into the beds in such a manner that settling does not occur during shipping, handling, installation, or operation. After packing, carbon fines must be blown out with clean, dry, oil-free air.

The mesh size of the carbon is limited by the availability of perforated steel retaining screens (see Fig. 3.7). Although some adsorber designs employ cotton fabric screen liners (scrims) to retain the carbon, permitting the use of very fine (12 × 30 Tyler mesh) carbon, the practice is not recommended for nuclear exhaust applications because the scrim could burn out or deteriorate, permitting the release of fines. There is also some possibility that the carbonaceous material (cotton) might contribute to converting elemental iodine to an organic compound, which would increase the loading on the impregnant. For stiffness, the screens should be made from as heavy a steel sheet as possible; the holes should be as small as possible to retain the smallest possible carbon granules; and the open area should be as great as possible to minimize air flow resistance. At present, 220 holes (0.045 in. diam) per square inch (open area = 35%) is the limit of the steel perforator's capability in 24-gage stainless steel and 22-gage carbon steel. This limits carbon size to 8 X 16 Tyler (8 X 14 U.S.) mesh.

Casing. – An adsorber casing must be rigid to resist warping, twisting, and breaking of welds during shipping and installation. The bed must be baffled to prevent direct impingement of high-velocity air that could cause channeling or fracture of the carbon granules (note end caps in Fig. 3.7). Units should be designed so that the carbon beds are as nearly horizontal as possible to minimize settling of charcoal that would permit bypassing. There should be a minimum of metal-to-carbon interfaces (through bolts, spacers) within the screen area that could provide leak paths through the bed. Screens should have nonperforated "margins" and be installed so that, should settling occur, no open holes can be above the carbon surface (see Fig. 3.7).

Screens should be supported to prevent sagging and to ensure uniform and minimum bed thickness throughout. A bed thickness tolerance of $+\frac{1}{8}$ in., -0 is recommended. Casings and bed screens should be of welded construction insofar as possible – caulked joints should not be permitted because the caulking compounds (even silicone sealants) tend to crack and delaminate from the metal surfaces in the environment of a contaminated exhaust system (the sealant may also deteriorate under radiation). Final closure seals with neoprene pads (see Fig. 3.7) are recommended, using ASTM D1056 grade SCE-43 neoprene; the pads must be tightly constrained to prevent any leakage should there be any significant deterioration of the neoprene in service. The sealing faces of casing flanges must be square (diagonals equal within $\pm\frac{1}{8}$ in.), flat (planar within $\frac{1}{16}$ in. total allowance), and smooth (125 μin. arithmetic average roughness height; all welds, projections, and offsets between adjacent surfaces ground smooth).

Stainless steel (ASTM A240 type 304L) casing construction is recommended for long life, particularly where it is intended to reuse the cases. Stainless steel gives the necessary protection against corrosion due to adsorbed SO_2 or NO_2 from the air (see Sect. 2.3.6). Impregnants may also dissolve and form corrosive solutions if water condenses in the charcoal. Because most of the cost in an adsorber is in labor and the charcoal itself, not too great a penalty is paid for stainless steel cases, and the cost may be recouped in longer life and rechargeability (at least for pleated-bed types).

Multiple-Tray Adsorber. – Multiple-tray adsorbers were originally built for the Army for use in chemical-biological-radiological (CBR) filter units. The unit shown in Fig. 3.8 has eight $1\frac{1}{8}$-in.-thick trays of 16 X 30 mesh charcoal. The pressure drop across the unit is 1.34 in. H_2O at 1000 cfm and 1.87 in. H_2O at 1250 cfm. The contact time between the gases and the

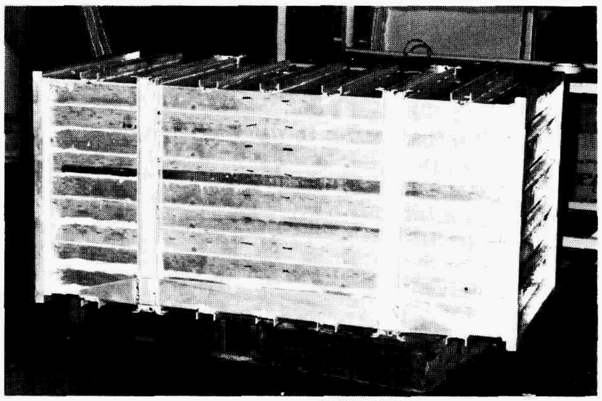

Fig. 3.8. Multiple-tray carbon adsorber unit. Note caulked joints between trays. Courtesy The Farr Co.

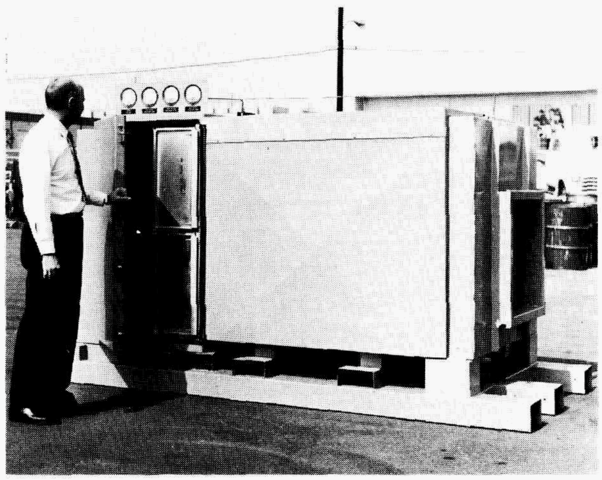

Fig. 3.9. A 5000-cfm CBR filter unit. Note HEPA filters showing through door; pressure-drop instruments for each bank of components at top. Courtesy The Farr Co.

charcoal, when operating at 1250 cfm, is approximately 2 sec. Shortcomings of this design are the caulked joints between screens and casings and between adjacent trays, the use of through bolts to clamp the screens together in each tray, and the use of cotton scrims to contain the 16 X 30 charcoal. Multiple-tray adsorbers having these construction features are not recommended for nuclear application.

In military applications, four tray assemblies, with four 1000-cfm HEPA filters and four prefilters, are sealed into a single housing as shown in Fig. 3.9. A fan and motor are then installed on an extension to the base to provide a complete, portable air-handling plant. The filtration assembly alone, as shown in Fig. 3.9, weighs about 3400 lb and costs about $8600. The CBR assembly may have some interest as an emergency cleanup unit.

Unit-Tray Adsorbers. – Unit-tray (drawer-type) adsorbers (Fig. 3.10) consist of two carbon beds with an air space between. The adsorber shown has 22½ X 26 X 2 in. beds of 8 X 16 carbon and has a capacity of 333 cfm. The contact time between the gases and the carbon is approximately 0.24 sec at rated flow. Depending on minor variations in designs, unit-tray adsorbers cost from about $350.00 to $400.00 (with stainless steel frames) and weigh from 80 to 100 lb. Some models have 12 X 30 mesh carbon and therefore require cotton scrims inside the screens, and some have caulked joints between the screens and the bed casings and between the individual beds and the outer casing. The design does not lend itself to recharging with new carbon. This design is preferred by most power reactor system designers because of its compactness and the ability to get the full 2-in. depth of carbon in a single unit.

Pleated-Bed Adsorbers. – A more conservative adsorber design is the pleated-bed type, shown in Fig. 3.11. This design is favored by contractors who operate AEC-owned reactors because there are no internal through bolts, spacers, or caulked joints; because the units fit the standard 24 X 24 X 11½ in. module; and because the units are light enough (160 lb) to be handled by two men. The unit shown has a 1-in. bed of 8 X 16 mesh carbon and a capacity of 800 cfm at 0.8 in. H_2O pressure drop. The contact time between the gases and the carbon at 800 cfm is slightly over 0.1 sec (two units in series are required for methyl iodide). Two-inch-bed models are also available. The cost of the unit shown is about $400.00 with a stainless steel case or $325.00 with a carbon steel (painted) case.

A sample specification for pleated-bed adsorbers is given in Appendix A. This type of bed has no internal metal-to-metal interfaces (note external bed spacers), no caulked joints, and no scrims. The end plates, which

Fig. 3.10. Unit-tray adsorber. Note through bolts within the screen area, caulked joints. Courtesy American Air Filter Co.

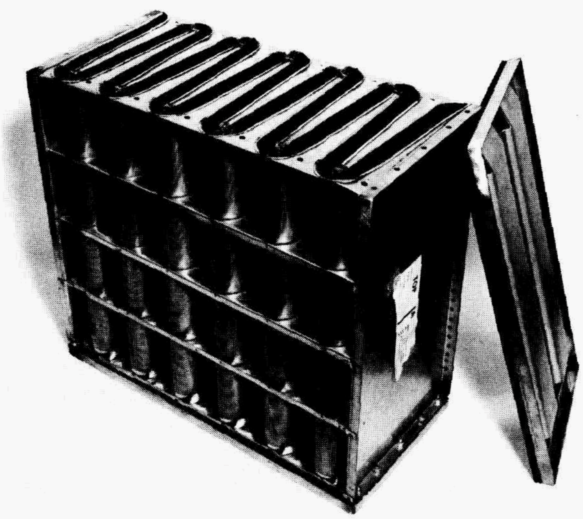

Fig. 3.11. Pleated-bed carbon adsorber. End plate removed to show bed. Courtesy Barnebey-Cheney Co.

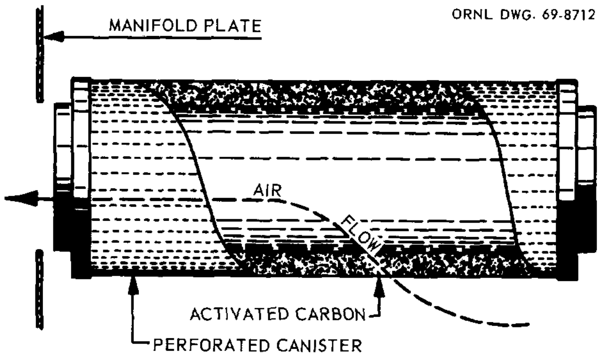

Fig. 3.12. Cartridge-type adsorber.

are sealed with highly compressed neoprene pads, can be removed for recharging with new charcoal.

Cartridge-Type Adsorbers. – Cylindrical adsorbers (Fig. 3.12) and gas-mask canisters are used in small installations such as glove boxes and machine-tool hoods. In general, they find little application in large adsorber systems. The cylindrical type shown is sometimes used for small-volume reactor and radiochemical plant off-gas systems.

3.5 Moisture Separators

Moisture separators are necessary in the air cleaning systems of many reactors to protect the HEPA filters and adsorbers. For several minutes following a loss-of-coolant or heat-exchanger accident, filters and adsorbers could be exposed to a mixture of wet steam and air at flow rates of several times rated capacity, at temperatures up to 275°F and pressures to 45 psig, unless adequate protection is provided. Following this initial burst, a mixture of steam, air, and water may continue to flow at a rate equivalent to rated filter capacity for periods of from a few hours to several days. HEPA filters, even the most moisture resistant, may plug, deteriorate, or rupture under such conditions.

Free water in the form of droplets ranging from 1 to 10 μ in diameter presents the greatest problem, both from the standpoint of filter damage and from the standpoint of removal. Droplets smaller than 1 μ probably do not account for enough total volume to be damaging, and droplets larger than 10 μ are removable by conventional moisture separating devices.

In systems not equipped with containment sprays, steam expanding and condensing in the containment space will be the major source of moisture, and free water will exist mainly as droplets in the 1-to-5-μ range.[28] With cooling sprays, most of the water will be in the form of large drops ranging in size from 100 to over 1000 μ, and practically a rain condition will exist in the containment space. Although most of the large drops will settle out as a film of water on the walls and floor, a significant number would probably be drawn into the air cleaning system if installed within or attached directly to the containment shell. In this latter case there will also be a large number of very small (1 to 10 μ) droplets, both from condensing steam and because the sprays themselves will produce a very large number of very small droplets.[30] Although agglomeration will remove many of these, a significant number, from the standpoint of filter damage, can probably get to the filters.

Wire-mesh Demisters[31] used in chemical processing operations and panel-type entrainment separators used in air conditioners and air washers are inefficient in the 1-to-10-μ range, and the highly compressed packed-fiber separators used for fume control in chemical plants, which are efficient in this range, have too high a resistance at the high flow rates required for reactor post-accident service. Two moisture separator designs have performed satisfactorily under simulated reactor post-accident conditions.[28,32] The first of these is a multilayer mat knitted from fine (approximately 20 μ) Teflon[33] filament on a stainless steel wire matrix. A closeup of the medium and a photograph of a complete 1650-cfm unit are shown in Fig. 3.13. The unit shown is 24 X 24 X 2 in. thick with a stainless steel casing and with ⅛-in. stainless steel reinforcing wires on each face. The second separator consisted of a wave-plate entrainment separator followed by three 2-in.-thick nonwoven fiber mats. An exploded view of a 25,000-cfm unit and details of a 1000-cfm test unit are shown in Fig. 3.14. The pads are installed in the cells as shown in Fig. 3.15. The mats are made of fine (10 to 20 μ) glass fibers with a waterproof binder. The grid assemblies shown in Fig. 3.15 permit the mats to take high overpressure (2 to 3 psi) without excessive damage (i.e., damage that would decrease performance significantly).

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[30]"Phase Separation," *Chemical Engineer's Handbook*, 4th ed., chap. 18, McGraw-Hill, New York, 1963.

[31]Trademark, Otto H. York Co., Inc.

[32]R. D. Rivers and J. L. Trinkle, *Moisture Separator Study*, USAEC Report NYO-3250-6, American Air Filter Co., 1966.

[33]Trademark, E. I. du Pont de Nemours and Co., Inc.

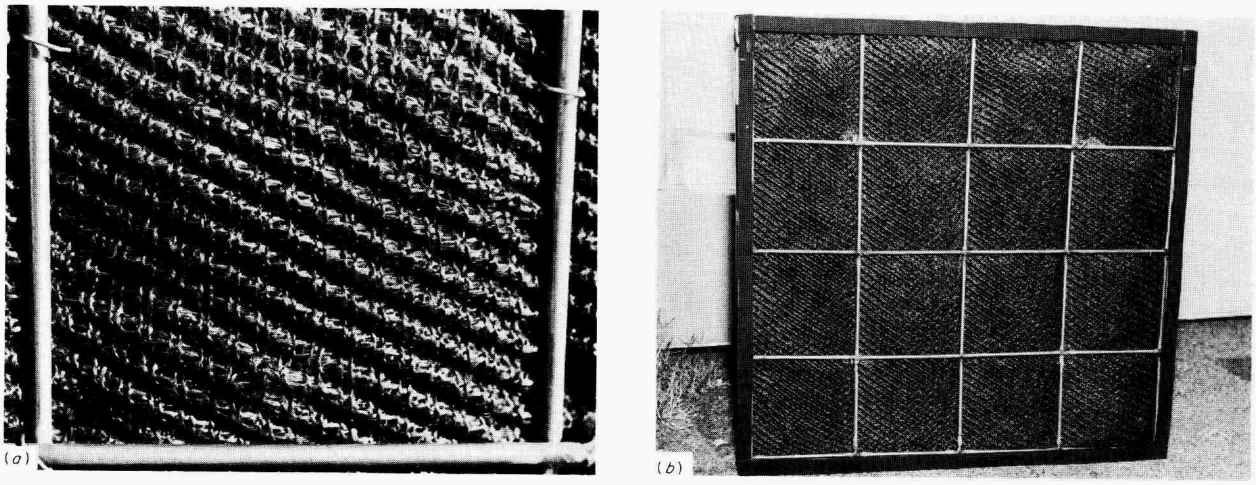


Fig. 3.13. Knitted-Teflon-stainless-steel mat moisture separator. (*a*) Medium; (*b*) complete unit. Courtesy Savannah River Laboratory.

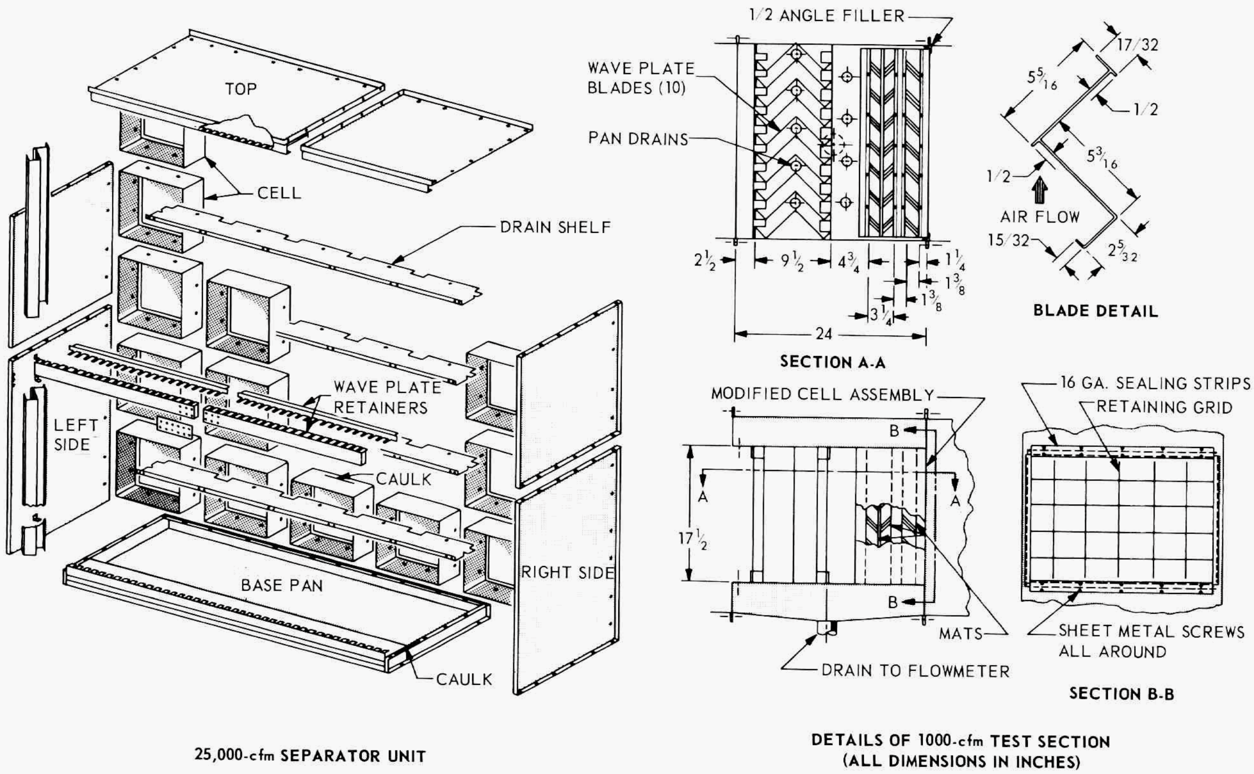


Fig. 3.14. Moisture separator consisting of a wave-plate entrainment separator followed by nonwoven fiber mats to trap very small (1 to 10 μ) droplets. Mats are installed in the cells as shown in Fig. 3.15. Courtesy American Air Filter Co.

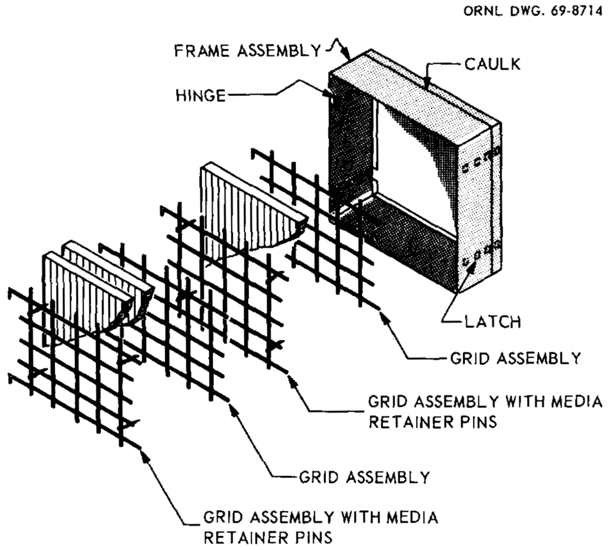
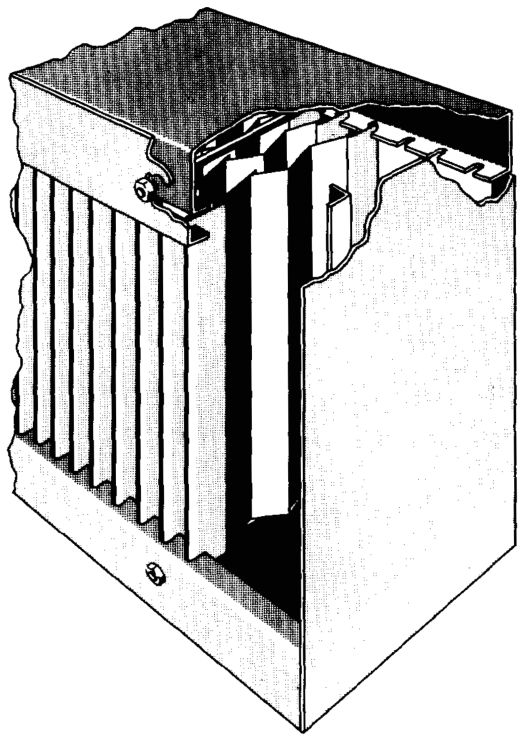


Fig. 3.15. Exploded view of nonwoven mat moisture separator showing method of installation (see Fig. 3.14).

3.5.1 Performance

The performance of moisture separators, like that of particulate filters, is defined in terms of removal efficiency for a specific particle (droplet) range, air flow capacity, and resistance to air flow. The forces acting on liquid droplets in an air stream are identical to those acting on solid particles, and the same mechanisms as in particulate filtration, diffusion, impaction, and inertia apply. In nuclear reactors the moisture separator must be able to remove 99% of all droplets down to about 1 μ at air flow rates of several thousand cubic feet per minute and at water rates of up to a gallon (8.4 lb) per 1000 cfm of steam-air mixture.

Wave-Plate (Bent-Plate) Separators. – Just as it is desirable to protect an HEPA filter from high concentrations of coarse particles, it is also desirable to protect knitted or nonwoven mat moisture separators from high concentrations of large water drops (50 to 1000 μ or larger). Because it takes more power to remove small drops (because of the higher resistance of the units capable of removing small drops) and because large quantities of water may unduly increase the water load and air flow resistance, it is uneconomical to use fabric (knitted) or fiber filters to remove the large drops produced by reactor post-accident cooling sprays.[32] Large drops are effectively removed by wave-plate (also called bent-plate) entrainment separators of the type shown in Figs. 3.14 and 3.16. Their efficiency is practically 100% for drops over 400 μ but drops off to 60%, or less, depending on blade geometry, for droplets in the range of 10 to 50 μ.[30,34] Wave-plate separators can handle very large volumes of air at high velocity (as high as 1500 fpm for some types) with low pressure drop (see curves, Fig. 3.16). Because the efficiency is dependent on impaction and inertial effects, operation at less than about 400 fpm is not recommended. With most types, some water carry-over may occur at velocities higher than 700 fpm.[34]



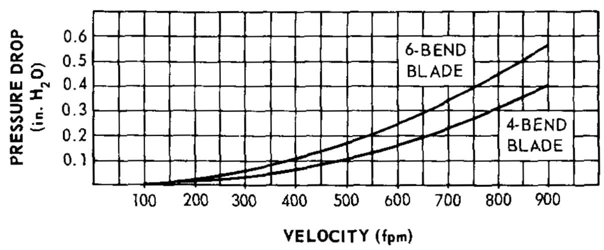


Fig. 3.16. Wave-plate moisture separator. Courtesy Air and Refrigeration Corp.

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[34]H. S. Dutcher, Air and Refrigeration Corp., personal communication to C. A. Burchsted.

Knitted Fabric and Nonwoven Fiber Mat Separators. -- Knitted fabric and nonwoven fiber separators of the types shown in Figs. 3.13 and 3.15 are the most acceptable devices for removing small and intermediate droplets (1 to 100 μ). Their design is a complex compromise between air flow capacity, resistance, size (i.e., materials cost), and service life. Recommendations of the manufacturer should be followed closely when supported by test data. Drop removal is effected mainly by inertial effects, and removal efficiency increases with flow velocity and decreases with fiber diameter. The maximum fiber diameter for effective removal of droplets in the 1-to-10-μ range is about 20 μ.[35] If a separator is considered to be comprised of a series of incremental layers, the droplet removal efficiency of the complete separator is the sum of the efficiencies of the layers. Therefore efficiency can be increased by increasing the thickness of the separator, but this would be at the expense of increasing the pressure drop and therefore the operating costs, and there becomes a practical limit on efficiency at a given velocity. The efficiency can also be increased to some extent by increasing the velocity, but this is also at the expense of increasing the pressure drop and the operating costs. Within limits, the higher the velocity, the thinner the separator (i.e., the fewer the layers) required for a given efficiency and the less the material required, which, of course, gives lower procurement costs.[35] It was found at the Savannah River Laboratory that increasing the air flow velocity from approximately 285 to 460 fpm permitted the use of twenty-four 2-in.-thick separators instead of forty 4-in.-thick separators of the type shown in Fig. 3.13, in a 40,000-cfm system. At a cost of $255.00 for the 2-in. units and $310.00 for the 4-in. units, this gave a capital cost saving of $880.00 for each of the five systems on the reactor.

For a given construction (fiber diameter and compaction), the air flow resistance of a separator at constant velocity increases directly with the number of layers. It is obvious, therefore, that there is a point of diminishing returns at which the cost of increasing the efficiency is offset by increased operating and materials costs. The efficiency can also be increased by compacting the mat, that is, by increasing the fiber density; however, the air flow resistance increases even more rapidly than the improvement in efficiency. For this reason, the very efficient packed-fiber mist eliminators that have gained wide acceptance in the chemical industry are not recommended for nuclear reactor post-accident cleanup systems.

The operating velocity of fabric and fiber mat moisture separators is not critical and can be varied within limits without seriously affecting the efficiency. In general, the higher the velocity, the thinner the pad required for a given efficiency, and therefore the lower the materials cost; but the higher the velocity, the higher the operating costs. Because of the possibility of flooding or "waterlogging" and resultant water carry-over, the permissible velocity for a separator installed horizontally (i.e., air flow vertical) is less than the permissible velocity of the same unit installed vertically (horizontal air flow). Approximate operating velocities of the separators discussed in this section are shown in Table 3.12.

Because mat-type moisture separators are efficient particle filters, they must be cleaned or replaced periodically. The knitted-fabric separator shown in Fig. 3.13 is steam cleaned; the nonwoven fiber mats shown in Fig. 3.15 are replaced. The pressure drop at which cleaning or replacement must take place is based on the maximum pressure drop which a water-loaded dust-filled unit can take without damage. The manufacturer's recommendations on overpressure capability must be followed closely, and units must be cleaned or replaced soon enough so that an adequate margin of safety is allowed for the potential increase in pressure that would result from water loading. The 24 X 24 X 2 in. knitted-fabric separator can accept about 8 lb of water without flooding or droplet carry-over. The capacity of the 24 X 24 X 6 in. nonwoven mat is higher, but 8 lb of water per minute is more than either is likely to encounter under the worst conditions so long as a wave-plate separator is provided in systems with containment sprays. The clean-filter resistance of the knitted fabric mat (2 in. thick) is 1 in. H_2O at 1650 cfm, and the resistance of the nonwoven mat (6 in. thick) is 0.27 in. at 1000 cfm.

Table 3.12. Economic Operating Velocities for Moisture Separators

Separator Type	Air Flow	Velocity (fpm)
Knitted fabric, 2 in.	Horizontal	420--480
	Vertical	280--320
Knitted fabric, 4 in.	Horizontal	270--300
	Vertical	220--260
Nonwoven fiber, 6 in.	Horizontal	240--280
6-bend wave plate	Horizontal	550--650

[35] T. E. Wright *et al.*, *High Velocity Filters*, USAF Report WADC 55-457, ASTIA Document No. AD-142075, Donaldson Co., Inc., 1957.

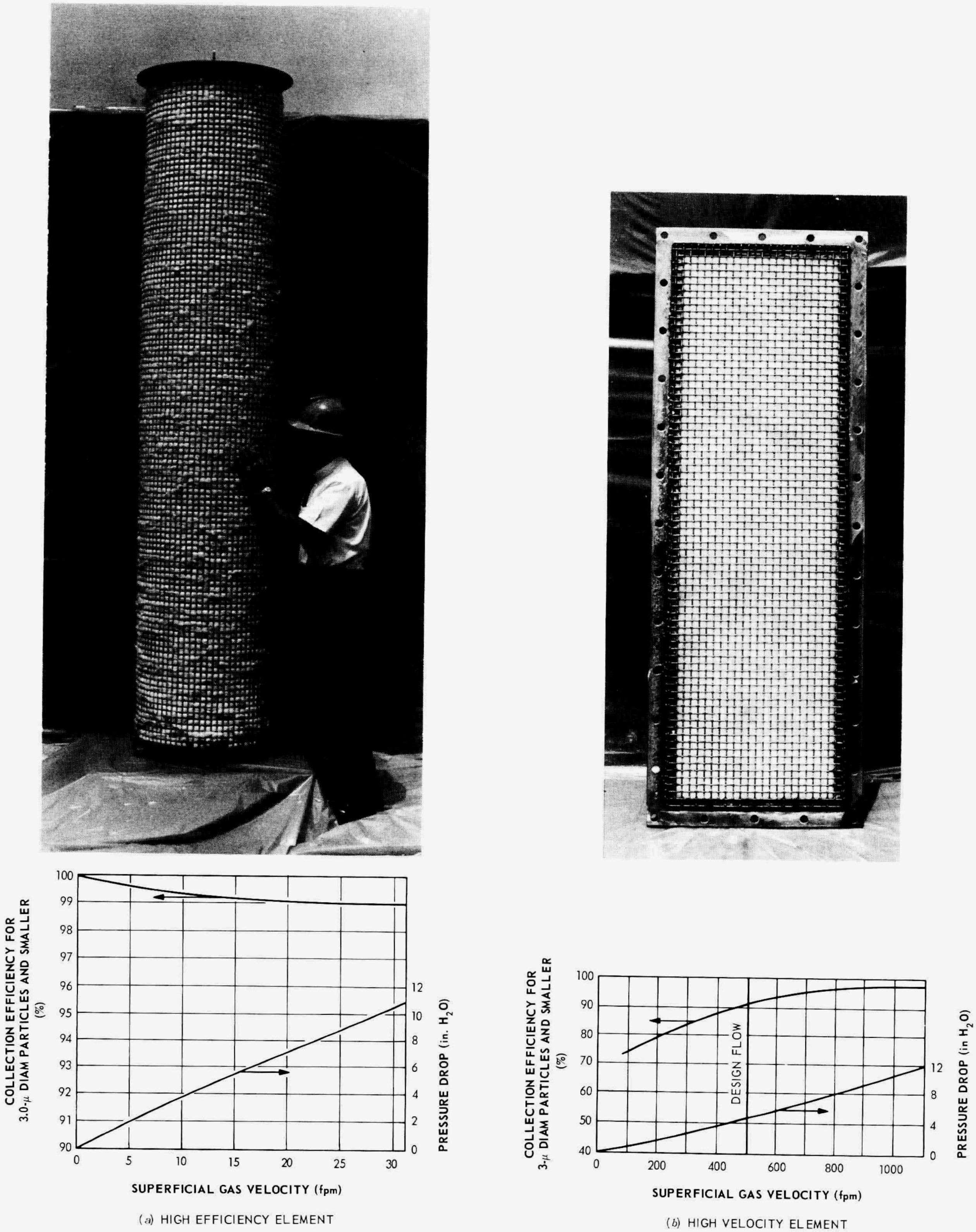

Fig. 3.17. Brink packed-fiber mist eliminators and operating characteristics. Courtesy The Monsanto Co.

It is obvious from the discussion above that the moisture separator, and its operating conditions, must be tailored for each situation and that performance tests must be made under simulated conditions to obtain the optimum design of separator and system.

3.5.2 Normal Off-Gas Mist Eliminators for Radiochemical Service

Mist eliminators are often required in off-gas systems to protect downstream filters from moisture and from acid or caustic fumes. Two types have given satisfactory service in radiochemical plant service.

Packed-Fiber Mist Eliminators. – Packed-fiber mist eliminators of the type shown in Fig. 3.17 have given excellent performance in industrial service and can be tailored, by selection of fibers and materials of construction, to a wide variety of applications.

The cylindrical element shown in Fig. 3.17*a* consists of a densely packed fiber bed, rigidly held between heavy corrosion-resistant screens. The unit shown is 24 in. in diameter and 120 in. long with a mounting flange for suspension from a support plate. Gas flows from the outside to the inside hollow core from which the clean gas exits at the top and the collected liquid exits at the sealed bottom through a drain pipe. Alternate designs with gas flow from the inside to the outside are also available. Fibers and other materials of construction are selected for their resistance to the reagents present in the off-gas. Operating velocities for this type of element range from 5 to 50 lineal fpm through the media, depending on design and performance requirements. The operating characteristics of two designs are shown in Fig. 3.17. Designs with collection efficiencies for submicron particles up to 99.98 wt % have been demonstrated on large-scale industrial processes.[36,37] The mechanisms of mist separation for this type of element are diffusion, impaction, and inertial effects, with diffusion controlling for submicron particles.

In one radiochemical operation, cylindrical elements with 3-in.-thick beds of 20-μ fibers and fiber packing density of 11.5 lb/ft^3, operating at a gas velocity of 15 fpm through the bed, gives 99.99 wt % efficiency for droplets 3 μ and larger and 99.3 wt % for droplets in the 0.3-to-0.5-μ range.[38] The pressure drop in this operation was 4 in. H_2O when the elements were clean and approximately 10 in. H_2O after a year of operation when the elements were wet and considerable solids had been collected. The maximum temperature is 200°F; the measured efficiency for ^{137}Cs was over 96 wt %.

High-velocity packed-fiber mist eliminators (250 to 500 lineal fpm through the media) have found extensive application in the chemical industry.[39] The rectangular element shown in Fig. 3.17 has overall dimensions of 18½ in. by 53 in. This type of unit utilizes impaction as the controlling collection mechanism. Collection efficiencies of essentially 100 wt % are achieved on particles over 3 μ in diameter with lower efficiencies (see Fig. 3.17*b*) for smaller particles. Elements similar in appearance to the high-velocity model have also been developed which have a pressure drop of 1 in. H_2O or less. This type, known as "Spray Catchers" have essentially 100 wt % efficiencies on particles greater than 5 μ in diameter but low efficiencies on smaller particles.

Packed-fiber mist eliminators are efficient solid-particle collectors and can be clogged by high dust loadings. Sometimes they can be made self-cleaning by adding atomized water to a gas stream containing acid or caustic fumes; under other circumstances they may have to be cleaned with steam or by backwashing. The units are particularly subject to clogging when operated completely dry, especially if there are viscous dusts or lint present. In low dust concentrations this type of unit has operated for years without cleaning, which indicates the desirability of efficient building supply air cleaning. In radioactive applications it is desirable to have two units arranged in parallel so that flow can be switched back and forth for maintenance or in the event of emergency without shutting down the system.

Perforated-Plate Mist Eliminators. – The perforated-plate mist eliminator consists of two perforated metal sheets spot-welded together and uniformly spaced a few thousandths of an inch apart, with perforations in adjacent sheets offset so the air entering the holes in the first sheet impinges on the second sheet and must make two 90° turns before it can escape. Moisture is removed by impingement of droplets on the water film flowing down between the sheets and on the face of the first sheet. The efficiency for large drops (50 μ and larger) is

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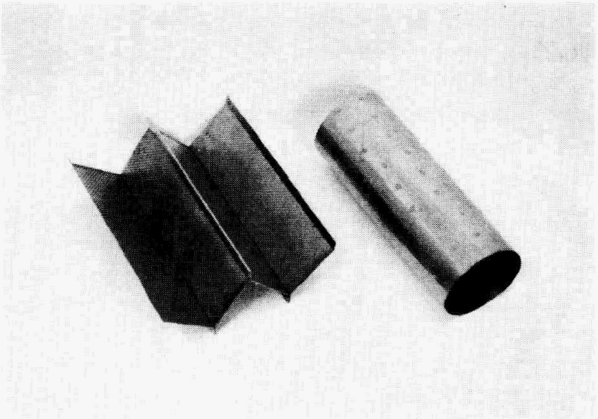
[36] J. A. Brink, "Removal of Phosphoric Acid Mists," *Gas Purification Process,* George Newnes, Ltd., London (1964), Chap. 15, Part B.

[37] J. A. Brink *et al.,* "Mist Eliminators for Sulfuric Acid Plants," *Chemical Engineering Progress* 64(11), 82–86 (November 1968).

[38] G. A. Johnson, Atlantic-Richfield Hanford Co., personal communication to C. A. Burchsted.

[39] J. A. Rauscher *et al.,* "Fiber Mist Eliminators for Higher Velocities," *Chemical Engineering Progress,* 60(11), 68–73 (November 1964).

virtually 100 wt %, and the efficiency for 1- to 10-μ droplets is greater than 99 wt % at air velocities of 500 to 600 fpm. The pressure drop is high, as can be seen from Fig. 3.18.



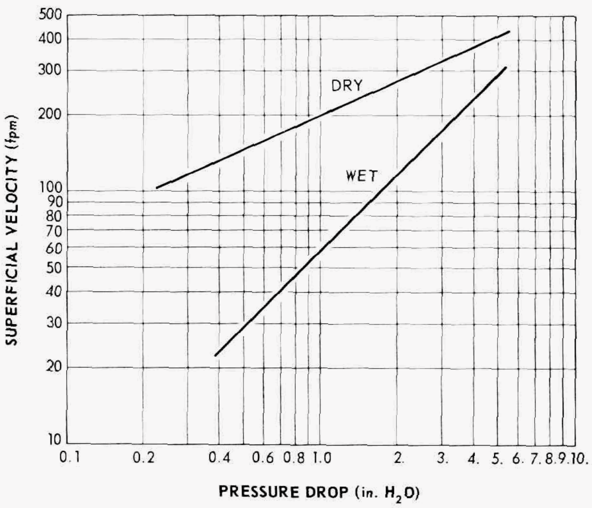


Fig. 3.18. Perforated-plate mist eliminator. Courtesy Multi-Metals.

The base material is made in flat sheets, which can be welded edge to edge to form separators of any size and capacity. The material lends itself to pleating, as shown in Fig. 3.18, and can be formed easily into cones, cylinders, or other configurations (except compound curves) to increase the surface area per square foot of frontal area. Experience shows that the units do not clog or flood easily, but they must be cleaned regularly to give satisfactory service. The plates can be cleaned in place by irrigation with acid or caustic solutions, flushing, and scraping (on the front plate). Separation of the plates can occur if the material is bent too sharply; a minimum radius of five times the metal thickness and a minimum saw-tooth angle (see Fig. 3.18) of 45° is recommended for fabrication. The plates must be installed so water can flow off them easily. Saw-tooth configurations should be installed with the pleats vertical, and cones should be installed point up to avoid flooding. Cylinders should be vertical or installed on a steep slope.

Application. – Both the packed-fiber and the perforated-plate mist eliminators have given satisfactory service in radiochemical operations, and both can be tailored to a wide range of corrosive conditions. The packed-fiber type is probably the better type where very high efficiency for small droplets at low flows is required. The perforated-plate type gives good service where flow rates are high and extremely high efficiency for droplets smaller than about 5 μ is not required. Neither type is suited to reactor post-accident cleanup applications. Neither the perforated-plate separator nor the high-efficiency packed-fiber separators are applicable for reactor postaccident air-cleanup systems. The high capacity, low pressure drop, packed-fiber separator has not been evaluated for reactor postaccident service but appears to be promising, particularly in view of its high strength and over-pressure resistance.

4. Multiple-Filter Systems

4.1 INTRODUCTION

Large-volume air supply and exhaust requirements may be met with a number of individual filter-blower installations operating in parallel, a central system, or a combination of both. Individual filter-blower systems, shown in Fig. 4.1, have the advantages of greater flexibility from the standpoint of system modification; less interference with operations during filter replacement because individual units can be shut down without affecting the remaining systems; better overall control of ventilation in the event of malfunction, fire, or accident to one or a few of the individual units; and minimum system balancing. On the other hand, batteries of individual filter-blower systems are more costly to build, operate, and maintain than a single central system of the same capacity.

Filters of a central system may be arranged in banks in a single filter house or in a multiple-single-filter array exhausting to a single fan and stack, as shown in Fig. 4.2. A multiple-single-filter array should be installed in a Zone II area that can be sealed off from adjacent operating, storage, and equipment areas and that lends itself to easy decontamination. In no case should a multiple-single-filter exhaust system be located without protection in an open attic or building space where problems of contamination spread could result should a filter be dropped during a change operation, or should the casing of a filter be breached by fire. The multiple-single-filter array has the advantages that all filters can be installed at a convenient height for replacement, and personnel do not have to enter what may be a highly contaminated filter house to change filters.

The design of multiple-single-filter arrays is similar to other single-filter installations discussed in Chap. 5. Careful alignment of filter inlet and outlet connections from the plenums is essential; if these are even slightly out of alignment, a poor seal will result and the condition will worsen with system pulsation and vibration. Inlet and outlet axes must be coincident within $\pm 1/16$ in. A minimum of 2 in., and preferably 4 in., should be allowed between filter elements for ease of maintenance. When tape-sealed open-face filters are used, this spacing between units should be at least 6 in., although tape-sealed connections are not recommended for nuclear exhaust applications. Aisle space on both front and back is desirable to permit inspection of seals.

In bank systems a number of open-face filters are installed in parallel on one or more mounting frames in a single housing. As filter banks are the more common type of central multiple filter system, the remainder of this chapter is devoted primarily to their design and construction, including spatial arrangement, mounting frames, housings, instruments, testing, and fire protection. The discussion primarily

Fig. 4.1. Battery of individual filter-blower systems exhausting fume hoods of a radiochemical laboratory. Courtesy Oak Ridge National Laboratory.

Fig. 4.2. Multiple-single-filter central exhaust system installed in a Zone II contamination area. Courtesy Chalk River Laboratory.

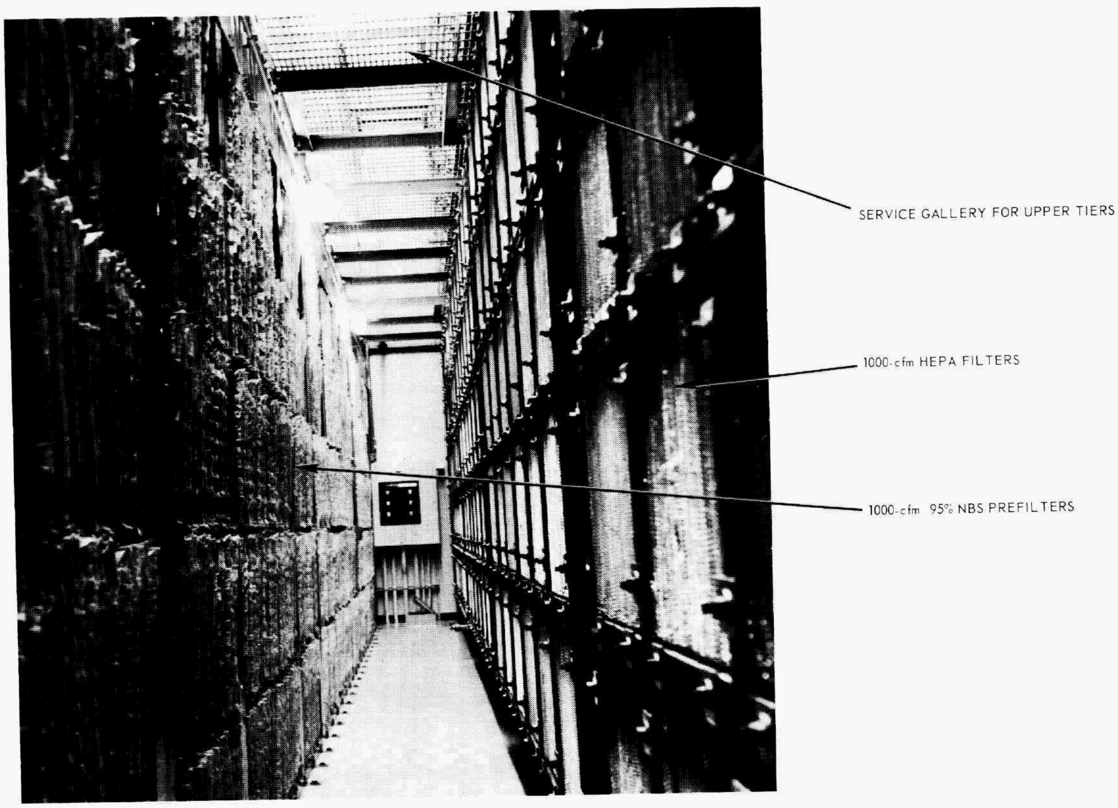


Fig. 4.3. Prefilter and HEPA filter banks of a large horizontal-flow laminar-flow clean room. Courtesy Union Carbide Corp., Y-12 Plant.

relates to exhaust filter systems, but much of the information is equally applicable to supply-air installations. Figure 4.3 suggests how large some of these installations can be, particularly in laminar-flow clean rooms and central exhaust systems for large nuclear installations.

Bank systems have the advantages of lower unit construction cost, lower unit operating cost, and lower space requirements as compared with multiple-single-filter systems. For example, the 36,000-cfm multiple-single-filter system shown in Fig. 4.2 occupies about 600 ft^2 of floor space and a volume of approximately 9000 ft^3, whereas a bank system of equal capacity would occupy less than 200 ft^2 of floor space and a volume of less than 1400 ft^3. The operating cost of a multiple-single-filter system may be 10 to 20% higher than that of an equivalent bank system because of friction and dynamic losses in the plenums and the individual filter inlets and outlets.

4.2 BANK SYSTEMS

A widely used framing system in earlier installations consists of commercially available "filter cells," made from light-gage cold-formed sheet steel, riveted or bolted together to form a honeycomb structure as shown in Fig. 4.4. Individual cells may vary in depth from 6 to 12 in. depending upon manufacturer and size of filter. Cracks between cells and between the outer surfaces of the frame and the housing are sealed with gaskets, duct tape, or caulking compound. The filters are clamped in place with spring clips, latches, machine screws, or other light-duty devices, depending on the particular manufacturer. Although honeycomb mounting frames are suitable for conventional air filters, they are not adequate for HEPA filters or charcoal adsorbers. Individual cells can be damaged easily during installation or filter change, and opportunities exist for air to bypass the filters at every cell joint. Even

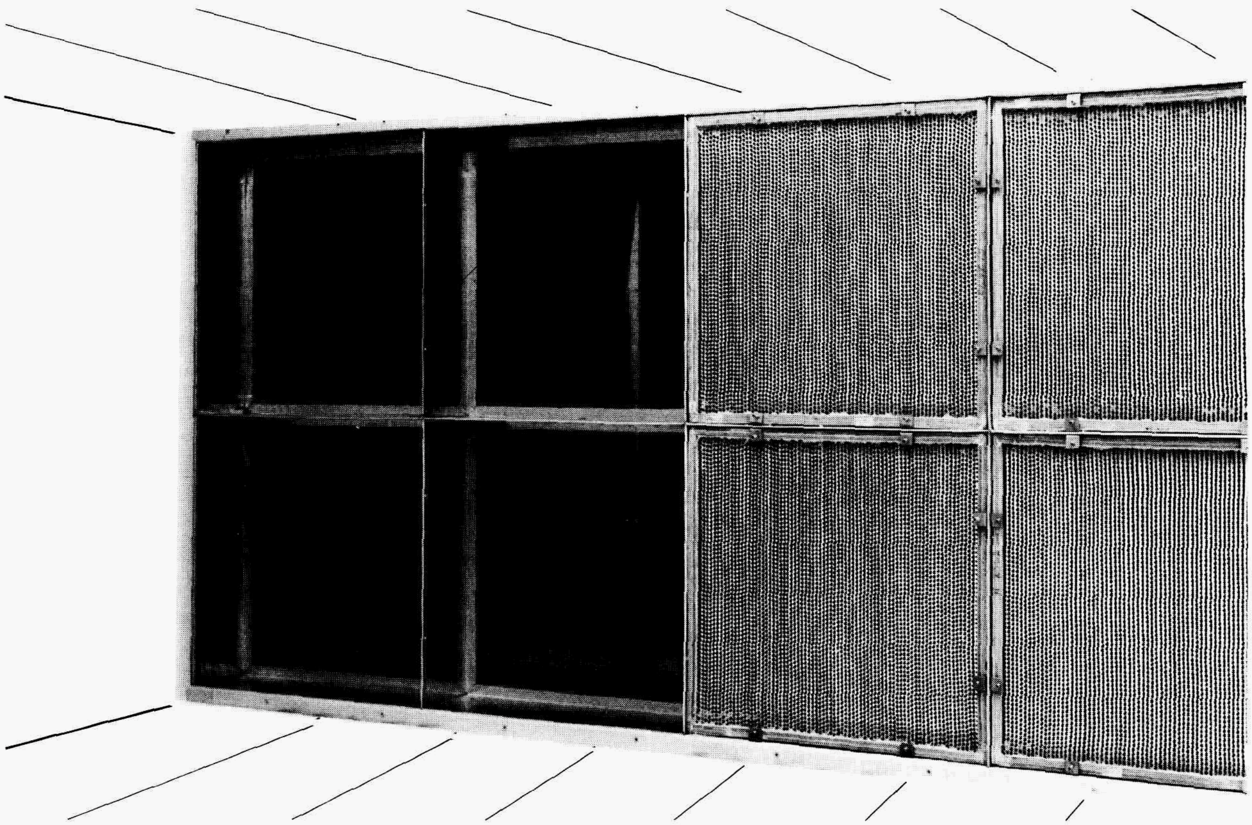


Fig. 4.4. Honeycomb mounting frame made up of individual filter "cells" bolted or riveted together. Note the caulked joints and the light-duty filter mounting frame and clamping devices. Mounting frames of this type are not suitable for nuclear exhaust applications. Courtesy Union Carbide Corp., Y-12 Plant.

when the assembled frame can be made tight enough to pass an initial DOP test with duct tape or caulking compound, leaks can develop when sealing materials fail from exposure to heat, cold, moisture, dry air, vibration, or similar conditions that are frequently encountered in the operation of contaminated-exhaust systems. These leaks are a continuing maintenance problem whenever high performance must be obtained, and they may not show up until the system is most urgently required, as in the cases of certain standby filter systems.

Because of the light-gage steel (No. 16 U.S. gage or thinner) used in such cells, twisting or buckling may occur if the filter bank is exposed to shock loading – the shock produced by sudden closing of a damper has been known to cause extensive damage to such frames. Filter clamping devices used on these cells are too light to develop the gasket pressures necessary to seal the filter adequately, particularly if the sealing flange has been bent or nicked, a common occurrence during construction and maintenance. In addition, the sealing flanges do not have sufficient strength to permit proper filter-gasket compression without damaging the flange.

Another unsatisfactory method of installing filters in banks is simply to stack the filter units in a rectangular opening and seal the spaces between and around them with duct tape or caulking compound. In a sense, they become their own mounting frame; as previously noted, tapes and caulking compounds often fail under service conditions and cannot be considered reliable for high-efficiency systems. Nor can a mounting system that provides no positive support for the filters be considered to be reliable. Stacking is not a suitable method for even low-efficiency prefilter systems.

Critical factors in the reliable operation of a high-efficiency exhaust filter system include:

1. structural rigidity of the mounting frame;
2. rigid and positive clamping of filters to the mounting frame;
3. careful specification of, and strict adherence to, close tolerances on alignment, flatness, and surface condition of filter seating surfaces;
4. welded frame construction and welded seal between the mounting frame and the filter housing;
5. ability to inspect the filter-gasket-to-mounting-frame interface during installation of filters;
6. adequate spacing between filters in the bank;
7. adequate spacing in the filter housing for men to work.

The filters and mounting frame must form a continuous barrier between the contaminated zone and the clean zone of the system; any hole, crack, or defect in the mounting frame that permits bypassing of the filters will result in leakage of contaminated air into the clean zone and a decrease of system effectiveness. A mounting frame that is not sufficiently rigid can be damaged during erection or maintenance, or it can flex so much in operation, particularly under abnormal conditions, that leaks may be opened up between the filters and the frame, between frame members (due to weld cracks or fatigue), or between the frame and the housing. Insufficient attention to maintenance provisions in the original design can increase operating costs and reduce the reliability of the system. Once the system is installed, defects are difficult to locate and costly to repair and may even require rebuilding of the system.

4.3 FILTER AND ADSORBER MOUNTING FRAMES

Mounting frames for HEPA filters and charcoal adsorbers should be all-welded structures of carbon or stainless steel structural shapes, plate, or heavy cold-formed sheet. Carbon steel frames are painted or coated with high-build vinyl or epoxy for corrosion resistance. Galvanized steel is not recommended because of welding difficulties and because the zinc coating does not give adequate protection in the environments that may be encountered in a contaminated exhaust system. Aluminum is not recommended because of pitting that may occur in some systems and difficulties in making reliable welds in the field (aluminum is not compatible with the containment-spray solutions proposed for some nuclear reactors). Because of the high cost of surface preparation, inspection, and rework usually incurred in obtaining high-quality vinyl and epoxy coatings, stainless steel is often the best choice in radiochemical plant applications. Suitable materials include:

carbon steel shapes and plate, ASTM A36;[1]

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[1] ASTM A36-68, *Specification for Structural Steel,* American Society for Testing and Materials, Philadelphia, 1968.

carbon steel sheet, ASTM A245, grade D;[2]

stainless steel shapes, ASTM A479, type 304L, class C, annealed and pickled;[3]

stainless steel plate, ASTM A240, type 304L, hot rolled, annealed, and pickled;[4]

stainless steel sheet, ASTM A240, type 304L, annealed and pickled, 2D or 2B finish.[4]

Applicable information relating to fabrication includes:

AISC *Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings;*[5]

AISI *Light-Gage Cold-Formed Steel Design Manual;*[6]

AWS *Welding Handbook;*[7]

Blodgett, *Design of Welded Structures.*[8]

4.3.1 Structural Requirements

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

$$W = 0.036(1.5)\ \Delta p\ A\ , \tag{4.1}$$

where

0.036 = conversion factor, in. H_2O to psi;

W = uniform beam loading, lb/in.;

Δp = pressure drop across bank, in. H_2O;

A = center-to-center spacing of filters on bank, in.

Assuming a center-to-center spacing of 26 in. for 24 X 24 in. filters, formula (4.1) reduces to:

$$W = 1.404\ \Delta p\ . \tag{4.2}$$

The value determined from formula (4.2) can be used in the standard beam formulas[9] to determine the minimum moment of inertia required. Knowing the minimum moment of inertia required for the member, the size and shape can be selected directly from the table of structural-shape properties of the AISC *Manual of Steel Construction,*[10] or can be determined by calculating the moment of inertia of a built-up or cold-formed section. For ASTM A36 steel, the standard beam formulas reduce to:

$$\text{major frame members: } I = \frac{\Delta p\, L^3}{1.59 \times 10^6}\ , \tag{4.3}$$

$$\text{cross members: } I = \frac{\Delta p}{149}\ , \tag{4.4}$$

where

I = minimum moment of inertia required, in.^{4};

Δp = maximum dirty-filter pressure drop across bank, in.;

L = length of member, in. (cross members assumed to be 22 in. long).

In addition to flexural strength, the frame for an exhaust filter system must also be able to withstand a shock loading of at least 2 psi across the bank without exceeding the elastic limit of the frame material. In most cases, members calculated using the above formulas will meet this requirement, but they should be at least checked. The section moduli

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[2] ASTM A245-64, *Specification for Flat-Rolled Carbon Steel Sheets,* American Society for Testing and Materials, Philadelphia, 1964.

[3] ASTM A479-63, *Specification for Stainless and Heat-Resisting Steel Bars and Shapes,* American Society for Testing and Materials, 1963.

[4] ASTM A240-67, *Specification for Corrosion-Resisting Chromium and Chromium-Nickel Steel Plate, Sheet, and Strip,* American Society for Testing and Materials, 1967.

[5] Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings, *Manual of Steel Construction,* American Institute of Steel Construction, New York, 1963, Part 5.

[6] *Light-Gage Cold-Formed Steel Design Manual,* American Iron and Steel Institute, New York, 4th ed., 1962.

[7] "Welding Processes," *Welding Handbook,* 6th ed., sect. 2, American Welding Society, New York, 1969.

[8] O. W. Blodgett, *Design of Welded Structures,* James F. Lincoln Arc Welding Foundation, Cleveland, 1966.

[9] Ref. 5, sect. 2.

[10] Ref. 5, sect. 1.

(S values) given in Part 1 of the *Manual of Steel Construction* can be compared with the minimum values obtained from the following formulas:

$$\text{major frame members: } S = \frac{13L^2}{f_a} , \tag{4.5}$$

$$\text{cross members: } S = \frac{6290}{f_a} , \tag{4.6}$$

where

S = section modulus, in.^{3};

f_a = maximum allowable fiber stress, psi;

L = length of member, in. (cross members assumed to be 22 in. long).

For ASTM A36 steel, these reduce to:

$$\text{major frame members: } S = 0.000361L^2 , \tag{4.7}$$

$$\text{cross members: } S = 0.175 . \tag{4.8}$$

For built-up and cold-formed members, the minimum S value calculated from these expressions can be compared with the actual value for the member calculated from the formula:

$$S = \frac{I}{c} , \tag{4.9}$$

where

S = section modulus, in.^{3};

I = moment of inertia of section, in.^{4};

c = distance from neutral axis of member to extreme fiber, in.

4.3.2 Frame Design

There are two general types of mounting frame construction: face sealed, in which the filter seals to the outermost surfaces of the frame members; and pocket, in which the filter fits into an opening of the frame and seals on an inner flange as shown in Fig. 4.4. The built-up pocket frame in Fig. 4.5 is made from I beams faced with ¼-in. plate. The major shortcoming of the pocket frame is that the filter gasket is obscured during installation. Also, if the openings are too snug, wood-cased filter elements may swell and jam after exposure to humid air. Face-sealed installations occupy slightly more space in the filter housing but require less materials and less welding, thereby presenting fewer opportunities for leakage.

A minimum face width of 4 in. is recommended for both major and cross members of face-sealed frames. This allows 1-in.-wide filter-seating surfaces to compensate for any misalignment of the filter during installation, and a 2-in. space between filters horizontally and vertically to give adequate room for handling, for use of power tools for filter installation, and for manipulation of a test probe between filter units. Although mounting frames made from members as narrow as 2½ in. have been used successfully, the slight increase in materials costs and building space required by the use of wider frame members will pay dividends in easier access and maintenance. A structural-steel mounting frame designed in accordance with this and the preceding sections is shown in Fig. 4.6. Minimum cost structural members for mounting frames suitable for most contaminated exhaust systems are given in Table 4.1.

A mounting frame made from a single sheet of ⅜-in. plate is shown in Fig. 4.7. The filter openings are flame-cut and finished by grinding. Reinforcing bars are intermittent-fillet-welded to the back of the frame to give the required moment of inertia [formulas (4.3) and (4.4)] as shown in Fig. 4.8. The frame, which is satisfactory for pressure drops up to 12 in. H_2O, is completely shop fabricated and installed in the housing by intermittent-fillet-welding the frame-reinforcing bars to backup columns, as shown in Fig. 4.7, and seal-welding Z strips to the face of the frame and the housing as shown in Fig. 4.9. The Z strips and corner pieces (Fig. 4.9) are prefabricated and provide the flexibility necessary to withstand vibration and pulsation. This design uses less material and requires much less welding than the structural frame shown in Fig. 4.6, has no welds on the face of the frame, eliminates frame-member alignment problems, minimizes filter-seating-surface preparation, and eliminates the need of high-heat-input field welding that could distort the frame or housing. Although two seal welds are required all around, both are with light-gage (No. 18 U.S. gage) material and can be made rapidly and with good quality by the MIG (inert-gas-shielded metal-arc) process.[7] The filter clamping devices (Fig. 4.10) have built-in filter supports well spaced from the face of the frame, which do not obscure any portion of the gasket seal during installation.

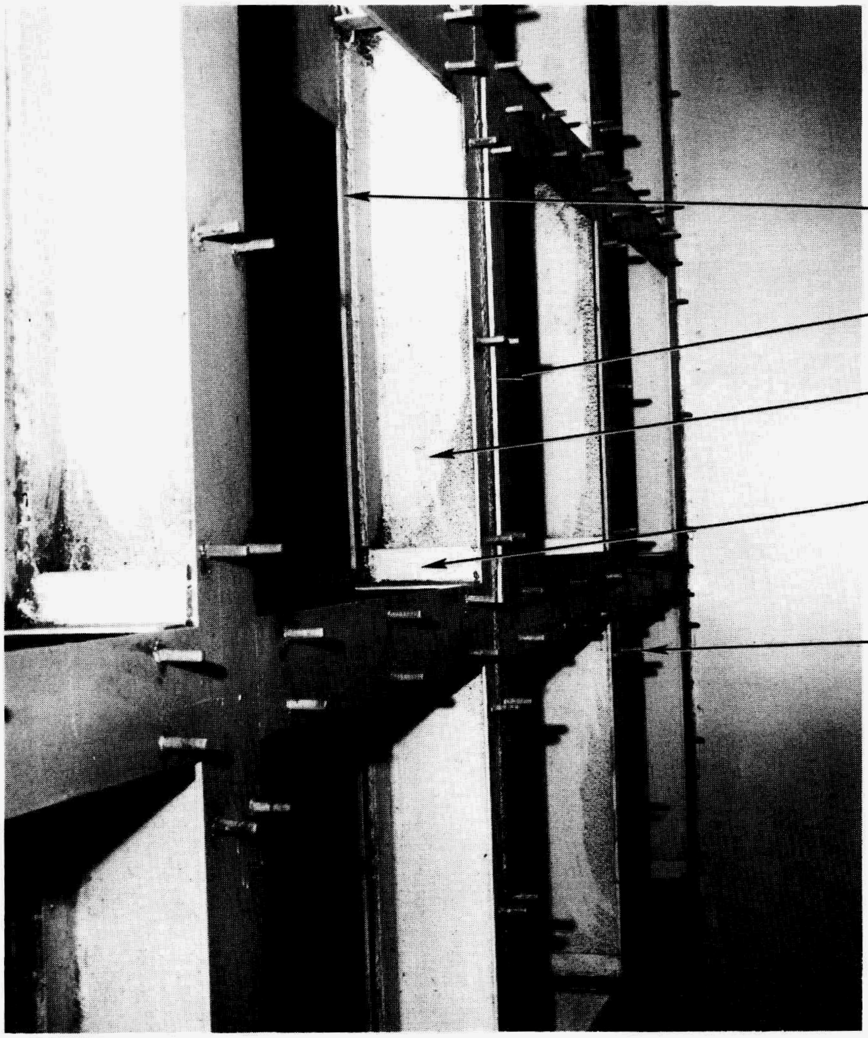

Fig. 4.5. Built-up pocket-type filter mounting frame for 500-cfm HEPA filters. Courtesy Mound Laboratory.

Table 4.1. Minimum-Cost Structural Members for HEPA Filter and Adsorber Mounting Frames

Maximum pressure drop to 12 in. H_2O

No. of 1000-cfm Units High	Principal Member[a]				Cross Members (span = 22 in.)
	Span[b]	Shape	Size	Pounds per Foot	
2	4 ft 8 in.	I beam	4 × 4 M	13	4 in. × 1¾ × 5.4 lb channels
3	6 ft 10 in.	I beam	4 × 4 M	13	4 in. × 1¾ × 5.4 lb channels
4	9 ft 0 in.	I beam	4 × 4 M	13	4 in. × 1¾ × 5.4 lb channels
6	13 ft 4 in.	I beam	6 × 4 B	16	4 in. × 1¾ × 5.4 lb channels
8	17 ft 8 in.	I beam	8 × 4 B	10	4 in. × 1¾ × 5.4 lb channels
10	22 ft 0 in.	I beam	10 × 4⅝	25.4	4 in. × 1¾ × 5.4 lb channels

[a]Principal members should span the shortest dimension of the bank.

[b]Span = [(number of filters)(26) + 4] in.

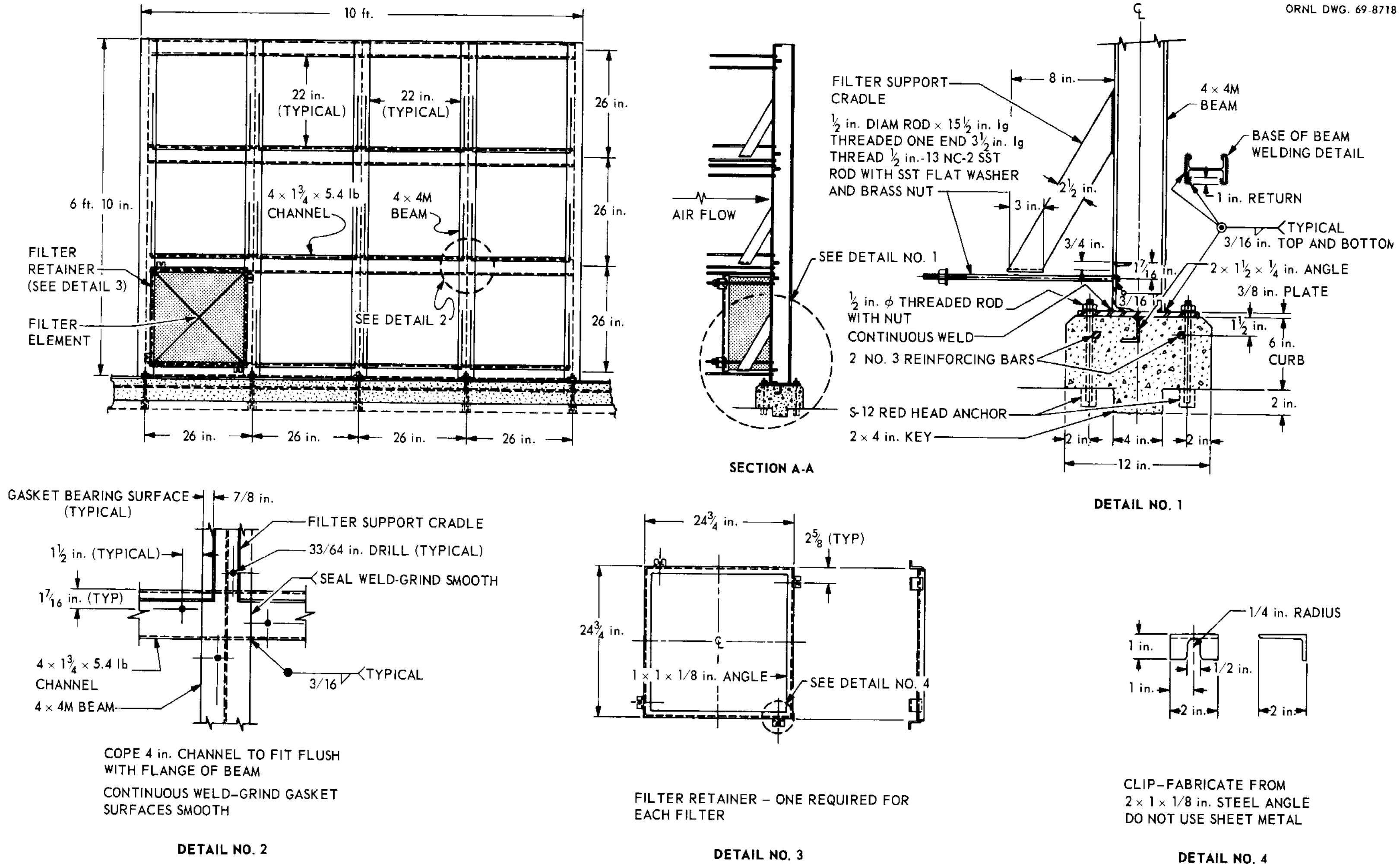

Fig. 4.6. Design details for structural steel HEPA filter and adsorber mounting frame. Courtesy Oak Ridge National Laboratory.

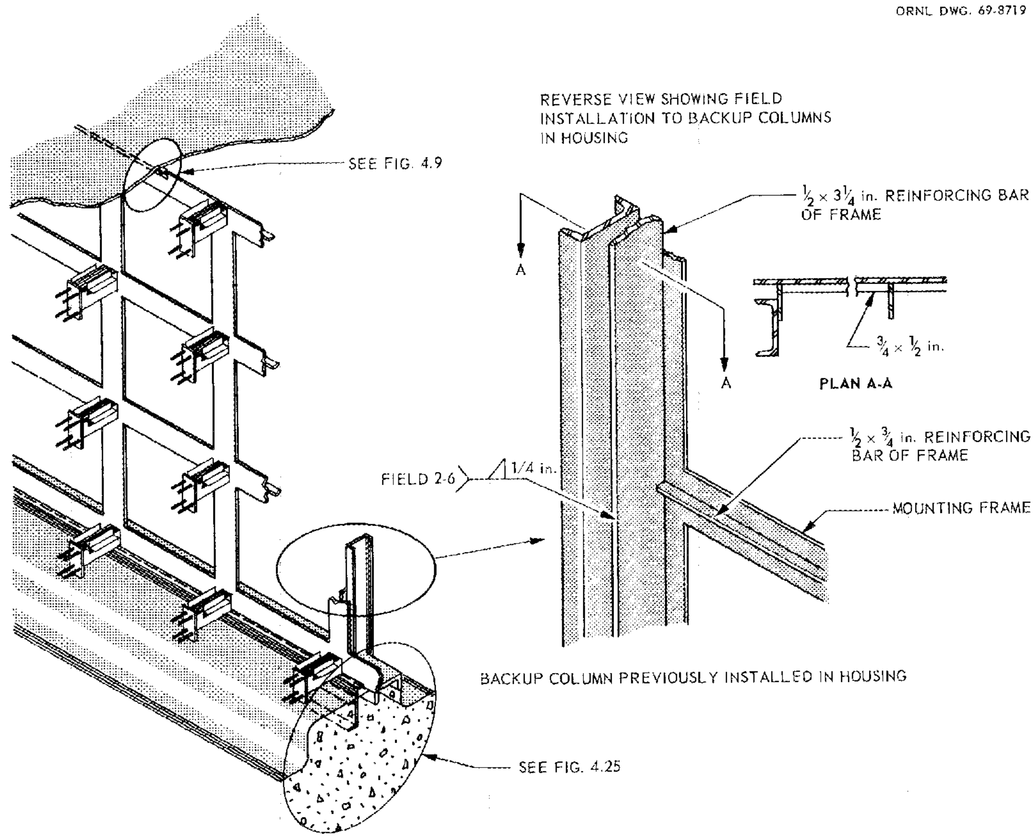

Fig. 4.7. Mounting frame for HEPA filters and adsorbers made from a single plate, showing installation to previously installed backup columns in filter house. See Figs. 4.8, 4.9, and 4.10.

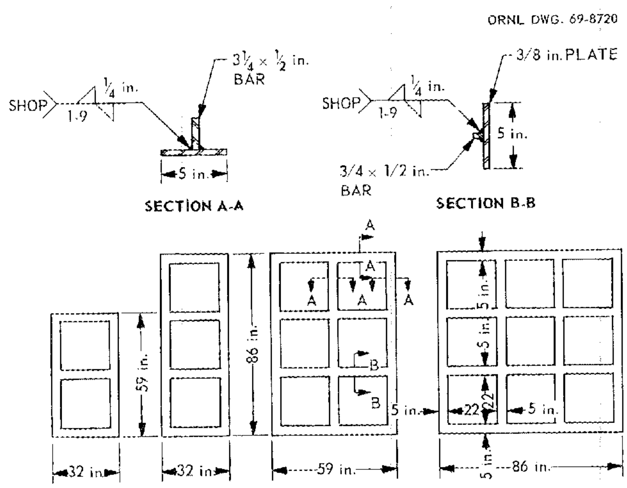

Fig. 4.8. Mounting frame made from a single plate. Module dimensions and details for reinforcing bars.

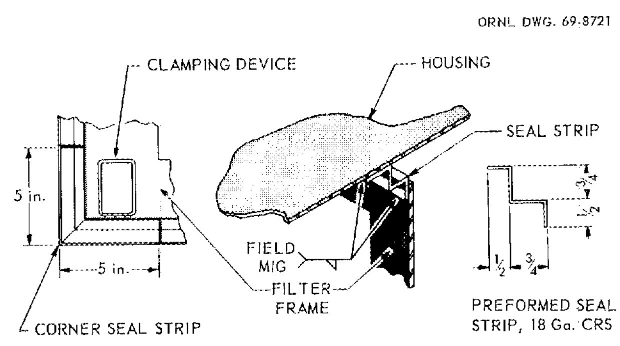

Fig. 4.9. Mounting frame made for a single plate. Details and installation of Z strips to seal frame into housing.

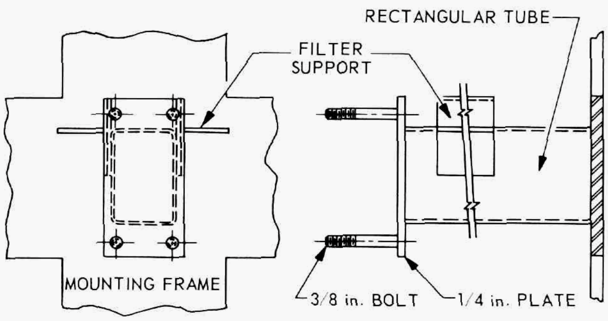

Fig. 4.10. Mounting frame made from a single plate. Details of filter clamping device.

4.3.3 Frame Fabrication

Filter mounting frames should be shop fabricated, as it is nearly impossible to avoid misalignment, warping, and distortion in field fabrication. Shop fabrication is less costly than field fabrication and permits better control over assembly, welding, and dimensional tolerances. Care must be taken to avoid twisting or bending of the completed frame during shop fabrication, shipping, and field installation. For proper performance and ease of maintenance of installed filters, frame tolerances must be tight and rigidly enforced. Minimum tolerances for the installed frame are given in Table 4.2. It is recommended that the frame be abrasive blasted with a fine grit or sand after welds on the filter-seating side of the frame are ground smooth and flush.

The inert-gas-shielded metal-arc (MIG) process or inert-gas-shielded tungsten arc (TIG) process is recommended for shop and field fabrication. The MIG process is particularly adapted to field work because it is fast, gives a reasonably good quality of weld when made by a qualified welder under good conditions, and has low heat input.[7] Seal welds between adjoining members and between the frame and housing should be full-penetration welds and must be made from the air-entering side. Only welders qualified in accordance with AWS standard D1.0-1969[11] or an equivalent qualification should be permitted to make welds on HEPA filter and adsorber mounting frames. Both seal and strength welds should be inspected carefully by a qualified inspector under a light level of at least 100 ft-c on the surface being inspected – inspection with liquid (dye) penetrant inspection in accordance with Appendix VIII, Sect. VIII of the ASME Boiler Code.[12] Particular care must be paid to the finish of seating surfaces. Welds and weld spatter must be ground smooth and flush, roll marks and scratches must be ground smooth, and faces of laterally misaligned members must be ground flush.

Table 4.2. Recommended Tolerances for HEPA Filter and Adsorber Mounting Frames

Alignment	Perpendicularity: Maximum offset of adjoining members, 1/64 in. per foot or 1/16 in., whichever is greater
	Planarity of adjoining members: 1/64 in. maximum offset at any point on the joint
Flatness	Each filter surface shall be plane within 1/16 in. total allowance
	Entire mounting fixture shall be plane within 1/2 in. total allowance in any 8 × 8 ft area
Dimensions	Length and spacing of members shall be true within +0, −1/16 in.
Surface finish	Filter seating surfaces: 125 μin. AA, maximum, in accordance with USA Standard B46.1. Pits, roll scratches, weld spatter, and other surface defects shall be ground smooth after welding, and ground areas shall merge smoothly with the surrounding base metal

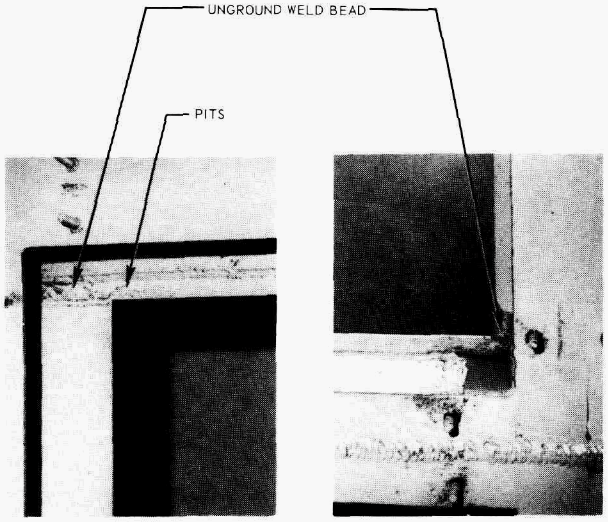

Fig. 4.11. Unacceptable finish on filter seating surfaces. Courtesy Mound Laboratory.

[11] AWS Standard D1.0-1969, Code for Welding in Building Construction, American Welding Society, New York, 1969.

[12] Methods for Liquid Penetrant Examination, *ASME Boiler and Pressure Vessel Code,* American Society of Mechanical Engineers, 1968, sect. VIII, Unfired Vessels, Appendix VIII.

Unsatisfactory conditions too often found in welded filter mounting frames, particularly where surfaces are difficult to reach with a power grinder, are shown in Fig. 4.11.

4.3.4 Filter Clamping and Gaskets

Filter units must be clamped to the mounting frame with enough pressure to enable the gasket to maintain a reliable seal under conditions of vibration, thermal expansion, frame flexure, shock, overpressure, and widely varying temperature and humidity that can be expected in service. The clamping devices must function easily and reliably after long exposure to hostile environments and, in addition, must be operable easily by personnel dressed in bulky protective clothing, gloves, and respirators (or full-face gas masks) while working in close quarters. Experience has shown that a simple bolt-and-nut system gives the most satisfactory service under these conditions. Eccentric, cam-operated, overcenter, or spring-loaded latches and other ingenious mechanisms designed for quick opening and closing often fail, get out of adjustment, or relax in service, resulting in inadequate clamping pressure after a period of use.

Major factors in the design of filter clamping devices are the magnitude and uniformity of gasket pressure. Experience in both clean rooms and contaminated exhaust applications has shown that flat closed-cell neoprene gaskets, ASTM D1056 grade SCE-43 or -44,[13] give the most satisfactory seal for high-efficiency filters and adsorbers. There is no advantage in using shaped (molded) gaskets – not only are they more expensive, but research has shown them more prone to leak.[14] Gaskets that are too soft (i.e., less than grade SCE-43) take an excessive compression set that may permit leakage if there is relaxation of the clamping bolts. Gaskets that are too hard (i.e., harder than grade SCE-44) require such high clamping loads to effect proper sealing that the filter itself can be damaged.

As little as 20% gasket compression is needed to effect a reliable seal when the thickness of the gasket is uniform to within ±0.01 in. and when the seating surface of the mounting frame is plane to within ±0.01 in.[14] However, these tolerances are much too restrictive for economical construction, and experience has shown that a gasket compression of at least 80% is usually necessary to effect a reliable seal over long periods of time. Eighty percent compression requires a loading of approximately 20 lb per square inch of gasket area, a total clamping load of about 1400 lb for a 24 X 24 in. filter unit. The recommended procedure for installing filters is to torque the clamping bolts to an initial 50% gasket compression and then to retorque them one or two weeks later to a total compression of 80% to minimize later difficulties from compression set and bolt relaxation.

Gaskets that are too thin may not give a reliable seal with the recommended frame tolerances (Table 4.2), whereas one that is too thick may be unstable and tend to roll or pull off the flange of the filter case as it is compressed, perhaps to the extent that sections may be extruded between the case and mounting frame and produce a serious air leak. Recommended gasket sizes are $\frac{1}{4}$ in. thick X $\frac{3}{4}$ in. wide and $\frac{1}{4}$ in. thick X $\frac{5}{8}$ in. wide. Gaskets must be glued to the filter unit, not to the mounting frame, because they must be replaced with each filter change. Gaskets should have cut surfaces on both faces because the "natural skin" produced by molding tends to bridge discontinuities or defects in the seating surface and because the silicone mold-release compounds prevent proper adhesion of the gasket to the filter case.

Mating metal parts (e.g., nuts and bolts) may corrode or seize after extended service in a contaminated exhaust environment. A clamping system made up of stainless steel bolts and brass or precipitation-hardening stainless steel nuts is recommended. When no pressure-distribution frame (detail 3, Fig. 4.6) is provided, eight pressure points are recommended per 24 X 24 in. filter unit. Where pressure-distribution frames are provided, four pressure points are sufficient. Individual clamping of each filter is recommended, that is, holding clips that bear on only a single filter and do not hold two or more adjacent filters. "Common bolting," in which holding clips bear on two or more adjacent filters as shown in Fig. 4.12, has been widely used because it is less expensive than individual bolting and requires fewer pieces to be manipulated during a filter change, and it has proven very satisfactory in many applications. However, it limits the ability to adjust or replace individual filters after installation without the possibility of upsetting the seals of adjacent filters. In

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[13]ASTM D1056-67, *Specification and Tests for Sponge and Expanded Cellular Products,* American Society for Testing and Materials, Philadelphia, 1967.

[14]F. E. Adley, Factors Influencing High Efficiency Gasket Leakage, *Proceedings of the Ninth Air Cleaning Conference,* USAEC Report CONF-660904, Harvard Air Cleaning Laboratory, September 1966.

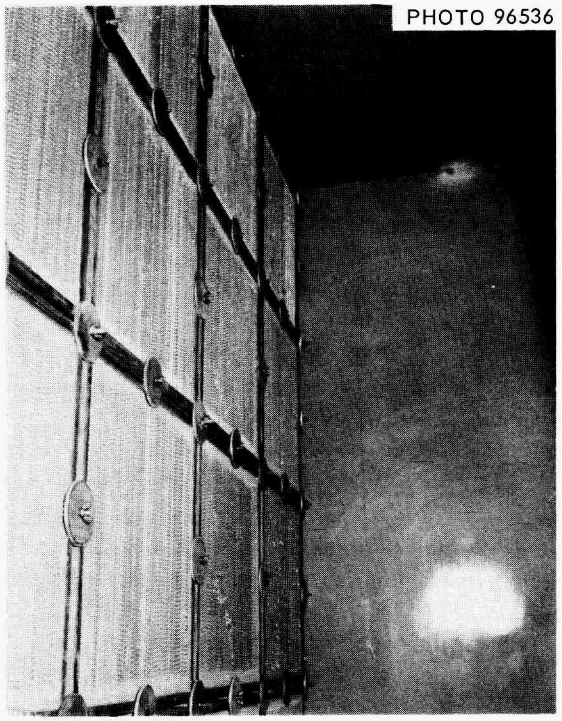

Fig. 4.12. Example of unsatisfactory filter clamping. Note corner clip which bears on four filters. Removal of one of the center filters would disturb the seals of eight surrounding filters. Courtesy Oak Ridge National Laboratory.

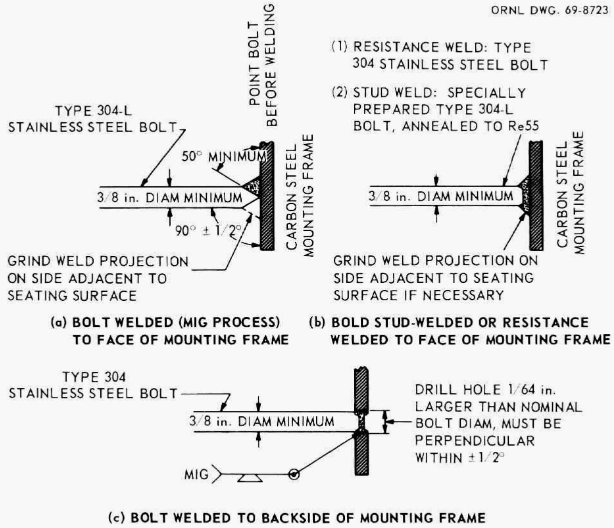

Fig. 4.13. Approved methods of welding clamping bolts to filter mounting frames.

Fig. 4.12, for example, replacement of one of the center filters might upset the seals of eight surrounding filters. If common bolting must be employed, no clip should bear on more than two filters.

The minimum bolt size recommended for individually clamped filters is $\frac{3}{8}$-16-UNC, but $\frac{1}{2}$-11-UNC or $\frac{5}{8}$-11-UNC bolts are preferred. For charcoal adsorbers, $\frac{5}{8}$-11-UNC bolts are recommended. When common bolting is employed, $\frac{5}{8}$-11-UNC bolts are recommended. Several methods of installing bolts to the mounting frame are shown in Fig. 4.13. The bolts are actually threaded rods. Methods *a* and *b* (Fig. 4.13) avoid penetration of the mounting frame (and thereby avoid future leaks) but give problems in alignment and location. Method *c* overcomes those problems and also the problem of a weld bead at the base of the bolt (if too large, the weld bead would interfere with proper seating of the filter). A method which overcomes all of these problems is shown in Fig. 4.10, where the bolts are mounted or welded to the face of the frame far enough from the filter seating surfaces that weld beads do not interfere with seating of the filters. This arrangement has the advantage that damaged bolts can be replaced easily without damage to the mounting frame. Of the methods shown in Fig. 4.13, *b* is probably the least expensive and *a* is the most expensive. Care must be taken with method *c* to avoid pushing the base of the bolt too far through the frame (which would appreciably increase the cost of welding) and to ensure complete seal welding.

4.3.5 Filter Support

A desirable feature from the standpoint of maintenance is a cradle or other means to support the filter element as it is moved into position on the frame. The cradle should not obscure any more of the filter-to-frame interface than possible to avoid interference with inspection as the filter is installed. An acceptable cradle design is shown in Fig. 4.14 and an unacceptable design in Fig. 4.15. An ideal filter support was shown in Fig. 4.10 in which the support is completely removed from the face of the mounting frame. In some installations filters are supported on the bottom clamping bolts; however, this risks damage to bolt threads. When it is planned to use the bottom bolts as filter supports, $\frac{5}{8}$-in. bolts should be used.

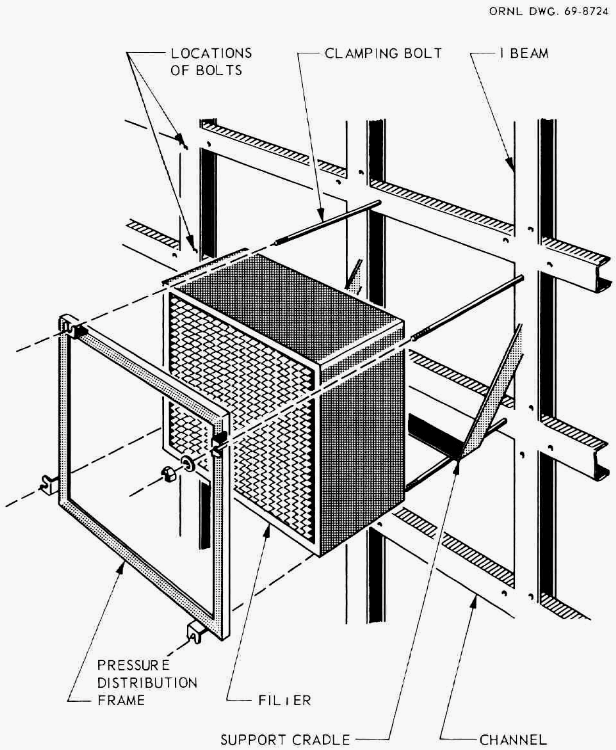

Fig. 4.14. Filter installation (exploded view) illustrating an acceptable filter support and alignment cradle. See Fig. 4.6. Support and bolts shown for only one filter.

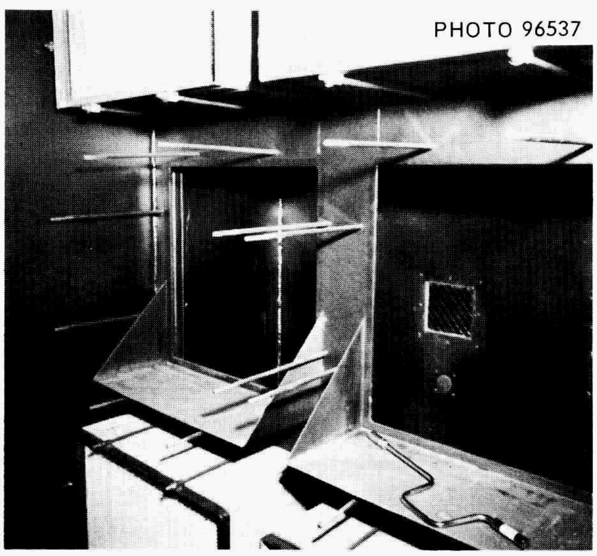

Fig. 4.15. Unacceptable filter support cradle. Courtesy Oak Ridge National Laboratory.

4.4 ARRANGEMENT OF FILTER AND ADSORBER BANKS

The orientation of filter banks (vertical or horizontal) and of filters in a bank (up- or downstream), the arrangement of filters in the bank, and the floor plan of the bank affect reliability, performance, and maintainability of the filter system. Savings gained by designing for minimum space and materials can be wiped out many times over by the higher operational, maintenance, and testing costs that will result from higher pressure drops and cramped working space in the filter housing.

4.4.1 Vertical Filter Banks

Vertical banks (horizontal air flow) are preferred over horizontal banks (vertical air flow) in contaminated exhaust systems because the filters are more favorably oriented with respect to ease of handling, mechanical strength characteristics of the filters, and collection of condensate (in horizontal banks, filter

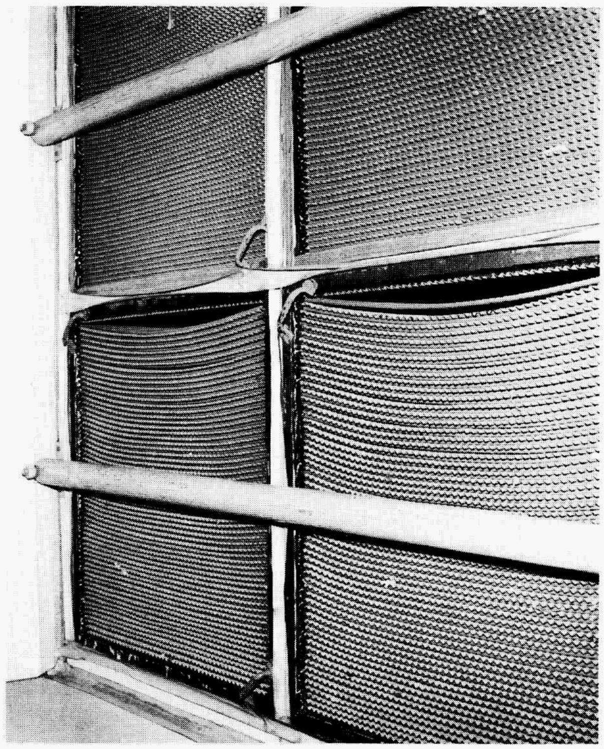

Fig. 4.16. Improperly installed HEPA filters. Pleats have sagged nearly 2 in. after six to eight months of service. Also note peeling duct tape used to seal between filters and between filters and housing. Courtesy Oak Ridge National Laboratory.

pleats can collect moisture, which, in time, may cause deterioration of the medium, separators, adhesives, and filter casings). Filters must be installed in vertical banks with pleats and separators vertical; horizontal pleats tend to sag over a period of time, as can be seen in Fig. 4.16, and may tear away from the case. The pleats or trays of charcoal adsorbers, on the other hand, must be horizontal to avoid settling of charcoal within the beds.

4.4.2 Horizontal Banks

When filter banks must be horizontal, upflow is preferred to downflow because sagging of the filter core is offset to some extent by air pressure and because there is less chance of cross contamination from the dirty side to the clean side of the system. With downflow, contaminated dust dislodged during a filter change will fall into the clean side of the system. Also, liquid collected in the pleats of filters in a downflow system will eventually seep through the medium and carry dissolved contaminants into the clean side of the system. On the other hand, upflow systems require withdrawal of contaminated filters into the clean zone. When horizontal installation must be used, filters should be mounted on the upper side of the mounting frame so their weight will load rather than unload the gaskets. Also, replacement of filters from above is easier and less costly than replacement from below. The discussion of structural strength of filter mounting frames was based on vertical banks. Design of a horizontal mounting frame must take the weight of the filters (Table 4.2) and the weight of the frame into consideration in addition to air-pressure loading, or provide tie rods or other means of supporting the frame.

4.4.3 Orientation of Filters with Respect to Air Flow

No clear-cut conclusion can be drawn for mounting filters on either the upstream side of the mounting frame or the downstream side. Both methods of installation are being used successfully. The AEC Division of Operational Safety usually recommends downstream mounting, whereas many AEC contractors prefer upstream mounting. The following advantages are cited for upstream mounting:

1. Filters are withdrawn into and handled within the contaminated side of the system during a filter change. No contaminated materials are brought into the clean side of the system, so there is more complete separation of the clean and dirty sides of the system.
2. Air flow tends to load the filter gaskets during operation, so there is less likelihood of leaks.

Disadvantages of upstream mounting are: (1) personnel have to work within a highly contaminated zone during a filter change, (2) there is the possibility that contamination can be tracked or carried out of the contaminated zone by workmen unless there is careful planning and execution of a filter change, (3) filter clamping devices are located in the dirty side of the system where they are most exposed to corrosion and dirt.

Advantages cited for downstream mounting of filters are:

1. Filters are withdrawn into and handled within the clean side of the system, therefore there is less likelihood of tracking or carrying contamination into the building during a filter change.
2. Personnel are not required to work in a contamination zone during a filter change.
3. Filter clamping devices are located on the clean side of the system.
4. Leak probing of installed filters is more sensitive. If there are gasket or casing leaks, the driving force of air entering the filter forces the test aerosol through the leak and it is readily detected. With upstream mounting, on the other hand, any test aerosol that goes through a leak in a gasket or filter casing mixes with the air and test aerosol passing through the opening in the mounting frame, so the leaks are obscured; although the fact that a leak exists may be disclosed by a test, the location of the leak cannot be easily determined by probing.
5. Only the upstream face of the filter is contaminated during operation; the outer surfaces of the filter case and the downstream face of the filter pack are not contaminated.

The disadvantages of downstream mounting are: (1) filter gaskets tend to be unloaded by air pressure during operation, increasing the likelihood of gasket blow-by and (2) the contaminated filters must be withdrawn into the clean side of the system in a filter change. The latter can be offset by "fixing" the contaminated dust by spraying the upstream side of the filter pack with paint or acrylic spray, or by taping cardboard over the upstream face of the filter; the possibility still exists of dislodging contaminated dust into the clean side of the system, either from the filter itself or from the edges of the frame opening (which is exposed to contaminated air during operation).

Filters have been mounted on both sides of a mounting frame in some installations when double filtration has been specified. This saves space and prevents carry-over of contamination to the clean side of the system when the upstream filter is removed from its frame, but this method makes reliable in-place testing of filters impossible. When new filters are installed, the first set that is installed can be tested, and then the two sets together can be DOP tested, but the first set will obscure the deficiencies of the second. In addition, the set of filters installed first, and found satisfactory by test, could be damaged during installation of the second set, and the damage could escape discovery. Double mounting of filters also has the disadvantage that fire in the first filter will jump nearly immediately to the second, so that any advantage of double filtration is lost. Double mounting is not recommended and is, in fact, prohibited by the AEC Division of Operational Safety where it has the authority to control design.

Similar problems exist when high-efficiency prefilters are installed in such a way that the HEPA filters and prefilters must be tested as a combination. Only when there are leaks in both filters could leaks be located by probing, and then only the leak in the downstream unit could be detected. Therefore the reliability of the individual filters remains unknown. A cardinal rule in contaminated exhaust systems is that no credit can be taken for untested and untestable filters, and although two sets of filters may be provided by double mounting, the operator cannot take credit for double containment. A third bank of filters in series with the double bank would be necessary by this rule, and, in fact, this type of multiplication of filter banks has occurred in some systems.

4.4.4 Arrangement of Banks

Spatial arrangement of filters on a mounting frame can influence operating performance and maintenance. If one were to specify twelve 1000-cfm-capacity filters (24 × 24 × 11½ in.) arranged in a six-wide-by-two-high array, it would create a serious installation and maintenance problem because personnel would be forced to crawl or work stooped over in the filter house, whereas arranging the same bank two wide by six high would make it impossible to reach the upper filters without bringing ladders or temporary scaffolding into the housing, always a major source of installed-filter damage, or providing a permanent work gallery. If the filters were arranged four high by three high there would still be a maintenance problem of access to the top tier of

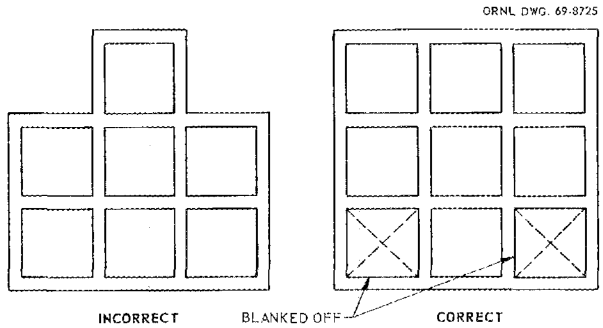

Fig. 4.17. Filter bank layout. Layout at left is much more expensive. If necessary to match installed filter capacity to calculated air-flow requirements, fill out the rectangle and blank off some of the openings, as shown at right.

filters. The best solution obviously is to arrange the filters in a four-wide-by-three-high array. For similar reasons, the proper arrangement for a 6000-cfm system would be two filters wide by three high.

Filter banks should be rectangular. The use of odd-shaped banks such as the one shown on the left in Fig. 4.17 in order to make installed filter capacity equal calculated system air-flow requirements increases construction costs significantly. By filling out the rectangle as shown at the right of Fig. 4.17, construction costs are reduced. If all nine spaces are filled with filters, operating costs may be reduced, as the additional filter would permit operation at a lower flow rate per unit, with attendant longer filter life and reduced filter-change frequency, as discussed in Chap. 2.

For filters with face dimensions of 24 × 24 in., maximum bank height should be no more than three filter units unless a permanently installed service gallery is provided for access to the upper tiers or unless space is left inside the housing for a powered man lift. In no case should filter changing require the use of ladders or temporary scaffolding; to require a workman who is dressed in bulky protective clothing, whose sight is obscured by a respirator or gas mask, and whose sense of feel is dulled by one or two pairs of gloves to manipulate a ladder or scaffold within the confines of a filter house is an open invitation to filter damage and personnel injury. Based on the 95th-percentile man,[15] the maximum height at which a man can effectively operate hand tools is 78 in., and the maximum load he

[15]The percentile value indicates the portion of the population who fall at or below a particular value of measurement; in this case only 5% of the population is tall enough to handle tools at heights over 78 in.

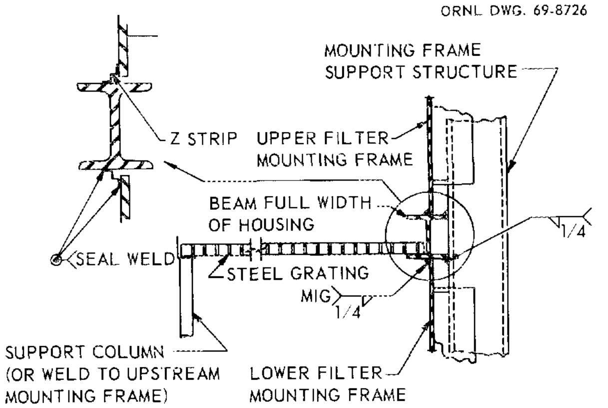

Fig. 4.18. Installation of service gallery using modular mounting frame shown in Figs. 4.7 and 4.8.

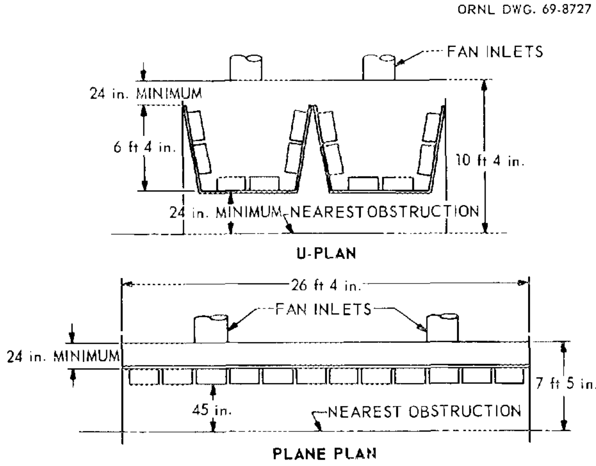

Fig. 4.19. Filter bank floor plans showing minimum clearances and floor space required.

can handle at a height of 5 ft or more is 40 lb,[16] so that some provision is necessary for access to the higher tiers of filters. A permanently installed steel service gallery, as shown in Fig. 4.18, is recommended. At costs of $60.00 to $80.00 per filter element, any savings realized in first cost by not providing such a gallery could be offset in only one or two filter changes. In addition, service galleries in high banks reduce the costs of preparing for and cleaning up after a filter change. The pay-out period for a gallery in a bank seven filters wide by six high is estimated to be about two years, based on labor savings only and taking no credit for prevention of potential filter damage.[17]

4.4.5 Floor Plan of Filter Banks

Vertical banks may be arranged in a plane or in a U or stepped pattern to permit more filter units to be installed in a given housing width. Although there is no appreciable saving in floor space with U or stepped banks (Fig. 4.19), such arrangements may lend themselves to more favorable building arrangements for the installation of nearby equipment. The use of a U or stepped bank in large systems may also have the advantage of improving inlet conditions to the fan or reducing the size and cost of duct transitions to the housing. Judicious layout of a bank can often reduce pressure losses in the system and bring about more uniform dust loading of filters, thereby equalizing the utilization of filters installed in the bank. If the open side of a U arrangement is centered on the fan inlet, for example, the distances from the filters to the fan are more or less equalized, and the bank may, in effect, form an inlet box which results in more favorable fan inlet conditions and more uniform pressure drop across and loading of the filters. On the other hand, straight (plane) banks are safer from the standpoint of fire spread than U or stepped arrangements.[18]

The procedures that will be required in construction and operational maintenance must be considered in planning. Adequate clearances for access must be left at turning points and between the bank and the nearest obstruction, and passageways between banks and between banks and the housing wall must be wide enough for welders to operate effectively and for workmen, dressed in bulky clothing, to get in to change filters, keeping in mind that they will have to kneel or stoop to get to the bottom tier. A 95th-percentile man in a kneeling position requires a minimum clearance of 36 in. from the face of the filters to the nearest obstruction,[16] not including withdrawal space for the filter unit itself; a minimum of 40 to 45 in. is recommended. Principal dimensions for a U arrangement are shown in Fig. 4.20; a maximum angle of 2 in 12 in. is recommended. Stepped (i.e., L) banks are usually laid out at right angles.

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[16]C. D. Morgan *et al., Human Engineering Guide to Equipment Design,* McGraw-Hill, New York, 1963.

[17]W. V. Thompson, *High Efficiency Particulate Filter History and Activities,* USAEC Report RL-REA-1000, General Electric Co., Richland, Wash., March 1965.

[18]P. D. Erickson *et al., Evaluation of Filter Flammability and Filter Bank Fire Detection Systems,* USAEC Report RFP-222, Dow Chemical Co., Rocky Flats, Colo., 1961.

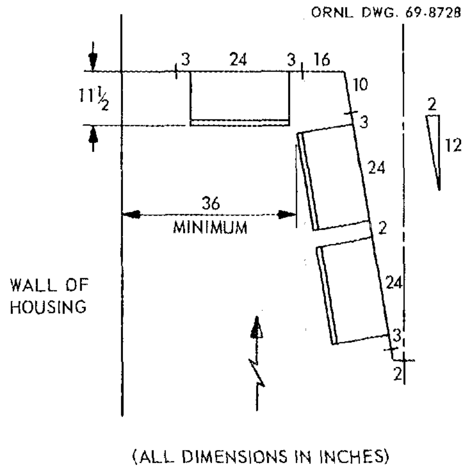

Fig. 4.20. Recommended dimensions for laying out U filter bank.

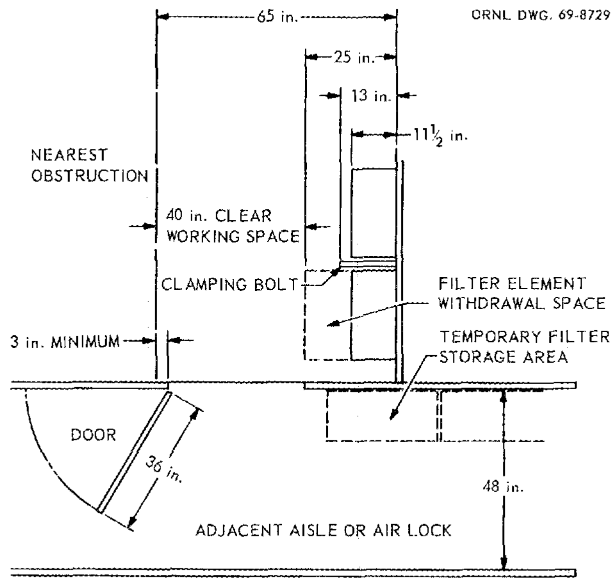

Fig. 4.21. Recommended space and clearance requirements for contaminated filter housings and adjacent aisle or air lock. Clear working space does not include filter withdrawal space.

4.5 FILTER HOUSINGS

Filter housings are sometimes shop fabricated but are usually fabricated onsite to meet the needs of the individual installation. Carbon steel is the commonest material of construction, although stainless steel may be used when corrosion is a problem. Stainless steel housings are much more expensive than carbon steel, roughly 5 to 1 for materials and 2 to 1 for labor. Aluminum is not suitable in most cases because of difficulty in obtaining reliable welds and the severe surface pitting that often occurs under service conditions. Galvanized steel may be used, but particular care must be paid to thorough removal of the coating prior to welding and to thorough cleaning and recoating of the weld area. Galvanized steel may not give adequate corrosion protection in many continuously on-line filter systems. When ionizing radiation must be considered, concrete or steel-lined-concrete housings or filter pits are necessary.

4.5.1 Arrangement and Location of Filter Housing

Maintenance is a major factor in the layout of the filter housing. Some systems have only a single bank of HEPA filters, many have a bank of prefilters in addition, and some may have as many as five or six banks of components in series within the same housing. Banks may be plane (straight), perpendicular to the air stream, or laid out in a U or step pattern. Adequate space and clearances for construction and maintenance personnel working inside the housing must be allowed, as was pointed out in the preceding section. In addition, there must be sufficient clear corridor space adjacent to the housing for handling filters during a filter change, and adequate corridor room to and from the housing. Dollies are often used to transport filters to and from the housing area, which makes for safer operations, from the standpoint of both personnel injury and contamination spread from dropped filters. When dollies are used, space must be allowed to get the dollies in and out and for unloading and loading. Additional space is desirable for stacking new filters, in their cartons, adjacent to the work area. Recommended clearances for the housing and adjacent aisle or air lock are given in Fig. 4.21.

A factor sometimes overlooked is proper access to the filter housing. Too frequently, housings have been crammed in among machinery and equipment where workmen are required to climb between, over, or under obstructions to get to the door of the housing, and then have inadequate space to work when they get there. In some installations it has been necessary to carry new and used filters, one at a time, over the roof top, and to rely on rope slings to hoist them up and down to a waiting truck. Plan the route for getting filters to and away from the housing, and provide elevators or cranes where they have to be hoisted to an upper story.

High-risk operations often require split systems, that is, two or more filter installations in parallel that exhaust from the same area and vent to the same stack. Each compartment must have inlet and outlet isolation dampers to permit one compartment to be held in standby or, when both are normally operated simultaneously, to allow one compartment to be shut down for maintenance or during an emergency. Whether or not operated as a split system, a large bank should be compartmented so that a fire in one compartment can be extinguished without damaging adjacent filters and without necessitating shutdown of the entire system. When high-activity alpha emitters such as transuranic elements are handled, it may be desirable to compartment the system in series, with separate compartments for prefilters and HEPA filters, as well as in parallel, for extra safety (see Fig. 2.9).

4.5.2 Steel Housings

Design practices used for conventional air conditioning and ventilation systems are not acceptable for the design of housings for high-reliability, high-efficiency contaminated-exhaust systems. Experience has shown that, under shutdown conditions, housing and duct leaks can result in the escape of contamination to clean areas, and even with the fans operating, reverse leakage of particles from the low-pressure side of a system (i.e., the interior of the housing or duct) to the high-pressure side (i.e., the occupied area) can sometimes take place because of Venturi and aspiration effects.[19]

Ordinary duct construction standards[20,21] call for proof testing under a negative pressure of only 2 in. H_2O. Under this pressure, a duct is permitted to deform by as much as 20% of its cross-sectional area.[22] This kind of construction is not permissible in systems operated at pressures more than 10 or 12 in. H_2O below atmospheric. Filter housings for contaminated-exhaust service must be able to withstand negative pressures at least up to fan cutoff, which may be 20 or more inches of water in many systems. A pressure differential of 2 in. H_2O between the inside and outside of a housing produces a load of more than 1000 lb over every 10 ft^2 of the housing wall; if the filters are operated to economical pressure drops, the housing may have to withstand ten or more times this load without appreciable deflection. Pulsation and vibration may aggravate the condition; in addition, the housing should be able to withstand reasonable shock loads without damage.

The references recommended in Sect. 4.3 for the design, fabrication, and welding of mounting frames are applicable for steel housing also. Housings should be all-welded with flange-and-bolt or welded inlet and outlet connections to the ducts and fans. Recommended sheet-metal thicknesses for sheet steel housings are given in Table 4.3, and minimum moments of inertia for steel reinforcing members are given in Table 4.4. Sheet-metal thicknesses in Table 4.3 are based on a maximum deflection of ¼ in. per lineal foot at a pressure differential between the interior of the housing and atmosphere equivalent to 1.5 times the maximum pressure at fan cutoff. The moments of inertia for reinforcing members in Table 4.4 were selected so as not to exceed the allowable stress of the steel. Members up to 20 in. long were considered to be uniformly loaded beams with fixed ends; members longer than 20 in. were considered to be uniformly loaded beams with simply supported ends. Values in Table 4.3 are given in U.S. gage numbers for sheet thicknesses and fractional inches for plate thicknesses.

In designing housings that will be installed inside a reactor containment, it should be recognized that there may be a pressure lag in the housing during the rapid pressurization of the containment following a major accident, and that this lag could result in a substantial negative pressure in the housing relative to the containment pressure at a given moment.

Reinforcing members should be spaced to minimize vibration and audible "drumming" of the housing walls that can be transmitted through the system. Reinforcements should be installed on the outside of the housing when possible to eliminate ledges and projections that collect dust and constitute hazards to personnel working in the housing. All sharp corners, welds, weld spatter, and projections inside the housing must be ground smooth. The housing design must minimize cracks and crevices that are difficult to clean and that may collect moisture that causes corrosion.

Mastics and caulking compounds, including the silicone-base sealants, are not suitable for sealing between panels and sections of a contaminated-exhaust housing. Lock seams, rivets, and bolts used in conventional construction for joining panels do not produce leak-tight joints (leaks upstream of the filters are not

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[19] W. J. Soules, Eastman Kodak Co., Rochester, N.Y., personal communication to C. A. Burchsted.

[20] Industrial Exhaust Systems, *ASHRAE Guide and Data Book, Applications*, American Society of Heating, Refrigeration, and Air Conditioning Engineers, New York, 1968, chap. 35.

[21] *High Pressure Duct System Design*, Sheet Metal and Air Conditioning Contractors Association, Chicago, 1965.

[22] UL-181, Safety Standard for Air Ducts, Underwriters' Laboratories, Chicago, 1962.

Table 4.3. Recommended Sheet Metal Thicknesses[a] for Steel[b] Filter Housings Under Negative Pressure[c]

Dimensions of Largest Unsupported Panel (in.)		Thickness (U.S. gage for sheet, fractional inches for plate) for Negative Pressure (Relative to Outside) of –								
Long Side[d]	Short Side	4 in. H_2O	8 in. H_2O	12 in. H_2O	20 in. H_2O	1 psi	2 psi	4 psi	8 psi	16 psi
54 (2)	12	24	22	18	15	14	11	8	1/4	3/8
	24	20	14	12	11	8	1/4	3/8		
	36	16	12	8	8	1/4	3/8			
	48	14	12	11	6	1/4	3/8			
80 (3)	12	24	22	18	15	14	11	8	1/4	3/8
	24	20	14	12	11	8	1/4	3/8		
	36	16	12	8	6	1/4	3/8			
	48	14	12	11	6	1/4	3/8			
106 (4)	12	24	22	18	15	14	11	8	1/4	3/8
	24	20	14	12	11	8	1/4	3/8		
	36	16	12	8	6	1/4	3/8			
	48	16	10	6	1/4	3/8				
132 (5)	12	24	22	18	15	14	11	8	1/4	3/8
	24	20	14	12	11	8	1/4	3/8		
	36	16	12	8	6	1/4	3/8			
	48	16	10	6	1/4	3/8				
158 (6)	12	24	22	18	15	14	11	8	1/4	3/8
	24	20	14	12	11	8	1/4	3/8		
	36	16	12	8	6	1/4	3/8			
	48	16	10	6	1/4	3/8				

[a]Based on flat plate, edges held but not fixed (R. J. Roark, *Formulas for Stress and Strain*, McGraw-Hill, New York, 4th ed., 1965), and maximum deflection of 0.25 in./ft between reinforcements.

[b]30,000 to 38,000 psi yield strength.

[c]Metal thicknesses less than 18 gage are not recommended because of welding problems.

[d]Length based on 2-in. spacing between 24 × 24 in. filter units; the numbers within parentheses denote number of filter units. The metal thicknesses are adequate for panel lengths within ±10 in. of the length shown.

permissible because of possible outleakage of contamination, and inleakage of air downstream of the filters results in reduced system performance). When bolted flange joints are used between the housing and ducts, 1½ × 1½ × ¼ in. angle flanges with ASTM D1056 grade SCE-45 to 30/40 durometer neoprene gaskets are recommended. Maximum flange-bolt spacing is 5 in.

4.5.3 Masonry and Concrete Filter Housings

Filter housings for low-activity systems are sometimes built as an integral part of a building. Portland cement concrete block or cast stone construction which meets the requirements for a 2-hr fire rating[23] is suitable, but not cinder block or other low-density material. Suitable constructions are shown in the UL *Building Materials List*.[24] Columns and bearing walls beneath such housings must have at least a 3-hr fire rating and preferably a

[23]UL-263, *Fire Tests of Building-Construction and Materials*, Underwriters' Laboratories, Chicago, 1959.

[24]*Building Materials List*, Underwriters' Laboratories, Chicago, current edition.

Table 4.4. Recommended Minimum Moments of Inertia for Selecting Reinforcing Members for Steel Filter Housings Under Negative Pressure[a, b]

Reinforcement		Moment of Inertia (in.^{4})[d] for Negative Pressure (Relative to Outside) of –								
Length[c] (in.)	Spacing (in.)	4 in. H_2O	8 in. H_2O	12 in. H_2O	20 in. H_2O	1 psi	2 psi	4 psi	8 psi	16 psi
54 (2)	12	0.04	0.04	0.04	0.04	0.04	0.08	0.16	0.31	0.63
	24	0.04	0.04	0.04	0.06	0.08	0.16	0.32	0.63	1.26
	36	0.04	0.04	0.05	0.09	0.12	0.24	0.47	0.94	1.88
	48	0.04	0.05	0.07	0.12	0.16	0.32	0.63	1.26	2.52
80 (3)	12	0.04	0.04	0.05	0.08	0.11	0.21	0.43	0.86	1.71
	24	0.04	0.06	0.09	0.16	0.21	0.43	0.86	1.72	3.42
	36	0.05	0.10	0.14	0.24	0.32	0.63	1.29	2.58	
	48	0.06	0.13	0.19	0.32	0.42	0.86	1.72		
106 (4)	12	0.04	0.09	0.13	0.22	0.30	0.60	1.19	2.38	4.77
	24	0.09	0.18	0.26	0.44	0.60	1.19	2.38	4.77	9.54
	36	0.13	0.27	0.39	0.66	0.90	1.79	3.57	7.15	
	48	0.18	0.36	0.52	0.88	1.19	2.38	4.76		
132 (5)	12	0.09	0.17	0.26	0.51	0.69	1.39	2.78	5.55	11
	24	0.18	0.34	0.52	1.02	1.39	2.78	5.55	11	22
	36	0.27	0.51	0.78	1.53	2.08	4.17	8.33	16.6	
	48	0.36	0.68	1.04	2.04	2.76	5.55	11		
158 (6)	12	0.15	0.29	0.44	0.73	1.0	2.0	4.0	8.0	16.0
	24	0.29	0.59	0.88	1.46	2.0	4.0	8.0	16.0	32.0
	36	0.44	0.87	1.32	2.19	3.0	6.0	12.0		
	48	0.58	1.16	1.76	2.19	4.0	8.0	16.0		

[a]Based on permissible deflection of $\frac{1}{8}$ in. per foot.

[b]Uniformly loaded beam 50% simply supported and 50% fixed ends assumed.

[c]Length based on 2-in. spacing between 24 X 24 in. filter units; the numbers within parentheses denote number of filter units. The data given are adequate for any length within ±10 in. of length given.

[d]Structural angles can be chosen from the tables given in the AISC *Manual of Steel Construction.*

4-hr rating. Interior walls and ceiling should be plastered with $\frac{1}{2}$ in. of gypsum plaster and painted with a nonadsorbent paint to seal the surfaces and to facilitate cleaning and decontamination. Blocks must be continuously sealed to the floors. After completion, a leak test should be made by spraying the joints between blocks and between the walls and ceiling and floor on the outside of the housing with DOP while pulling a negative pressure inside with the fan. This type of construction is particularly suitable for the Zone II area in which a multiple single-filter exhaust system is installed.

When high radiation levels are present or may be expected following an accident (e.g., nuclear reactor or radiochemical plant), filters may have to be installed in poured-concrete housings or underground concrete pits. A typical installation of this type is shown in Fig. 2.10. When unusually leak-tight construction is required, as for a filter system connected directly to the containment vessel of a nuclear reactor, a complete steel lining may be required inside of the pit. Concrete housings and pits must be designed in accordance with recognized radiation shielding principles* in addition to the standards of the American Concrete Institute (ACI) and the Concrete Reinforcing Steel Institute (CRSI). Barite, magnetite, or other high-density concrete is recommended for shielding blocks and portions of the housing or pit that extend above ground.

Particular care must be taken in concrete construction to avoid spalling and cracking that could result in leakage of unfiltered air, and rough surfaces that are difficult to decontaminate. Surfaces that are exposed to radioactive substances must have a smooth finish that is resistant to wetting and free of defects that can trap contaminants. A condition that is all too frequently found in concrete construction is shown in Fig. 4.22. Cracks such as these can be repaired by heavy undercutting and grouting with epoxy; however, this is time consuming, costly, and subject to the deficiencies of poor workmanship. Cracks can be minimized by the use

*Theodore Rockwell III (ed.), *Reactor Shielding Design Manual,* Van Nostrand, Princeton, N.J., 1956.

Fig. 4.22. An unacceptable concrete surface. Note cracks, spalls, and surface roughness that could result in leakage under the filter frame, which would trap contaminated material, and which would interfere with decontamination. Courtesy Oak Ridge National Laboratory.

of high-strength concrete (3000 lb at 28 days) and the liberal use of reinforcing steel. High-strength concrete also minimizes spalling problems. Curbs and steel embedments should be provided for installation of filters as discussed in the following section, and interior corners should be rounded or coved with a minimum 2-in. radius to facilitate painting and decontamination.

4.5.4 Seal Between Mounting Frame and Housing

A critical point in housing construction is the mounting-frame-to-housing seal. Except for remotely maintained systems, in which a gasketed seal is used to enable removal of the entire assembly of mounting frame and filters following an accident, a seal weld should be employed. Caulked seals are inadequate. The usual method of welding the mounting frame into a steel housing is shown in Fig. 4.23. The perimeter angle is welded to the housing on both sides all around. The frame-to-housing seal weld sometimes fatigues and cracks under service conditions, particularly when the housing is subjected to excessive vibration, shock loading, and frequently, when materials of construction of frame or housing are too light. Two alternate frame-installation methods which minimize the possibility of bypassing the filters in the event of seal-weld cracks are shown in Fig. 4.24.[25] Any of the methods shown are acceptable.

[25]K. E. Stewart, Dow Chemical Co., Rocky Flats, Colo., personal communication to C. A. Burchsted.

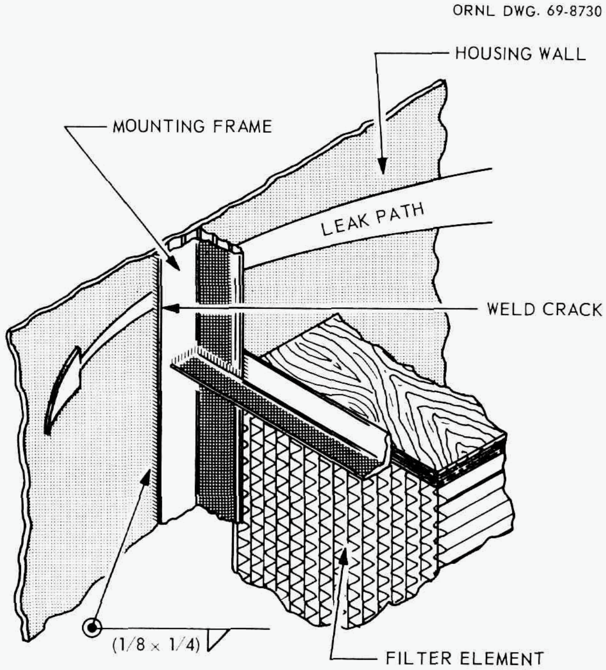

Fig. 4.23. Acceptable method of seal-welding mounting frame to housing. Weld crack and leak path show how a fatigued weld could result in bypassing the filters.

When a steel housing is installed on a concrete floor, the seal between mounting frame and floor is made by welding to a structural member embedded in the floor as shown in Fig. 4.25. An angle (as shown) or a channel or I beam with web vertical may be used to provide a labyrinth seal between embedded member and concrete. Channels and I beams should never be embedded with flanges pointing down, as this would trap air and cause voids in the concrete, providing a possible leakage path. Anchors, as shown in Fig. 4.25, are desirable with angles or channels to oppose overturning forces on the mounting frame due to air pressure. For masonry and concrete housings and pits, embedments in walls and ceilings, as shown in Fig. 4.26, are also required. Wall, ceiling, and floor embedments are welded together at the corners to form a continuous frame for the mounting frame.

4.5.5 Housing Floor

Steel housings should, if possible, have steel floors welded continuously to the walls of the housing. In no case should the housing be installed on a wood floor or on a floor having less than a 3-hr fire rating. A channel or I beam welded to the floor is recommended to raise the filter mounting frame off the floor. When steel housings are installed on concrete floors, curbs should be provided under the mounting frame (Fig. 4.25) and walls. An embedded member must be provided in the curb under the mounting frame and is desirable in the wall curb to enable the wall to be seal welded also. As a minimum requirement for steel housings installed on concrete, the walls should have a continuous perimeter

ORNL DWG. 69-8731

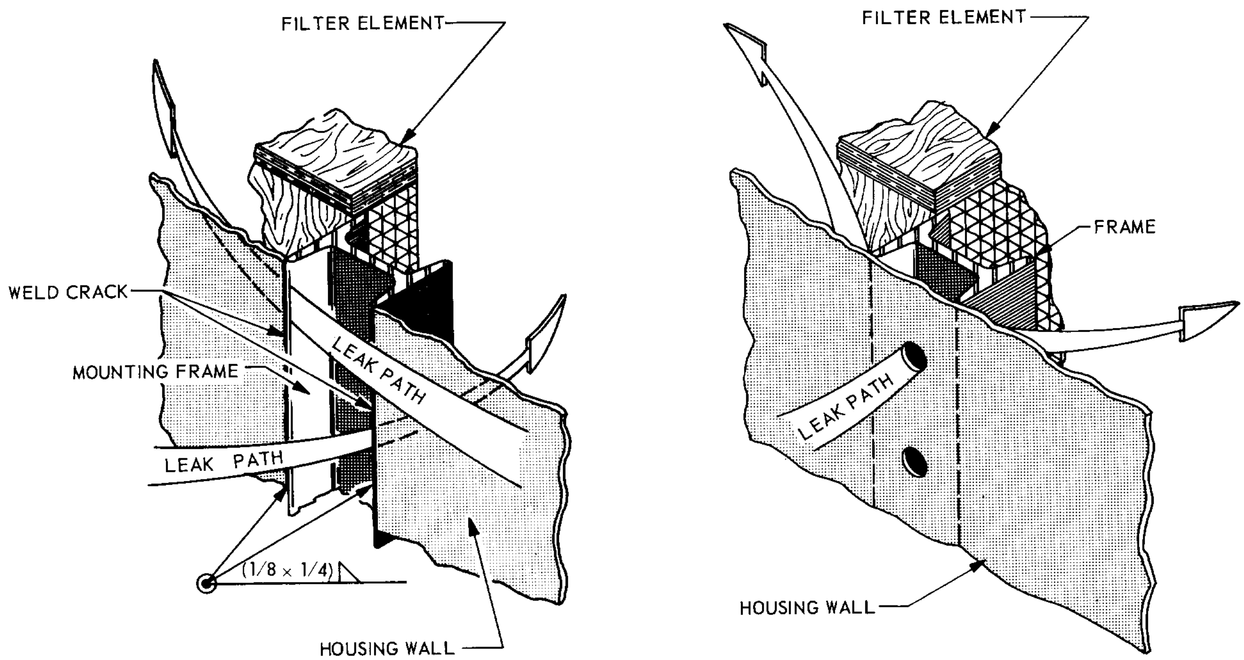

Fig. 4.24. Methods of welding frame to housing to ensure that weld cracks result in inleakage instead of outleakage. In both installation methods, both legs of the I beam are seal welded to the housing. Because pressure inside the housing, both upstream and downstream of the filters, is below atmospheric, a crack in either seal weld will result in inleakage to, rather than outleakage from, the housing.

ORNL DWG. 69-8732

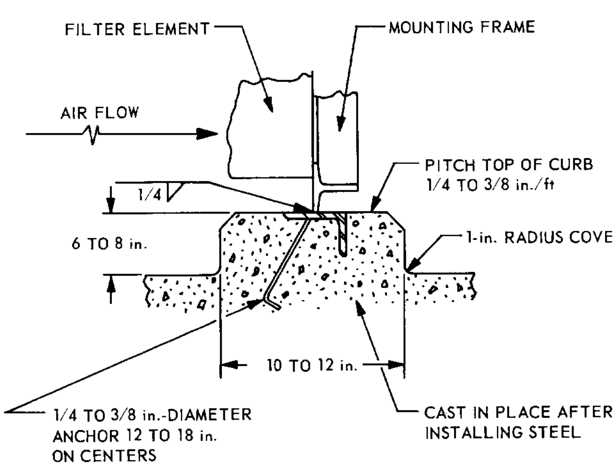

Fig. 4.25. Embedded structural member for seal-welding filter mounting frame to a concrete floor. Note anchor bolts, curbs, seal weld from air-entering side.

ORNL DWG. 69-8733

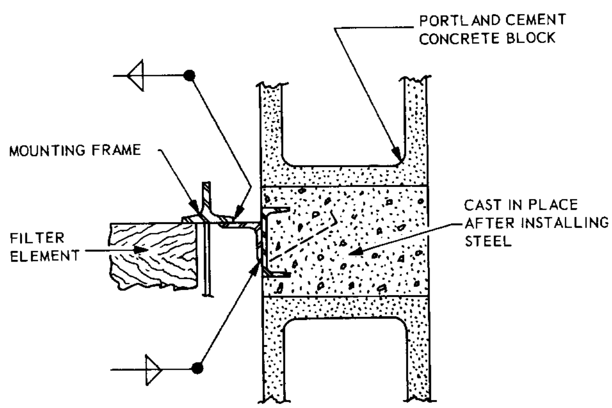

Fig. 4.26. Embedded structural member for walls and ceilings of masonry (shown) or concrete housing. Channel with flanges down, as shown, is not suitable for floors because trapped air would cause voids.

angle welded on the outside, with the leg pointing away from the housing and bolted to the concrete on 12-in. centers. "Butter" the underside of the angle with a silicone sealant before lowering the housing to the floor, and caulk the joint with silicone sealant on the inside after the housing is bolted down. The concrete surfaces must be etched with muriatic acid, and the steel surfaces must be rust free and cleaned with methyl ethyl ketone (MEK) or acetone before caulking, or the joint will fail in service.

Floors of filter housings should be pitched about $^1/_4$ to $^3/_8$ in./foot to a drain. The section of flooring between two banks of components must be considered as a separate floor and be sloped and drained independently. Tops of curbs must be pitched away from the steel to prevent corrosion from standing water. Concrete floors must be smooth and free of cracks and spalls, as discussed under masonry and concrete housings. Floors must be free of obstructions and raised items that would be hazardous to workmen.

4.5.6 Floor Drains

Floor drains are essential in contaminated-exhaust filter housings, particularly when sprinkler protection is provided. Even if moisture or condensation is not expected under normal conditions, occasional washdown may be required for decontamination, and water will be needed in the event of a fire. When the housing is above grade, provision for drainage need be no more than a half Chicago coupling, sealed with a bronze pipe plug, using TFE plastic "ribbon dope" so the plug can be easily removed when needed. When the filter is at or below grade, drains should be piped to an underground contaminated-waste system during initial construction, as later installation is likely to be very costly. In cold climates, water seals, traps, and drain lines must be protected against freezing if they are above the frost line. When fire sprinklers are installed in the filter house, the drains must be sized to carry away the maximum sprinkler flow without backup of water in the housing.

A separate drain is needed for each chamber of the filter house, and each drain must have its own water seal or trap. The spaces between two banks of components in series and between a bank and the housing are considered separate chambers. The water-sealed drain system for an underground filter pit is shown in Fig. 4.27. There are no float valves or traps that can malfunction and permit escape of air in this system, but integrity of the seal is dependent on careful maintenance of the water level in the sump. The lengths of the water legs and the elevation of the sump must be adequate to ensure a positive seal in each chamber and still prevent any possibility of backup or siphoning under any pressure condition from atmospheric to fan cutoff; the pressure characteristics of the system will determine the minimum height of each water leg. An automatic makeup system is used to maintain proper

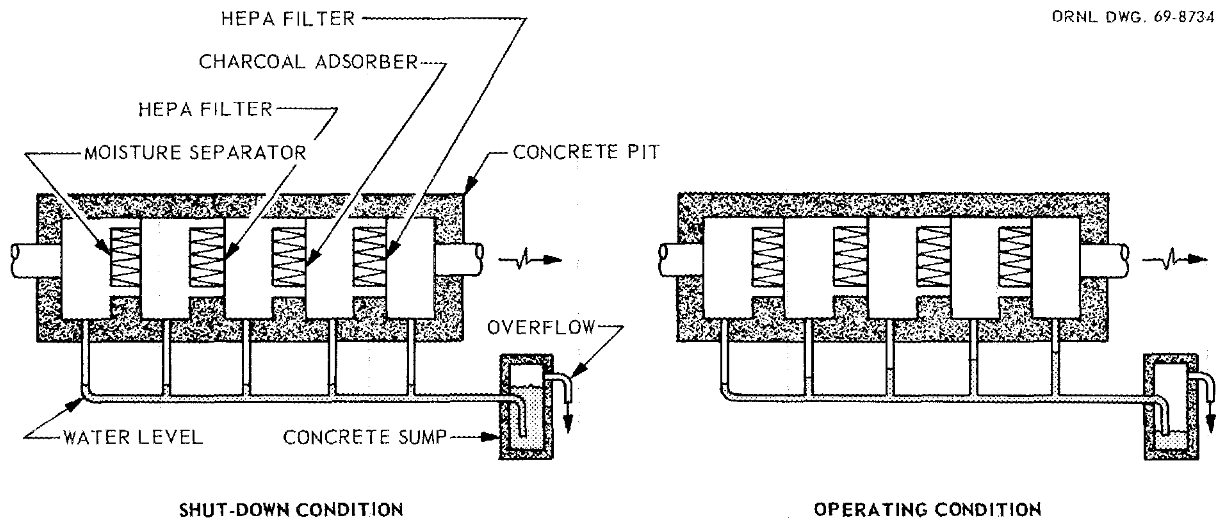

Fig. 4.27. Water-sealed drain system for a multichamber underground filter installation. Note water seal in sump. Automatic makeup keeps water in sump at proper level. However, if seal is broken, bypassing from one compartment to the next and to the atmosphere could take place. Water seals require regular maintenance and understanding of details of operation by operators.

water level in the sump, and regular inspections of the level in the sump are needed to ensure reliable operation.

4.5.7 Housing Doors

More than a single access door is desirable. A door should be provided to each compartment (space between banks) where maintenance or inspection may take place. To require a workman to gain access to the downstream side of a bank by crawling through a filter opening is poor economy at best and can result in cross contamination of the system, damage to installed filters, or personnel injury. The use of bolted-on removable panels for access to filter compartments should be avoided for even the smallest filter housings because of the time loss when necessary to get into the housing (the time loss could be disastrous in the event of a fire) and because nuts tend to rust or freeze after a few months of service. Sliding doors should never be used for filter housings because they cannot be sealed and because they could be jammed with any distortion of the housing.

Sturdy hinged doors with rigid, close-fitting casings and positive latches should be provided. Door gaskets must maintain a hermetic seal under positive and negative pressure equal to at least fan cutoff pressures. Doors must open outward, and, as they may have to be opened against suction, means for "breaking the vacuum" or for mechanically assisted opening is desirable. Doors should have heavy-duty hinges and positive latching devices operable from inside and outside. Means for locking, preferably a padlock, should be provided to prevent unauthorized entry. The stiffness of doors is important, as flexible doors can be sprung when opened against suction or allowed to slam shut under load. Provision of an air lock at the entry to the housing will eliminate problems of opening doors against suction and slamming and also, if large enough, provide an intermediate work area for personnel during filter change. Marine bulkhead doors of the type shown in Fig. 4.28 are recommended. The door should have a minimum of two dogs. Neoprene door gaskets, ASTM D1056 grade SCE-45 to 30/40 durometer, are recommended.

When sizing doors, keep in mind that personnel dressed in bulky protective clothing will have to enter and leave the housing while carrying cartons as large as 27 X 27 X 14 in., weighing up to 40 lb (160 lb or more for charcoal adsorbers). At the same time, doors must be kept as small as possible to preserve the structural strength of the casing and the housing when an air lock is not provided. An opening 76 in. high will permit the 95th percentile man to pass through erect; the maximum breadth of the 95th percentile man in street clothes is 23 in.[16] Recommended door and hatch dimensions, based on these characteristics, are given in Fig. 4.29. With bulkhead doors a maximum coaming height of 6 in. is recommended. The coaming should be high enough to prevent water from running out of the housing during fire-fighting operations; a minimum coaming height of 2 in. is recommended. The ladder and hatch dimensions shown are also suggested for access hatches in work galleries for high banks.

Fig. 4.28. Marine-bulkhead-type door for nuclear reactor exhaust filter house. Note dogs operable from outside and inside, heavy-duty hinges, heavy door-case rim. Internal housing reinforcement visible through door is not good practice. Courtesy American Air Filter Co.

4.5.8 Housing Leak Rate

Permissible housing leak rates are based on the criteria of Federal Regulations 10-CFR-20 and 10-CFR-100. Leak testing of filter housings is covered in Chap. 7.

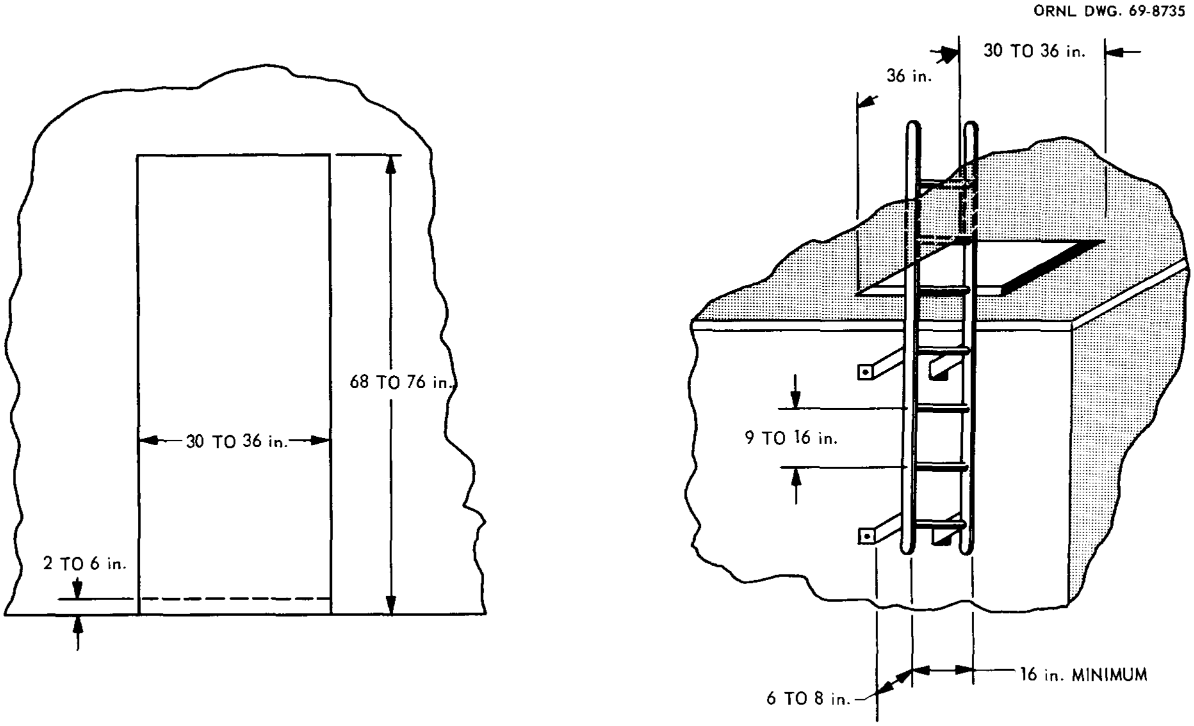

Fig. 4.29. Recommended filter house door and hatch dimensions.

Suggested maximum leak rates are as follows:

Hazard	Max Leak Rate
Zone III to zone IV[a]	5 to 6 ft^3/1000 ft^3 of housing volume/min
Zone I to zone II[a]	0.5 to 1 ft^3/1000 ft^3 of housing volume/min
Reactor postaccident cleanup[b]	
Vented containment	5 to 6 ft^3/1000 ft^3 of housing volume/min
Pressure containment	0.1% of housing volume/24 hr
Pressure containment with secondary containment	0.5% of housing volume/24 hr
Secondary containment	5 to 6 ft^3/1000 ft^3 of housing volume/min

[a]Table 2.4.
[b]Chap. 8.

4.5.9 Other Requirements

Figure 4.30 illustrates a number of features that are desirable in a contaminated-exhaust filter housing. The housing is all-welded construction with $\frac{1}{8}$-in. steel walls and ceiling, $\frac{1}{4}$-in. steel floor, and 3 X 3 X $\frac{1}{4}$ in. reinforcing angles on 24-in. centers. The housing is one of six which were shop fabricated for a series-parallel prefilter-HEPA filter installation for a high-hazard exhaust system for a research laboratory. Each housing contains either a bank of nine 1000-cfm prefilters or nine 1000-cfm HEPA filters. The housings are valved as shown in Fig. 4.30. Features of the housing include:

1. shop fabrication;
2. permanently installed DOP injection nozzles (inside housing) and probe and sample ports;
3. wired-glass view ports on each side of filter bank for visual inspection without entering housing;
4. permanently installed lights on each side of filter bank, two in parallel on each side, with switch at door and second switch under view port on back of housing; lights on independent switches;
5. lights installed in vapor-proof or explosion-proof globes, replaceable from outside of the housing;
6. wiring installed on outside of the housing (mounting frame penetrations for wiring are a common source of bypassing);

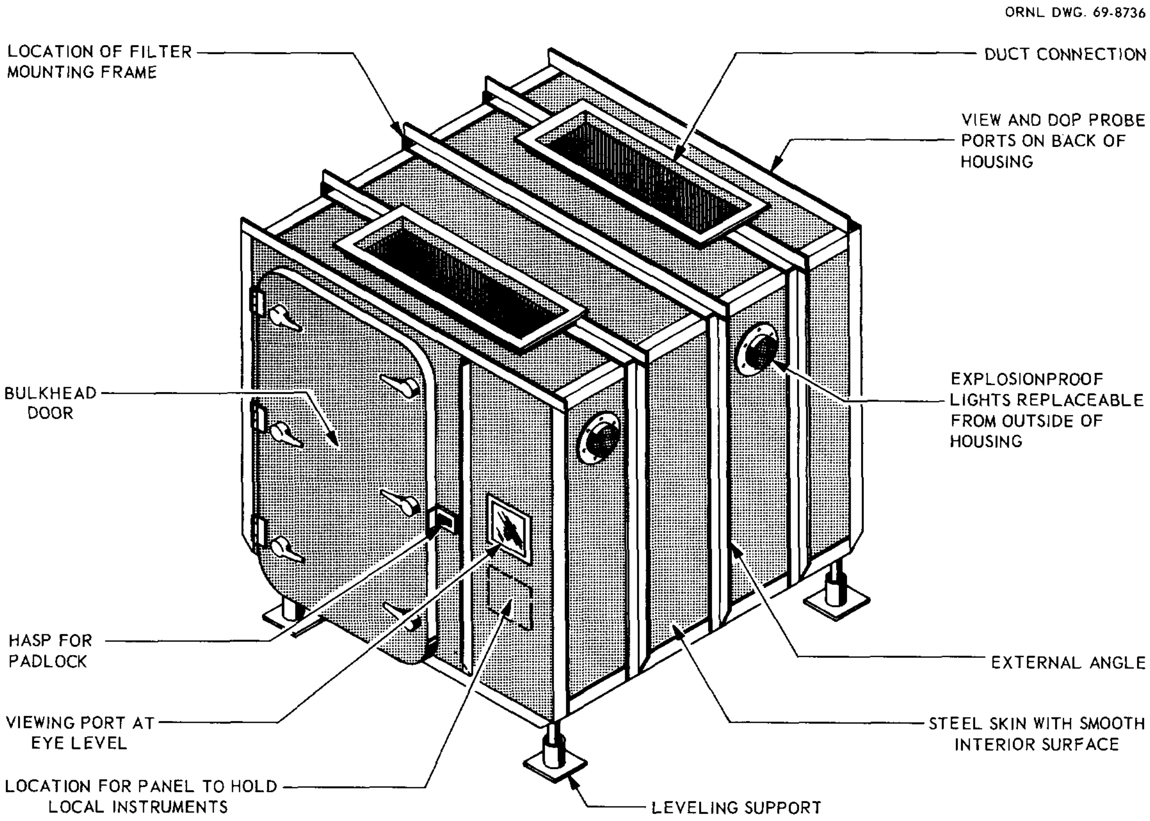

Fig. 4.30. Steel filter housing illustrating desirable features (see discussion in text).

7. shock-mounted instrument panel close to housing door, with pressure-drop manometer across each bank of filters;
8. large marine-bulkhead-type door with dogs operable from inside and outside of the housing;
9. ample space (approximately 4 X 7 ft) inside of housing for personnel to work during a filter change;
10. all reinforcements on outside of housing;
11. housing opens on aisle which can be controlled during filter change and which serves as work space during a filter change;
12. compartmented system – any housing of the six can be isolated for service or emergency without necessitating shutdown of system;
13. housing is isolated from the building; leveling feet for adjustment;
14. all-weld construction eliminates leaks to occupied areas.

4.5.10 Painting

The mounting frame and housing interior of carbon steel and masonry housings must be painted for corrosion protection and to facilitate cleaning and decontamination. Surfaces must be prepared properly, and both prime and top coats must be applied in strict accordance with the paint manufacturer's directions in order to obtain the necessary wet-film and dry-film thicknesses. Film thicknesses should be tested during and after application. Steel surfaces should be abrasive-blasted to white metal to a profile of 1 to 2 mils in accordance with Surface Preparation Specification No. 5 of the Steel Structures Painting Council.[26] The first prime coat must be applied within 2 to 3 hr at the most after blasting, and in no case should it be delayed to the next day. Hand or power-tool cleaning (Surface Preparation Specifications 2 and 3 of the Steel Structures

[26]SSPC Surface Preparation Specification No. 5, White Metal Blast Cleaning, *Steel Structures Painting Manual,* Steel Structures Painting Council, Pittsburgh, vol. 2, 1964.

Painting Council) is usually sufficient for exterior steel surfaces. Ambient temperature and metal temperature should be at least 10 to 20°F above the dew point before starting to paint, and there must be adequate drying time between coats. Thick runs and streaks must be avoided, particularly on gasket seating surfaces, where they may chip off and leave uneven surfaces that will interfere with proper sealing of the filter. After painting, gasket seating surfaces must be coated with a silicone oil or grease to prevent the filter gasket from adhering to the paint in service. Clamping bolts should not be painted, because the paint will scrape off and jam the nuts. Mask the threads during painting; then coat with a silicone grease.

High-build epoxy-polyamide or modified-phenolic coating systems are recommended for interior steel and masonry surfaces. Although inorganic zinc primers are often recommended for steel, their use is not recommended for housing interiors because the zinc particles are difficult to hold in suspension properly and tend to surface, causing blistering and peeling of top coats.[27] Airless spray is recommended for application of both prime and top coats.

Inorganic zinc primers are acceptable for exterior steel surfaces; however, complete curing may take from two days to six weeks, depending on temperature and humidity conditions. One or two coats of high-build epoxy, vinyl, acrylic, or silicone paint is recommended for exterior steel surfaces exposed to the weather. Epoxy-polyamide coatings are superior to epoxy amines for water and salt resistance and have better tolerance for moisture during application. Vinyls are excellent for general marine and chemical plant exposures and do not chalk as much as the epoxies when exposed to sunlight; on the other hand, they are inferior to the epoxies in abrasion resistance, solvent resistance, and resistance to severe water or brine splashing. Acrylic coatings give the best protection against chalking and discoloration due to sunlight and ultraviolet but are suitable only as top coats over an intermediate epoxy or vinyl coating. Silicone-base paints are useful for high-temperature applications, and aluminum-filled silicones give good protection up to 1000°F. For a housing or duct located indoors that is exposed only to normal building atmospheres, an acrylic paint is suitable and gives good protection against color fading.

Because of the difficulties in applying high-quality coatings and their often unsatisfactory performance in service, the designer should seriously consider stainless steel for mounting frames and housings in applications where corrosion or frequent decontamination will be encountered. Although quoted prices for high-quality coating systems generally run about 20 to 25% of stainless steel, experience shows that delays and difficulties of proper application often raise the finished cost of coated carbon steel to as much as or more than stainless steel.

[27] J. P. Jarvis, Oak Ridge National Laboratory, personal communication to C. A. Burchsted.

4.5.11 Commercially Available Housings

Figure 4.31 shows a type of housing that is commercially available in capacities from 1000 to several thousand cubic feet per minute. Because filters are removed and replaced in a manner that permits complete isolation of the housing interior and contaminated filter from the room, this type of housing is often acceptable in low- to moderate-hazard applications (see Table 2.2), and in higher-hazard applications where two sets of filters are installed in series, without installation in a Zone II area. Housings are available in coated carbon steel and stainless steel; stainless steel is recommended because of the poor experience with the commercially applied coatings. A description of the "bagging" technique for changing filters in this type of housing is given in Chap. 5.

Another type of commercially built housing is the side-loading type in which the filters (not bagged) are pushed onto rails, side by side, from the side of the housing, then clamped against a gasket seal by means of a screw-driven toggle or spring-loaded clamping device.

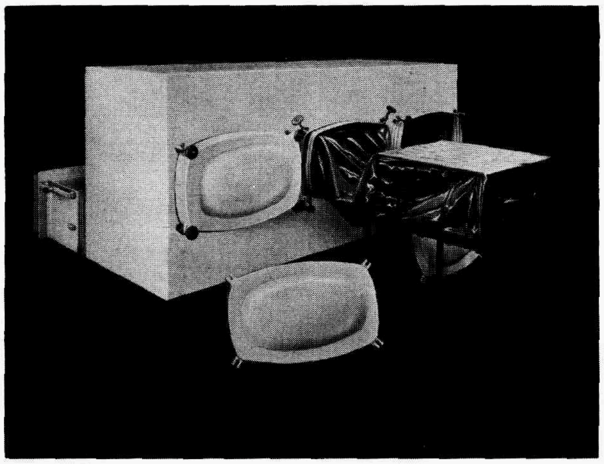

Fig. 4.31. 3000-cfm commercially built filter housing. Note contaminated filter being "bagged out," seal between interior of housing and room during filter change. Courtesy Nuclear Safety Systems, Inc. (S.G.N.).

These are suitable only for low- to moderate-hazard applications and then only when installed in a room that can be isolated from work or storage areas in the building and when thoroughly tested to prove that they can meet the recommended requirements for filter housings. Some side-loading housings have knife-edge seals that are not suitable for contaminated-exhaust service because they are so easily damaged and because filters cannot be repositioned after they have been installed for more than a few hours. Some also have spring-loaded clamping devices that do not generate enough pressure to properly seat the filter.

The capability of commercially built housings, particularly those of the side-loading type, should be proven by prototype tests before being specified on a job.

5. Single-Filter Systems

The information in this chapter is intended to serve as a guide for the design and installation of single-HEPA-filter systems that will provide economical operation and efficient performance. Single-filter systems are used when flow requirements are within the capability of one of the standard sizes of HEPA filter units. An individual HEPA filter may serve as a particle collector in a room, fume hood, or gloved box exhaust stream or in any other application where protective filtration is required. Many of the isotopes encountered in these installations and their relative levels of radiotoxicity are given in Table 2.3. Even though single-filter installations are relatively small and sometimes temporary, the designer of the system is required to apply principles that achieve an approved installation, that is, a maintainable system that gives reliable performance consistent with the HEPA filter unit used in it.

Economy of a system is dependent upon operating reliability and convenience for maintenance and testing. Through proper design and installation the performance efficiency for a single-HEPA-filter system can be maintained equal to the tested performance of the filter used. The conditions under which a system must operate, such as dust load, moisture, corrosive fumes, allowable pressure drop, etc., will be important factors in filter selection and system arrangement. Single HEPA filters may be open-faced rectangular units, enclosed rectangular units, or cylindrical units. When planning a single-filter installation, the most-used standard sizes and types of filters should be selected to guarantee continued availability of replacements. The sizes and types of HEPA filters that are most available were mentioned in Sect. 3.2, and this chapter's discussions will be confined to installations using these filters. Use of filters having special sizes and constructions to lessen cost and overcoming suspected operational problems should be considered only after a need has been validated by actual operating experience.

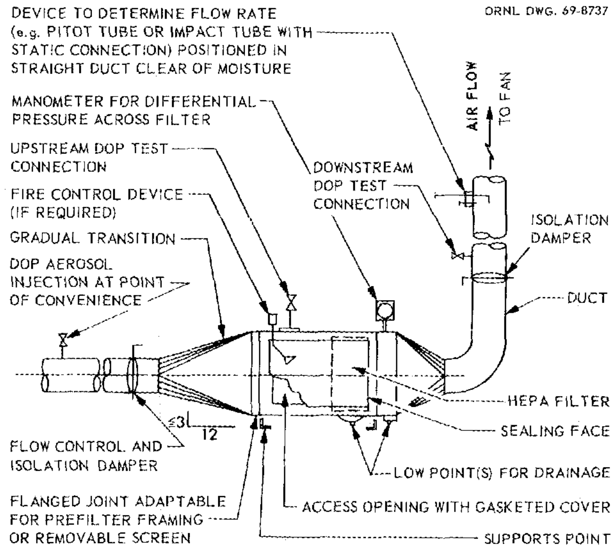

Fig. 5.1. Relationship between the HEPA filter and the supporting components of a single-filter installation.

The next step is to arrange the components in a manner that will provide the greatest functional efficiency, as illustrated in Fig. 5.1. Every system may not include all the items shown in Fig. 5.1, but relative positions should be maintained; for example, a manometer should always be connected to indicate air resistance (pressure drop) across the filter, and access doors, or panels, should always be sited to provide easy access to the filter. The downstream DOP test connection should be sited so that the sample withdrawn will be well mixed and representative. When a fan is situated a short distance downstream of the filter housing, a more representative sample will be obtained when the sampling point is located beyond the fan.

The main features to be considered for a single-filter installation are selection of a filter unit, housing, mounting frame, method of sealing (clamping) the filter to the mounting frame, fire protection, manometers, test connections, and provisions for maintenance. Special considerations are required for filter installations where moist and corrosive conditions are present;

these conditions are often a characteristic of fume hood exhaust gases and systems designed for emergency usage only.

5.1 OPEN-FACED HEPA FILTER INSTALLATION

The open-faced rectangular HEPA filter is most commonly used in single-filter systems. To assure that the performance of the system will equal the tested performance of the HEPA filter, just as desired for a multiple-filter system, careful consideration must be given to the filter housing, mounting frame, and clamping and sealing of the filter. Fire protection should be provided for the system when it is necessary to minimize the possibility of contamination spread. Review Sect. 2.4.2 and the discussion given in Chap. 4 concerning installation features.

5.1.1 Housings

Single-filter housings may be either shop fabricated or commercial prefabricated units. As discussed here, a commercial filter housing is a device which contains a filter and includes internal framing for mounting the filter. When the housing is shop fabricated to meet the requirements of a special application, carbon steel is the most common material of construction; however, stainless steel or carbon steel with a protective coating may be required when corrosion could be a problem. Recommended steel construction materials are the same as those specified in Sect. 4.5.2, and the welding methods and standards discussed in Sect. 4.3.3 are applicable for single-filter housings as well. The basic requirements for shop-fabricated and commercial single filter housings used in radioactive exhaust systems are as follows:

1. A single-filter housing must accommodate one of the standard sizes of open-faced HEPA filters, and its construction should make possible direct access to the filter for convenient replacement, inspection, and performance testing. When required, the compartments upstream and downstream of the filter should be adaptable to the installation of drainage connections.

2. A single-filter housing must have a rigid mounting frame and filter unit clamping devices able to compress the filter sealing gasket (¼-in.-thick sponge neoprene, ASTM Standard D1056,[1] grade SCE-43) to at least a 21-psi compression load.

3. A single-filter housing and mounting frame must be virtually leak-tight and strong enough to withstand repeated pressure surges ($\geqslant$10 in. H_2O) without damage. A maximum leakage rate for housing or mounting frame of 0.5 ft^3/hr per 1000 ft^3 of housing volume is recommended when tested at 3 in. H_2O differential pressure. This corresponds to the high-hazard system leakage rate recommended for multiple-filter housings (Sect. 4.5.8). Greater leakage rates are not recommended, and lesser rates may be required where housings are employed in critical systems, for example, postaccident cleanup systems (Sect. 4.5.8). A housing must operate with a differential pressure (positive or negative) of at least 10 in. H_2O in order to allow maximum filter life, as well as to contain mild pressure surges during operation.

4. A single-filter housing must be self-supporting and the duct connections must be airtight. Gasketed and bolted flanges are preferred for duct connections to housings.

5. A single-filter housing must be constructed of corrosion-resistant materials or be coated when corrosion resistance is required.

These features are necessary to make single-HEPA-filter housings perform satisfactorily and give long service life. However, there are additional requirements when a system is used to collect particles having high activity levels. The housing should have accessories that permit a contaminated filter to be "bagged out" and a replacement filter to be "bagged in," as illustrated by Fig. 5.2.

Housings should also have system cutoff dampers, upstream and downstream, that stop the air flow and isolate the filter chamber during filter removal and replacement operations. How completely air flow is cut off from the housing prior to removing the filter is dependent upon the tightness of the dampers upstream and downstream. After the isolating dampers have been closed, pressure within the housing is allowed to equilibrate to a level near atmospheric by opening a bleed-in (or breather) valve, step 2 in Fig. 5.2, and then adjusting this valve to compensate for any damper leakage.

Maintaining a small negative pressure ($\cong$0.5 in. H_2O) on the housing will help ensure inward leakage and still leave the plastic bag manageable for handling the filter. The bleed-in path may be equipped with a temporary filter, as illustrated in Fig. 5.2, to prevent the escape of material should the bleed-in flow be accidentally reversed by pulsing the bag. Steps 3, 4, and 5 (Fig. 5.2) show removal of the dirty filter into the plastic bag

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[1] ASTM Standard D1056, "Specification and Methods of Test for Sponge and Expanded Cellular Rubber Products," American Society for Testing and Materials, latest edition.

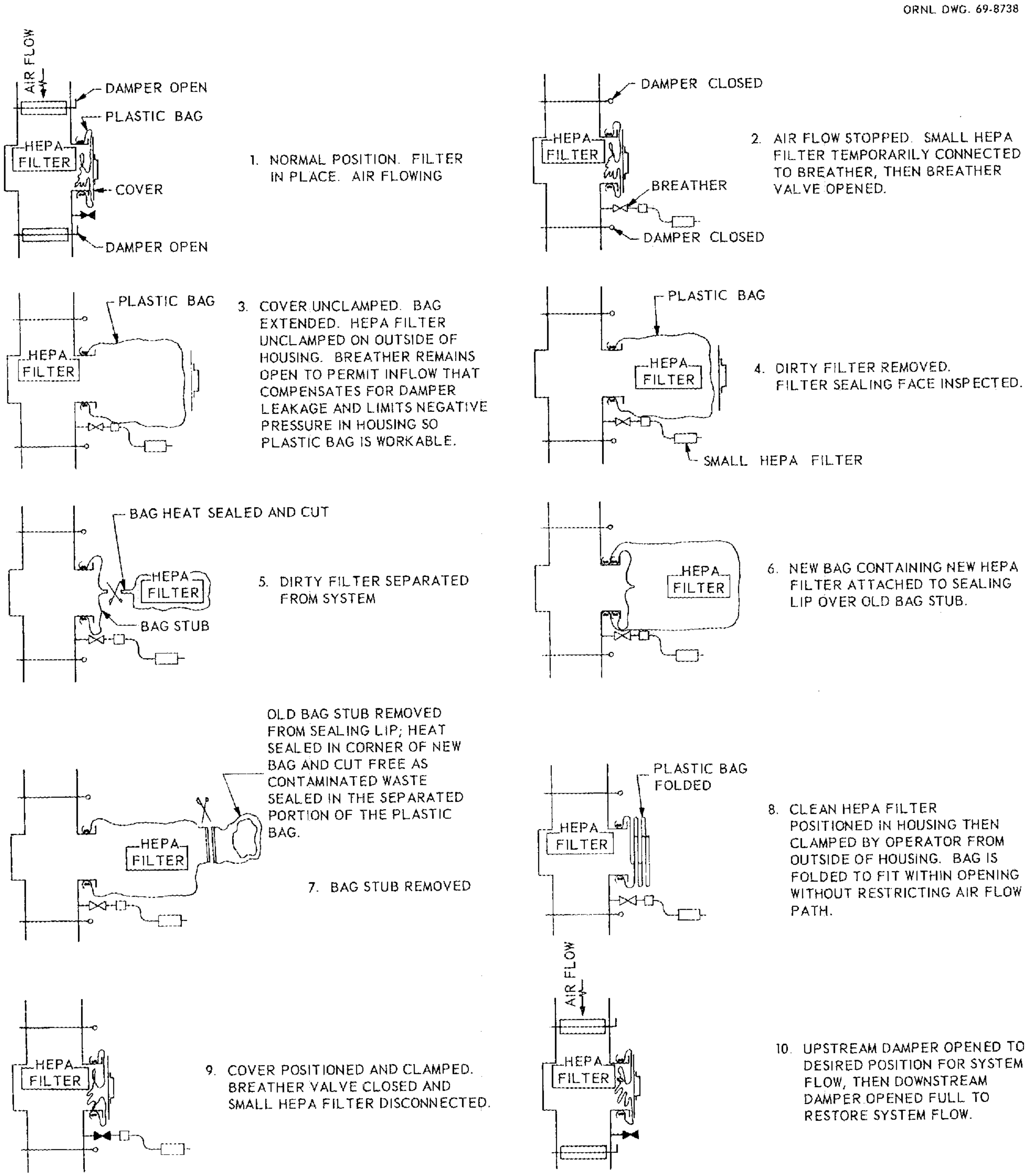


Fig. 5.2. Approved bagging procedures for changing filter in housing. This method allows filter change without exposing personnel to the contents of used filters and housing interior which may be contaminated.

attached to the housing, heat sealing the dirty filter in the rear portion of the bag, and then cutting it free, thus leaving the filter sealed in a portion of the bag and the housing sealed by the remaining stub of the bag. Steps 6 and 7 show the new (clean) filter being introduced into the closed system via a new full-size plastic bag, and removal of the bag stub that maintained the seal. Step 8 positions the clean filter in the housing; then the clamping force is applied by the mechanical levers on the housing exterior. Steps 9 and 10 secure the cover, close the breather-path valve, and remove the temporary filter. Air flow can then be restored through the housing by opening the valves to the settings necessary for system flow with a clean filter. Now the installed HEPA filter is ready for its initial in-place DOP test.

Plastic bagging materials commonly used are polyvinyl chloride and polyethylene, 6 and 8 mils (0.006 and 0.008 in.) thick. These materials deteriorate under continued exposure to ventilation streams and heat and should therefore be kept free of the ventilation stream. Enclosed bagging or bagging under continuous strain by fastenings or differential pressure can disrupt ventilation flow through critical areas or tear and rupture to permit leakage. Bagging should be exposed only to low pressure differentials, preferably less than 0.5 in. H_2O. The housing access opening must be kept closed when not in use to protect the bag or bag stub that is required to remain in place. Covers that are not airtight can cause a loosely folded bag to balloon and restrict air flow or rupture. Note in step 8 (Fig. 5.2) that the bag is evenly folded (or rolled) to fit within the opening to prevent "ballooning" or being pinched by the cover, probably causing a bag rupture or cover leakage. Filter housings for this type of service should have permanently installed test connections so that in-place DOP aerosol testing is convenient and less time consuming. Also, means should be provided for positioning the filters so that dust particles or scale will not be dislodged from the upstream (contaminated) ducting and fall into the clean side while the filter is being changed. Housings used in systems where microbiological contaminants are present should be sterilizable with heat or steam-formaldehyde sprays, usually requiring drainage connections.

Prefabricated housings for single HEPA filters have become available in recent years; these can be grouped in two general categories:

1. Housings suitable for systems subject to particles of low radiotoxicity (class 4, Table 2.3). This type is not purposely prepared for toxic materials and is characterized by light construction suitable to only 3 or 4 in. H_2O gage differential pressure and/or framing that is not sufficiently rigid to provide high gasket pressures (e.g., up to 21 psi). Side-loading frames (housings) are considered to be in this category.

2. Housings suitable for systems that will encounter particles having moderate radiotoxicity (class 3, Table 2.3). These housings are purposely made for collecting toxic materials and for higher differential pressure operation (primarily negative). The SGN Caisson and the HGS absolute filter enclosure are examples of this type.

No one type of commercial housing will meet the requirements of every user. Housings like the SGN Caisson and the HGS absolute filter enclosure are considered adequate for class 3 isotopes (Table 2.3), but *used singly* they are not recommended for systems subject to high radiotoxicity (classes 1 and 2, Table 2.3) that discharge to the atmosphere.

To provide for class 1 and 2 isotopes, a single housing (one stage of HEPA filters) is not sufficient; there must be at least two stages of testable HEPA filters used with series flow, that is, so that all effluents are HEPA filtered twice before release to an uncontrolled environment such as the atmosphere. Prefabricated housings like the SGN Caisson may be used for either or both stages of this filtration; however, other features, for example, accessories for bagging filters, cutting off air flow, and DOP testing, need to be included to lessen the risk to personnel and contamination of the environment. Greater costs are involved to double up on housings, both in space and equipment. The cost of other accessories – for example, dampers, duct transitions, instruments, etc. – represents a significant part of the cost of a total filter housing installation and must be examined in the light of function and reliability, as the cost of the housing itself must. An isolating damper of low-leakage quality is necessary on the upstream and the downstream side of the housing (Fig. 5.2), so that plastic bags used during filter changes will not be under excessive suction (>0.5 in. H_2O) and become unmanageable. Also, damper leakage must be minimized so that unfiltered blow-by during a filter change will not cause an intolerable release. Housings must have supports and duct adapters for their end connections.

Among commercial housings for open-faced filters are those previously mentioned: the HGS 1000-cfm absolute filter enclosure made by HGS Technical Associates, Inc., and the single-filter SGN Caisson made by Nuclear Safety Systems, Inc., both shown in Fig. 5.3. Filters can be transferred into and out of both these housings in impervious plastic bags.

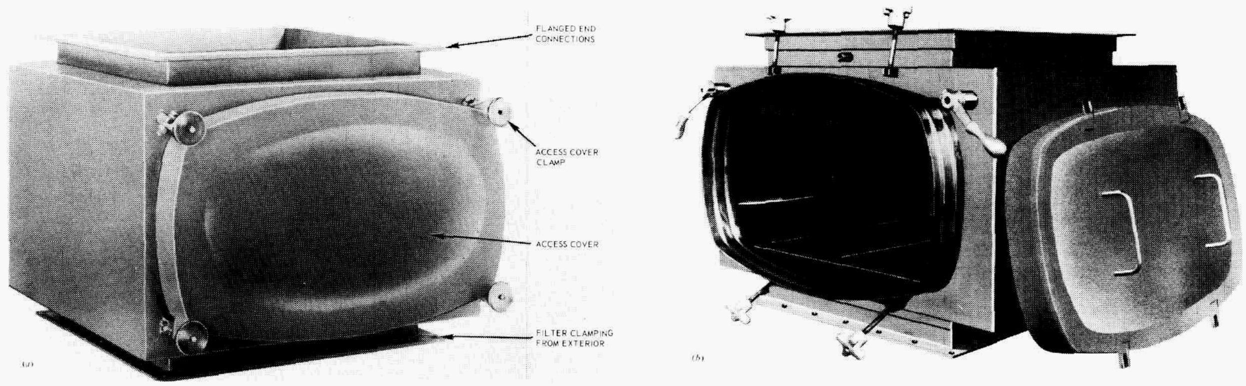


Fig. 5.3. Examples of commercial housings for single HEPA filter use. (*a*) SGN Caisson, manufactured by Barnebey-Cheney, Nuclear Safety Systems; (*b*) HGS filter enclosure, manufactured by HGS Technical Associates, Inc.

5.1.2 Mounting Frame

Recommended construction and installation of structural steel mounting frames for single-open-faced-filter systems are basically those for the bank systems discussed in Sects. 4.2 and 4.3. The sealing face must be flat and smooth for good gasket seating, the frame must be rigid, filter hold-down bolts must be arranged for easy access and uniform gasket compression, and the filter change procedure must be an approved method for the materials being collected.

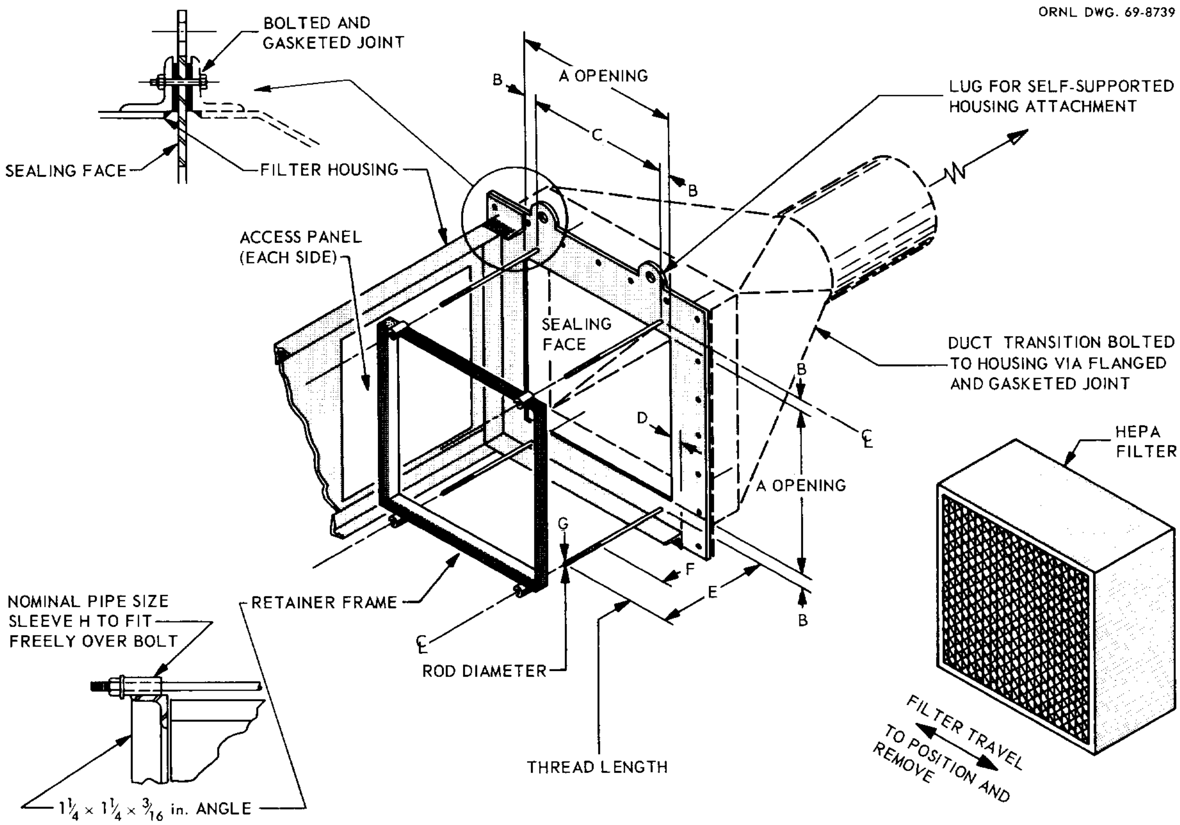
An example of a good frame arrangement for mounting a single HEPA open-faced filter is shown in Fig. 5.4. There is adequate room in this arrangement for proper sealing of the filter, and the bolting arrangement allows the filters to be inserted and withdrawn from the side. Minor modifications to this design will permit filter removal from the top if required by space restrictions. Filter removal from the bottom is the least desirable procedure because of condensation, spillage of particles from the housing or duct, and greater risk of dropping the filter because of overhead handling.

Careful alignment and good preparation of welds and sealing surfaces are important for quality framing. The dimensional tolerances for single-filter mounting frames are the same as those for frames in bank systems, as given in Table 4.2. The desired relationship of the filter gasket to the sealing face of the mounting frame is shown in Fig. 5.5.

Because the operator's sight and feel will be limited under almost any installation conditions, other aids can be included to reduce downtime and labor. To more easily align and position the filter a removable rest can be installed on the lower two clamping bolts, as shown in Fig. 5.6. This removable rest is 24 in. long to match the width of a 24-in.-wide filter casing. The sleeves are designed to slide over the lower clamping bolts on the frame in Fig. 5.4, thus centering the filter rest with the frame opening. When the filter is inserted from the side, it is slid across the filter rest until the edges of the filter casing and rest match. Then the filter is pushed forward to contact the sealing face with the retainer frame (see Fig. 5.4), and the gasket seating is inspected. The protruding pipe sleeves on the rest keep the edge back from the gasket sealing face to permit easier inspection of the gasket. By having a way to ensure proper alignment of the filter the first time, the chance of bypassing (leakage) is greatly reduced. Usually leakage can be discovered only by a DOP leak test after time has been spent in tightening the clamps and closing the housing in preparation for a test.

Full-height access doors or panels, that is, 25 in. or greater for a 24-in. HEPA filter, eliminate the need to tilt the filter to insert it into the housing. Access openings should be at least 24 in. wide by 25 in. high (for 24-in. HEPA filters) to enable an operator to reach all clamping bolts from one side, thereby using the panel on the far side only when necessary for inside cleaning or when the normal side is inaccessible.

Complete enclosure of the filter, as illustrated by Fig. 5.4, is considered more desirable by most users as it provides better protection against spillage of collected dust and moisture than methods which expose the gasketed joints and casing of the filter. *Fire-retardant* wood-cased filters employed with their casing exposed as part of the duct exterior do not comply with the general requirements of NFPA No. 91-1961. Paragraph 231 of this standard requires that ducts be constructed



Filter Size (in.)	Frame Dimensions in Inches							
	A	B	C	D[a]	E	F	G[b]	H
8 × 8 × 3 1/16	6 1/4	1 1/4	3 3/4	1 1/8	5 1/4	1 1/2	3/8	1/2
8 × 8 × 5 7/8	6 1/4	1 1/4	3 3/4	1 1/8	8 1/4	1 1/2	3/8	1/2
12 × 12 × 5 7/8	10 1/4	1 1/4	7 3/4	1 1/8	8 1/4	1 1/2	3/8	1/2
24 × 24 × 5 7/8	22	1 1/2	19	1 1/4	8 1/4	2	1/2	3/4
24 × 24 × 11 1/2	22	1 1/2	19	1 1/4	13 3/4	2	1/2	3/4

[a]D = width of prepared sealing face around A by A opening.
[b]Shouldered nuts not shown but one is required for each bolt.

Fig. 5.4. Design of mounting frame for single HEPA open-face filters.

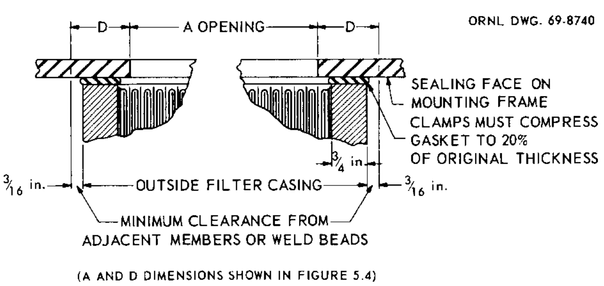


Fig. 5.5. Relationship of filter gasket to sealing face of mounting frame.

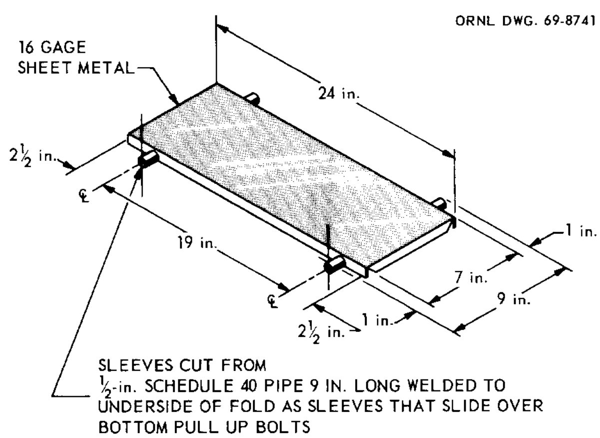
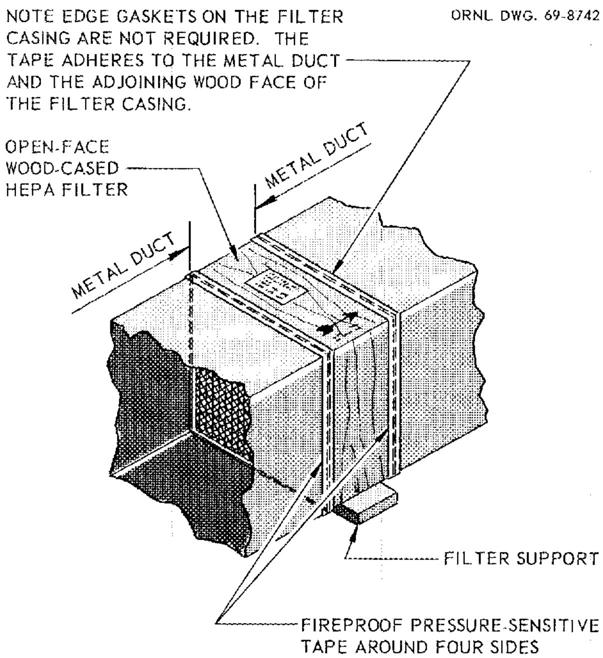
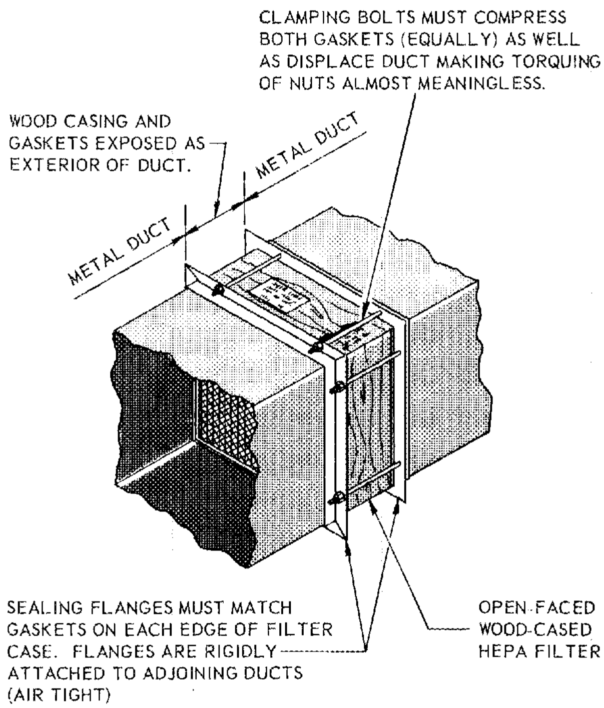


Fig. 5.6. Removable rest for support and alignment of a single 24 × 24 × 11½ in. HEPA filter.



(*a*) **FIREPROOF TAPE**



(*b*) **SANDWICHING FLANGES**

Fig. 5.7. Common methods for sealing single HEPA filters into ducts. These installations are not recommended for systems encountering materials having high radiotoxicity.

entirely of sheet metal or other noncombustible material. Several common practices have been follwed that compromise this requirement when designing systems intended to meet the NFPA codes. Two of these are shown in Fig. 5.7.

The method illustrated in Fig. 5.7*a* using "fireproof" tape has been widely used under moderate and light service conditions. Its use in systems designed to contain materials having high radiotoxicity or where moisture can be present is not recommended, because corrosive fumes, heat, moisture, sunlight, and vibration can have a deleterious effect on the tape. This is in addition to any system weakness that may be created by the exterior exposure of the wood casing on the HEPA filter. Metal-cased open-faced HEPA filters do not have enough flat surface on their folded edge frame to receive tape properly, so that their use in this type of installation is impractical.

The flanging method shown in Fig. 5.7*b* has been more widely practiced than using tape (Fig. 5.7*a*). Many faults can be cited when applying this flanged method, even though it appears very simple, economical, and easy to apply. One problem frequently encountered is the difficulty of installing and maintaining the flanges parallel to ensure uniform gasket compression and good sealing pressures. Although air leakage may be inward, as is the case when under suction, dusts and condensates can flow through a loose gasket area and contaminate surrounding surfaces. Pull-up bolts that clamp the filter must both compress the two gaskets and provide any needed elongation of the duct run to achieve a seal. This method of sealing HEPA filters into ducts is not recommended for service outdoors or for materials having high radiotoxicity or where moisture can be present either on the exterior or the interior surfaces (condensation).

In a corrosive atmosphere the carbon steel mounting frame, housing interior, and other interior components should be painted or coated for protection, as discussed in Sect. 4.5.10, or fabricated from stainless steel. Although resistant to many damaging fumes, nonmetallic framing members — for example, glass fiber reinforced polyester resin — lose strength at temperatures above 150°F and are neither rigid nor strong enough for this service. Therefore their use is not recommended for any part of the framing or intermediate housing even when corrosive conditions are present.

Painted and coated surfaces that are attached to or rub against another part will become damaged, and the value of the protective coating will be lost. Therefore, for corrosive environments, uncoated stainless steel bolts (e.g., type 304) and hardenable stainless steel nuts (to prevent galling) are recommended in painted and coated carbon steel housings. As an alternative, where corrosion is mild, brass nuts on stainless steel pull-up (clamping) bolts can provide good service life and easy handling without galling. Heavy protective coatings (>6 mils) should be avoided on filter sealing surfaces because gaskets may stick to coated surfaces, especially after heat and corrosion have deteriorated the coating. In addition, old gasket material can be cleaned from uncoated stainless steel sealing surfaces much more easily than from coated carbon steel ones. Surfaces and mating parts of uncoated stainless steel are preferred for housing internals used in moist or corrosive conditions.

5.1.3 Filter Clamping and Sealing

The method selected to clamp and seal a filter against the mounting frame is one of the most important factors in obtaining a serviceable filter installation. Good sealing is dependent primarily upon clamping methods and the provision of a smooth and rigid sealing face on the mounting frame. The preferred method of sealing open-faced HEPA filters is to clamp the gasketed filter against a prepared sealing face by using threaded pull-up rods, as shown in Fig. 5.4. When a filter retaining frame is used in the single-filter installation, four rods are sufficient for uniform gasket compression. The rods and frame must be strong and rigid enough to permit compression of a ¾-in.-wide by ¼-in.-thick sponge gasket (grade SCE-43) to a pressure of 21 psi, meaning a net load of 367 lb for each of the four pull-up rods when a 24 × 24 in. filter is used. The rods should be welded to the mounting frame, using the same methods of attachment discussed in Sect. 4.3.4. The rod diameters tabulated in Fig. 5.4 were selected to provide adequate strength and continued rigidity after welding, and the use of smaller sizes is not recommended.

Table 5.1 lists approximate values of torque required to load various sizes of bolts common in filter mountings. Table 5.2 gives the areas for standard-size HEPA filter edge gaskets.

By selecting the initial gasket pressure desired for the type of material being used (see Sect. 4.3.4) and multiplying this pressure value by the area of the gasket from Table 5.2, the total clamping load can be determined. After deciding the number of bolts to be used to clamp a single filter, the individual bolt loading can be determined and Table 5.1 used to establish the approximate torque needed for the initial filter installation.

Table 5.2. Areas of Edge Gaskets for Standard Open-Faced HEPA Filters

Filter Face Dimensions (in.)	Gasket Area[a] (in.^{2})
8 × 8	21.8
12 × 12	33.8
24 × 24	69.8

[a]Based on ¾-in. width of standard casing.

Table 5.1. Approximate Torque Values to Load Threaded Bolts[a]

Bolt Size	Joint Condition[b]	K	Torque T (lb-in.) for Bolt Load P of –				
			80 lb	100 lb	120 lb	140 lb	160 lb
⅜-UNC 16	Dry	0.20	6	7.5	9	10.5	12
	Lubricated	0.15	4.5	5.6	6.8	7.9	9
7/16-UNC 14	Dry	0.20	7	8.7	10.4	12.1	14
	Lubricated	0.15	5.3	6.6	7.9	9.2	10.5
			Torque T (lb-in.) for Bolt Load P of –				
			250 lb	280 lb	310 lb	340 lb	370 lb	400 lb
½-UNC 13	Dry	0.20	25	28	31	34	37	40
	Lubricated	0.15	19	21	23	26	28	30
⅝-UNC 11	Dry	0.20	31	35	39	42	46	50
	Lubricated	0.15	23	26	29	32	35	38

[a]Based on the relation $T = KDP$, where T = torque, lb-in.; K = average torque coefficient; D = nominal diameter of bolt, in.; P = bolt load, lb.

[b]Nut bearing on flat steel washer.

Once a filter is properly sealed against the frame it should not be disturbed during its operating life. However, as discussed in Sect. 4.3.4, gasket deterioration, fatigue of framing members, and the relief of strains in the filter casing may result in leakage at a later time even though the installation passed the initial in-place DOP penetration test. Experience has shown that it is necessary to tighten clamping nuts to compensate for gasket set and relaxation of the filter case after two or three weeks of system operation.[2] Although reasonable loading tolerances (±20%) can be achieved by torquing clamping nuts on pull-up rods when surfaces and threads are clean, this ability is lost after the clamps become dirty or corroded. It is safer, faster, and more effective to advance each nut an equal amount rather than retorque with a tool. For ⅜-UNC 16 and ½-UNC 13 threaded rods the suggested advance is ¼ to ½ turn of nut after two to three weeks of system operation. Continued advance of the nut beyond this amount must be avoided to prevent damage to the filter casing, even though the nut is easily turned using a 10- or 12-in. wrench. Should overclamping be discovered, it is essential that the filter casing be thoroughly inspected and, if damaged, the filter replaced before the system is returned to service.

For small single-filter installations where operation must be continuous and stoppage to tighten filter clamping nuts is impractical, the user's only alternative is to apply greater initial gasket compression when the filters are first installed. The practical limit is 120% of normal loading for the same gasket material. Higher initial gasket compression can shorten gasket life as well as cause greater strain on the casing. Where above-ambient temperatures or high humidity (90% relative humidity) will occur, expansion or wood swelling can cause gasket loading problems to be even more acute. Providing greater flatness and smoothness of the gasket sealing surface is the greatest single improvement that will reduce the need for greater gasket pressures. Spring-loaded clamping devices and adjustable toggle clamps that may be selected to compensate for gasket fatigue or casing expansion have generally been unsatisfactory because the maintenance required to keep them serviceable has offset any clamping improvements.

5.1.4 Filter Face Guards

Wire mesh face guards, sometimes provided on HEPA filters, protect the faces of the filter against damage during handling, storage, and installation, but they do not offer satisfactory protection when one face is exposed, as will be the case for a room wall installation or at an exhaust point leaving a decontamination enclosure. The 4 X 4 galvanized wire mesh supplied on open-faced HEPA filters is too light to repel thrown objects, compressed-air jets, and water or steam sprays. Protective face guards are simple to fashion and require very little space. Two types, constructed by modifying the filter retaining frame, are shown in Fig. 5.8. Both guards can be removed with the filter retainer frame, so they do not interfere with filter replacement or inspection procedures. The sheet metal face shield

[2]F. E. Adley, "Progress Report, Factors Influencing High Efficiency Gasket Leakage," *Proceedings of the Ninth AEC Air Cleaning Conference,* USAEC Report CONF-660904, 1966.

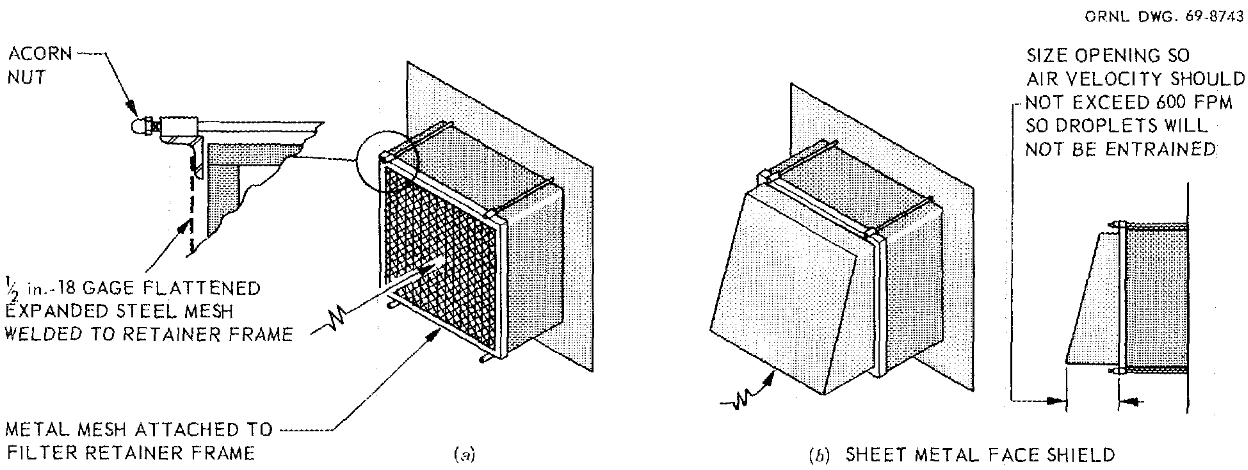


Fig. 5.8. Filter face guards attached to filter retainer frame.

shown as Fig. 5.8*b* is recommended where water or air jets are to be used in the vicinity of the filter installation. The air opening must be oriented so that a water or steam spray is deflected away from, and not into, the filter medium. Drainage must be conveyed away, and filters must be situated high enough off the floor (or wall) so that hose splash will not be deflected into the air opening.

5.1.5 Fire Protection

Section 2.4.2 discusses fire protection and control. It can be concluded that single-filter installations are provided protection from fire much like a larger system. The filters collect combustible fuel as dust, lint, chemicals, etc., and the probable source of ignition is from outside the system housing. Protection for the single-HEPA-filter installation starts by using a fire-resistant HEPA filter unit (Sect. 3.2.5), followed by physically separating the HEPA filter from the nearest source of combustible material. This takes the form of arranging a 40-square-mesh (0.010-in. wire) metal cloth at least 4 ft upstream of the HEPA filter face in an accessible location for inspection and easy cleaning. Figure 5.9 shows how the prefilter and HEPA filter may be separated using a metal cloth to arrest sparks that might be released should the prefilter be afire. Such a cloth affords good protection for the HEPA filter from heavy sparks and burning materials.[3] It is essential this metal cloth be kept clean. Preferably it should be installed downstream from a prefilter made of UL Class I materials.[4] Without a good prefilter (Group II, Sect. 3.3) a 40-square-mesh metal cloth will clog, requiring frequent (weekly) cleaning where average dust loads occur.

Fire detection and extinguishing systems should be incorporated into all systems where there is a fire risk caused by the materials handled and where continuous air flow during fire conditions is essential to the operation. When continuous air flow is required, the installation of an alternate parallel filtered air flow path with automatic or manual actuation should be considered. It is recommended that the air flow diversion or reduction be made by manual actuation when attendants are on duty full-time because manual or delayed changeover allows judgments to be made regarding preplanned actions for emergency situations and regard for system balance when air flow is diverted from a used filter (high pressure drop) to a clean filter (low pressure drop). A system whose function is essential enough to require continuous air flow during a fire condition requires a fire protection system having equipment for continuous surveillance.

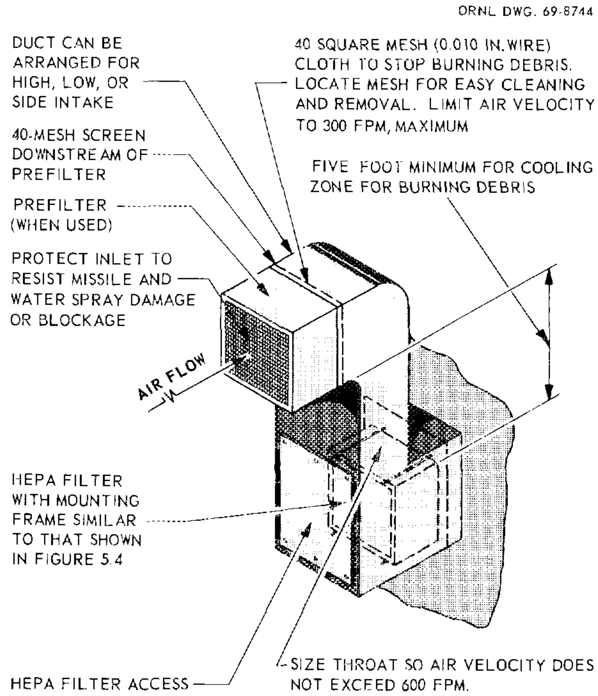


Fig. 5.9. Separation of prefilter and HEPA filter aiding fire protection in a single filter installation.

Rapid detection of and response to a fire are imperative for effective fire control. Therefore detectors with a remote alarm that automatically actuate fire control devices are recommended. The most sensitive detection is achieved through the use of smoke detectors of the ionization type, because a smoke detector can sense combustion deep within the pleats of an HEPA filter that might not progress to the surface, where it would affect an infrared light-sensing device, until later. Infrared fire detecting devices are second choice for rapid detection. Other devices, such as eutectic-salt, continuous-cable fire detectors, are less attractive for use in single-filter installations because of their high cost.

When water is compatible with the materials being conveyed in the exhaust system, an automatically actuated sprinkler system with fog nozzles is the

[3] S. E. Smith *et al.*, "Protection Against Fire Hazards in the Design of Filtered Ventilated Systems of Radioactive and Toxic Process Buildings," AWRE 0-24/65, Atomic Weapons Research Establishment, H.M. Stationery Office, July 1965.

[4] "Building Materials List," Underwriters' Laboratories, Chicago, Ill., latest edition.

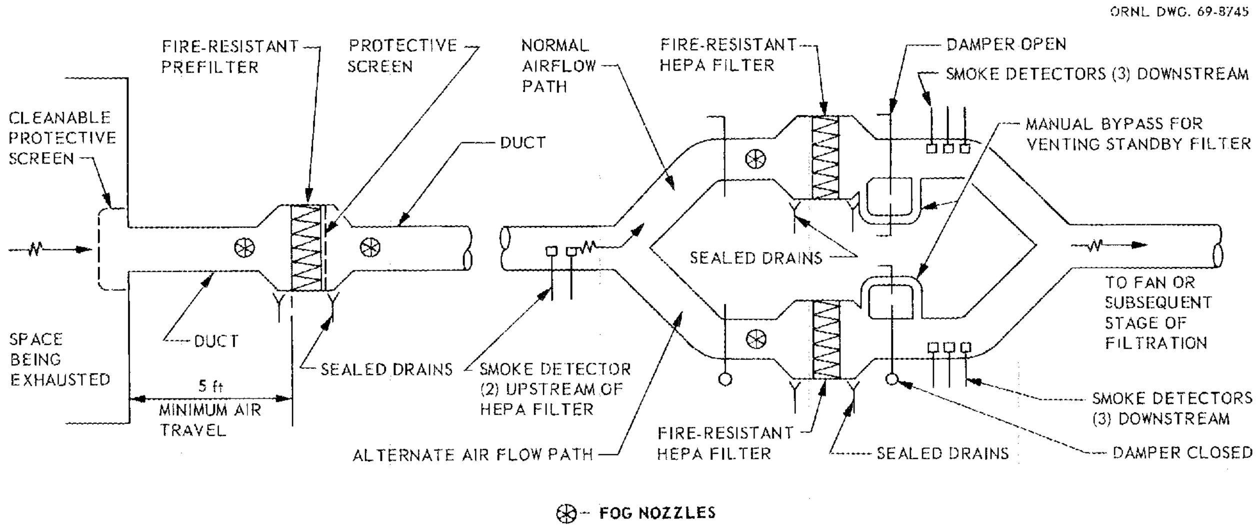


Fig. 5.10. Arrangement of fire detection and control devices in a single-filter system.

recommended method of fire control. Drains should be provided in the filter housing to carry away the excess water. Fog nozzles with water droplet sizes of 5 to 10 μ and water rates of 0.6 gpm per square foot of filter frontal area can be operated for several minutes before the HEPA filter is likely to become clogged with water. Continuous air flow is needed to draw the water droplets into the filter pleats, but only 20% of the normal air flow rate is needed to draw water into the filter medium and purge the housing of explosive fumes that might be generated by heat from a local fire. Complete closing off of a housing containing a burning filter can create sufficient internal positive pressure to cause massive leakage or rupture of the housing and the spread of contamination. Some metal particles, such as plutonium, burn violently at high temperature (500°C) even when very little oxygen is present and produce enough heat to destroy the filter and, perhaps, distort the mounting frame and housing beyond salvage.

An arrangement of fire detection and control devices for a small single-filter system with an alternate, parallel filtered air flow path is illustrated in Fig. 5.10. One group of two smoke detectors is located upstream of the HEPA filters to detect smoke from an upstream source and signal its presence as a warning to operating personnel. A coincident group of smoke detectors is located downstream of each HEPA filter, and the sensing of smoke emanating from one HEPA filter by two of the three detectors would initiate an alarm and automatically actuate the fog nozzles upstream of the affected filter. The use of a coincident group of smoke or fire detectors where two of the three sensors must detect combustion products to actuate the alarm and fire control devices permits inspection and maintenance of the system without disarming the detection circuitry.

5.2 ENCLOSED HEPA FILTER INSTALLATIONS

When containment during filter change operations is required, an enclosed HEPA filter is often better than an open-faced filter. The end connections are smaller than the faces of an open-faced filter and less exposed to physical contact or air currents that may release and spread contamination.

5.2.1 Framing and Sealing

Supports for the enclosed HEPA filter must carry the weight of the unit and maintain its alignment so that end connections are not crimped or strained. The enclosed filter may be clamped or strapped in position, but it should never be held by screws or bolts fastened directly to the casing or clamped so tightly that the filter casing is distorted. The small weight of a single enclosed filter unit does not require elaborate supports. An example of an acceptable but simple mounting structure is shown in Fig. 5.11. Airtight end connections are made with flexible ducts, or hoses, with cuffed ends and hose clamps. Flexible connections permit easy positioning and replacement of the filter. The filter casing should not bear the weight of the connecting hoses or ducts because it is not capable of supporting

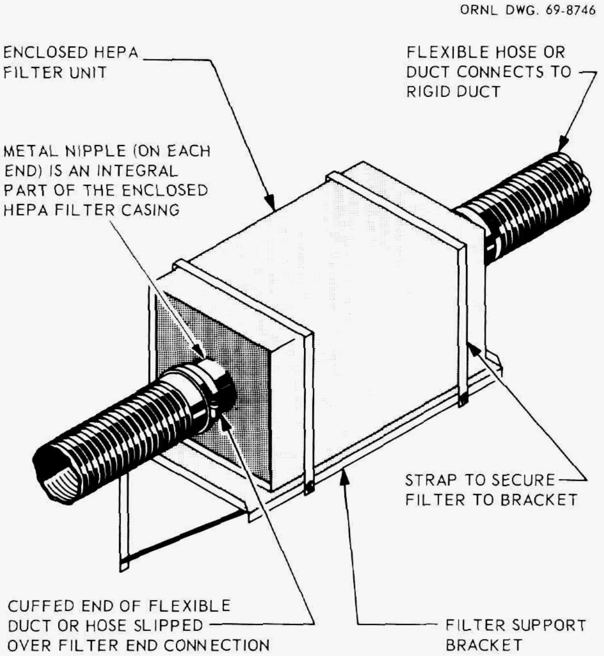


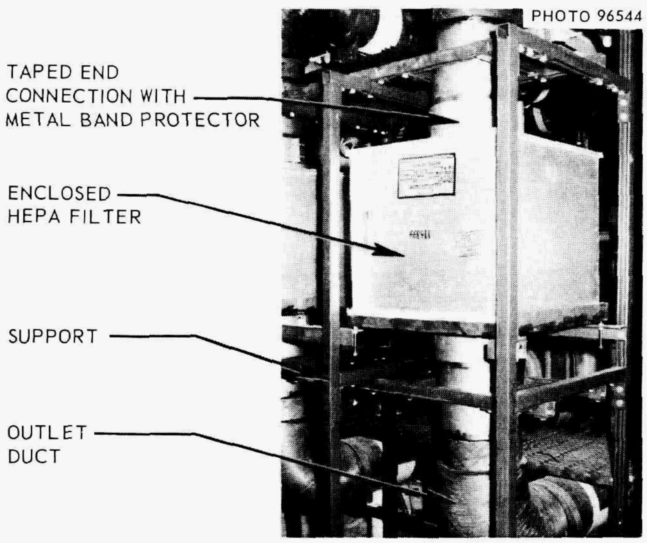
Fig. 5.11. A recommended method of installing an enclosed HEPA filter with clamped end connections and simple support.

external forces, and leakage at the junction of filter frame and nipple may result. Enclosed filters can be coupled leak-tight to a system with resilient glands, with gasketed and bolted flanged joints, or with taped joints. A metal-cased HEPA filter positioned for downward air flow is shown in Fig. 5.12. This filter is sealed into the system by taped end connections protected by metal bands. This method of sealing requires good alignment of the ends of the joining ducts, which must be held in position rigidly to keep them from straining the taped ends and causing leakage.

5.2.2 Fire Protection

The fire detection and control devices that can be used to protect enclosed HEPA filters in single-filter systems are the same as those described for open-face HEPA filters in Sect. 5.1.5. Although enclosed HEPA filters do not carry the Underwriters' Laboratories approved label because their Standard UL-586[5] is limited to open-face filters of five specific sizes and specific construction materials, enclosed filters are available with identical materials and construction features.

[5]Standard UL-586, "High Efficiency Air Filter Units," Underwriters' Laboratories, Inc., 2d ed., June 1964.



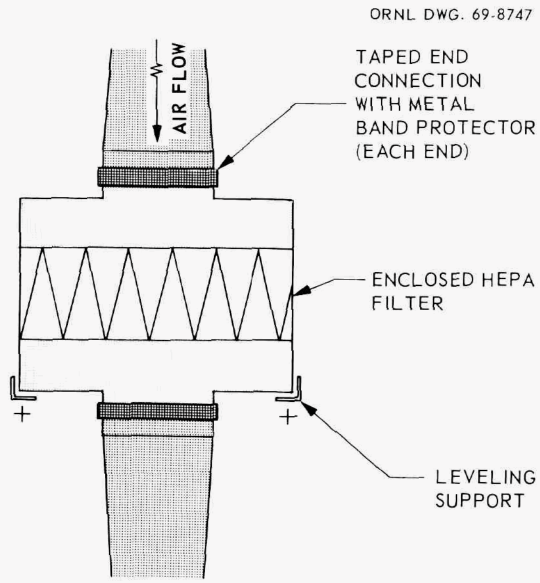


Fig. 5.12. A recommended method of installing an enclosed HEPA filter with taped and clamped end connections. Courtesy Oak Ridge National Laboratory.

5.3 CYLINDRICAL HEPA FILTER INSTALLATIONS

Cylindrical HEPA filters are available in many configurations, including flanges on one or both ends. Units are available with end gasket faces and without gasket flanges extending from the cylinder. A girth gasket must be applied to seal the latter type in its operating position. Past experience indicates that manufacturers do not stock large numbers of the cylindrical HEPA filters they catalog, but fabricate to suit specific orders. Metal casings are the most common style; however, fiberboard casings have been used in smaller sizes. None of the cylindrical HEPA filters are rated by Underwriters' Laboratories,[5] even though materials of construction can be identical with those of acceptable units (Sect. 3.2.2). They cost considerably more than standard open-faced HEPA filters of equal flow capacity. This fact plus some experiences of poor adhesion between medium and cylindrical metal casing and other problem areas has discouraged their general use.

An advantage of cylindrical HEPA filters is close conformance to the shape of round ducts, which can result in smaller and cheaper duct transitions and less space requirement. However, when adequate space is provided for replacing a single cylindrical filter flanged into a duct, the space advantage over rectangular filters is slight. As there are no commercially available housings to accommodate cylindrical HEPA filters, their use requires a custom-built mounting frame and sealing arrangement. Other obvious disadvantages in using cylindrical filters must include the difficulty in handling them (they roll easily when laid down on their side to protect the medium faces); casing and flanges are normally made of light sheet metal and therefore bend easily when strained.

An approved method of mounting a single cylindrical HEPA filter with a single end flange, when the direct method of filter change is permissible and when adequate space is available, is shown in Fig. 5.13. The inside diameter of the duct in which the filter is mounted should be at least ¼ in. larger than the outside diameter of the filter casing (having a tolerance of +0 −1/16 in.). By welding two ⅛-in.-diam wires to the inside of the duct (30° each side of the bottom center line) the filter can be centered in the duct opening. When needed, the bearing ring can be replaced by a filter face guard or shield, as described in Sect. 5.1.4. A prefilter should not be sandwiched against the front face of a round HEPA filter unit with the one clamping arrangement for both. Instead, a prefilter should be placed upstream of the HEPA filter so that the seal on

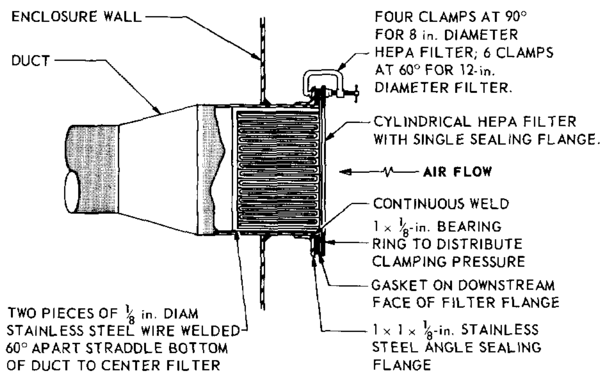


Fig. 5.13. An approved mounting method for a single-flanged cylindrical HEPA filter when direct maintenance is permissible.

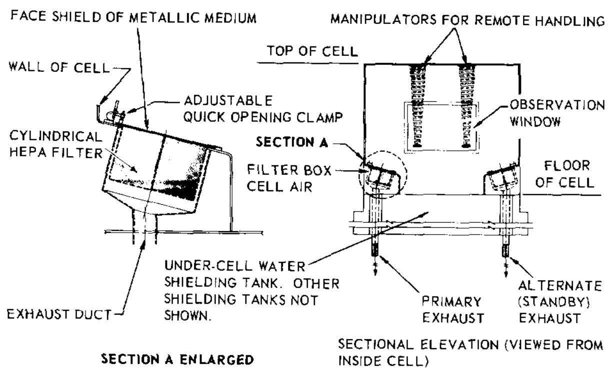


Fig. 5.14. A recommended installation of cylindrical HEPA filters in a shielded cell where maintenance is performed remotely with manipulators.

the HEPA filter will not be disturbed when the prefilter is changed and to lessen the chances of fire reaching the HEPA filter.

Another type of mounting arrangement for cylindrical HEPA filters is shown in Fig. 5.14. This shows an 8-in.-diam HEPA filter installed in a small shielded work cell where all filter handling must be done remotely with master-slave mechanical manipulators. The filter mounting in this application is sloped to permit easier remote handling and more complete runoff of any liquid accidentally spilled on the inlet area of the installed cylindrical HEPA filter. The entire face area of the bearing ring is covered with a metallic-medium (Neva-Clog[6]) face shield. Although the filters are not in

[6]Trade name of Multi-Metal Wire Cloth, Inc., 501 Route 303, Tappan, N.Y. 10983.

the best locations, space requirements within the cell for manipulator reach and gravity positioning relegated the cell exhaust filters to the positions shown. One principal reason for choosing a cylindrical filter rather than a rectangular unit for this application originated from the need for smooth edges having less chance to puncture plastic bagging when the filter was remotely handled as waste.

Whether the cylindrical HEPA filter is mounted for direct or remote maintenance, care must be exercised in aligning the filter to achieve satisfactory sealing. The sealing face should be flat over its entire surface to within $^1/_{32}$ in. total allowance, when $^1/_4$-in.-thick gaskets are used. The cavity holding the cylindrical body of the filter should have a generous tolerance of $+^1/_4$ in. and -0 in. to prevent direct contact with the filter casing. As for open-face filters, the clamping pressure applied to the gasket should be capable of being as much as 21 psi, and the gaskets must be one-piece cutouts from flat sheet neoprene sponge, grade SCE-43;[1] gaskets must not have spliced ends.

Cylindrical HEPA filters are used frequently for vacuum cleaner filters as final cleaning devices where radioactive and toxic dusts are being collected. Another example of the use of cylindrical filters is in the circular air purifier shown in Fig. 5.15. This air purifier is a single-use device that is discarded when the overall collection efficiency is reduced below a predetermined level. The unit shown in Fig. 5.15 was designed and constructed to clean a low-volume flow of off-gas evolved during processing of high-level transcurium elements.[7] However, an open-face HEPA filter could have been used in a somewhat different arrangement, meaning that use of a cylindrical filter was the designer's choice and not mandatory.

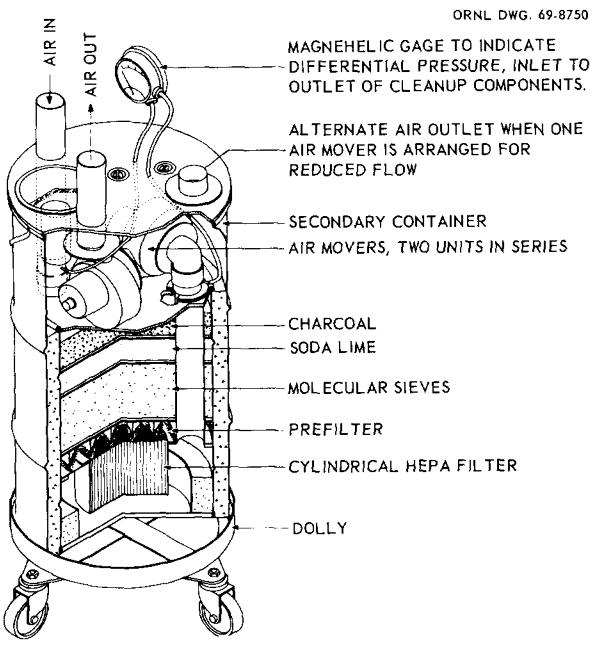


Fig. 5.15. Dry air purifier with a cylindrical HEPA filter (from ref. 7).

5.4 MANOMETER INSTALLATIONS

It is recommended that every single-HEPA-filter system have a permanently installed manometer to indicate the differential pressure across the filter when air is flowing through the system. When correlated with the flow through the filter (usually measured periodically by instrument traverse, for example, 20-point Pitot tube traverse), the manometer reading will permit surveillance of the filter resistance with respect to particle storage and indicate when a filter change or flow adjustment is required. The operating range of the manometer should be selected by noting the initial resistance of the filter and making an appropriate allowance for the resistance increase caused by particle buildup in the filter. The maximum clean-filter resistance of open-faced HEPA filters at rated flow is 1 in. H_2O, and a manometer range of 0 to 4 in. H_2O is the minimum recommended. The HEPA filter is capable of withstanding differential pressures of more than 4 in. H_2O, as discussed in Sect. 3.2.4; therefore manometer range selection must suit the particular application in a system. Manometer divisions should indicate resistance changes as small as 0.10 in. H_2O or less to permit accurate readings on a week-to-week or month-to-month basis.

An aneroid-type manometer installed with three-way vent valves to allow easy zeroing of the instrument is shown in Fig. 5.16. This type of manometer requires less maintenance in locations where temperatures may be below freezing or in equipment areas where temperatures are high, like unvented attics, or where the manometer is exposed to direct sun. Most liquid manometer fluids will freeze or congeal at temperatures below freezing or dry up rapidly in high-heat locations. The Magnehelic[8] gage is a typical aneroid manometer that is available for many pressure ranges and has useful

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[7]Jensen Young, W. T. Pearce, and T. C. Parsons, "Dry Scrubber Unit for Low-Peak Ventilation Systems," USAEC Report UCRL-10953, Lawrence Radiation Laboratory, University of California, August 1963.

[8]Trade name of F. W. Dwyer Co., Michigan City, Ind.

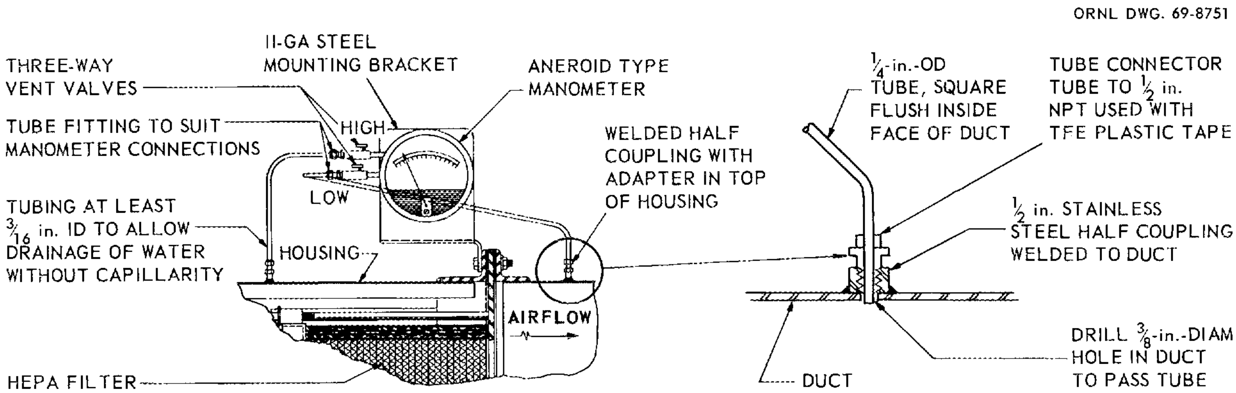


Fig. 5.16. Manometer installed on housing to indicate HEPA filter pressure differential.

accessories. The instrument shown in Fig. 5.16 can be obtained in a weatherproof model when ordered for outdoor use. All models must be protected from heavy vibration such as would be produced by a fan unit close-coupled metal to metal on the downstream side of the filter housing. To avoid damaging vibration to the manometer as well as to the installed HEPA filter the vibrating source must be isolated. Examples of this type of isolation are discussed in Sect. 2.9.3.

Manometers should be mounted in accordance with the manufacturer's recommendations, as calibration may be affected by the mounting position. Since connecting tubing must be kept clear of debris and accumulated liquids (water) the minimum line size should be 1/4 in. OD (3/16 in. ID). Larger tubes are preferred in all cases and are necessary for moderately sloped (longer than 5 ft) positions when condensation can occur. When possible, the connecting tubing should be sloped to drain to the housing from the vent valves to eliminate pocketing of liquid that would otherwise have to be drained periodically by hand. A series of valved drain points should be installed when the slope of the connecting tubing is too small to drain the collected moisture completely.

When a static pressure tube is installed on the end of a connecting tube, it should be located where it can be cleaned and inspected conveniently. The small holes in a properly designed static tube clog easily and must be kept clean to give reliable readings. Static pressure tubes should not be located where moisture or particulate matter can plug the sensing holes.

5.5 CONNECTIONS FOR DOP TESTING

Single-HEPA-filter systems should have permanently installed and properly positioned connections for in-place testing with dioctyl phthalate (DOP) "smoke" to test the leakproof efficiency of the filter system. The principles of DOP testing of HEPA filter systems are discussed in Chap. 7 and are contained in a proposed USA Standard entitled "Efficiency Testing of Air-Cleaning Systems Containing Devices for Removal of Particulates."[9] Regardless of system size, sampling points must be selected where good mixing has occurred to ensure that samples are truly representative of the gas stream. Suggestions for aerosol injection points and DOP sampling points for a single-filter system are shown in Fig. 5.1.

Sampling connections may be a half coupling welded around a 1/2-in.-diam hole in the duct and closed with a threaded pipe plug and TFE plastic tape, as shown in Fig. 5.17. With this type of connections, the pipe plug is removed and a sampling probe inserted into the duct long enough to produce stable readings on a photometer, after which the probe is removed and the connection closed. When a filter in a closed system is to be tested, the use of a valved sampling connection, as shown in Fig. 5.18, is recommended. A sampling line is attached to the valved connection to convey a gas sample to the meter chamber. After the line is connected, the valve may be opened and the meter read without producing uncontrolled leakage into or out of the system.

The DOP aerosol must be injected into the system well upstream of the filter. This may be a contaminated portion of the exhaust system, and care must be taken when making this penetration to avoid release of

[9] Proposed USA Standard, "Efficiency Testing of Air-Cleaning Systems Containing Devices for Removal of Particulates," United States of America Standards Institute, Task Group N5.2.11, Aug. 10, 1966.

contamination. A valved connection comparable with the one shown in Fig. 5.18 should be used for an injection port, and it should be sized for approximately 10% of the test flow rate. The air stream carrying the highly concentrated DOP aerosol mixes with the normal or reduced air flow of the system to produce a dilute aerosol at the sampling point. The system should be tested at or near its normal operating flow rate, but reduced flow rates are used to test for the presence of pinhole leaks in the HEPA filter medium. A commonly used reduced test flow rate for HEPA filters is 20% of the normal rated capacity of the filter.

ORNL DWG. 69-8752

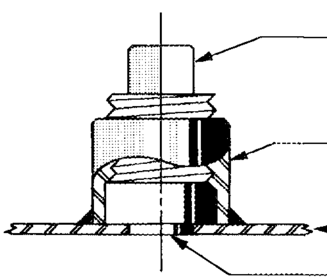


Fig. 5.17. Threaded half coupling and pipe plug DOP sampling connections.

It should be remembered that DOP generators require a supply of clean compressed air at a minimum pressure of 50 psig (so that the generator pressure can be regulated from 0 to 40 psig), sufficiently sized to flow 25 cfm for each six-nozzle generator required for the test. One standard six-nozzle generator is adequate for testing a single HEPA filter (1000 cfm) when using high-sensitivity test equipment. The photometer requires a source of 115-v ac single-phase electrical power. These services must be convenient to the system to be tested.

ORNL DWG. 69-8753

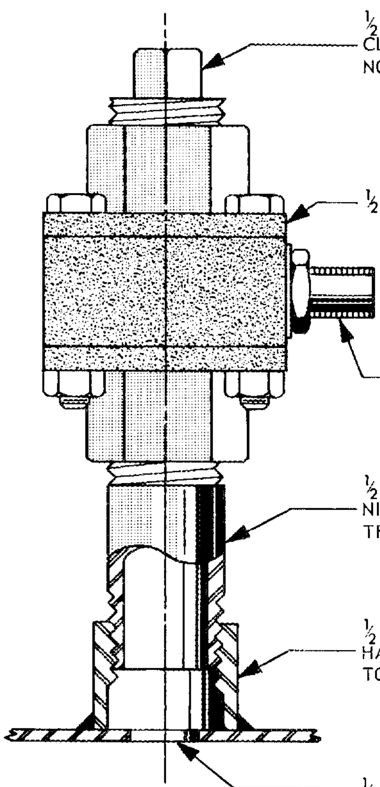


Fig. 5.18. Recommended sampling connection with valve.

5.6 DRAINS

Regardless of size, HEPA filter systems in nuclear facilities must provide for drainage of moisture. A small system installed outdoors where the duct from an inside fume hood is exposed to outdoor temperatures is shown in Fig. 5.19. In cold climates, condensation is certain to be present in this type of system, particularly during winter, and provisions for draining condensate are needed at a low point in the filter housing. In this example the pressure-sensing tubes for a manometer located inside the building form a pocket at a low point that will hold moisture and make accurate pressure readings impossible.

There should be a separate drain connection with an individual air seal at the bottom of a filter housing upstream and downstream of the filter. Several methods of draining filter compartments are diagrammed in Fig. 5.20. Methods *a*, *b*, and *c* are most used for small single-filter systems, although small condensate pumps, commonly used in steam systems, might be less costly than inconveniently located gravity drain lines in some locations.

Drainage from a contaminated-air exhaust system must be handled and treated as a contaminated liquid and not mixed with any other system drainage unless similar contaminants are present. The volume of these contaminated wastes should be kept as low and their concentration as high as possible for easier handling and processing.

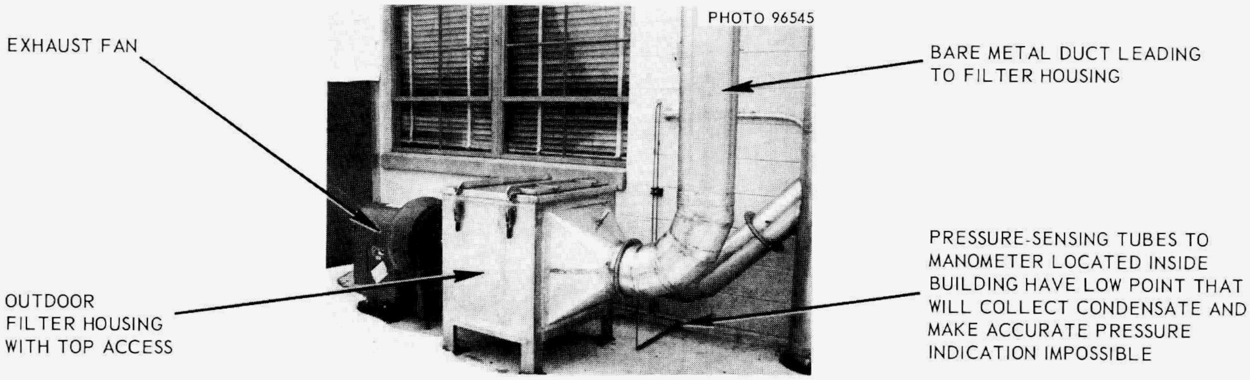
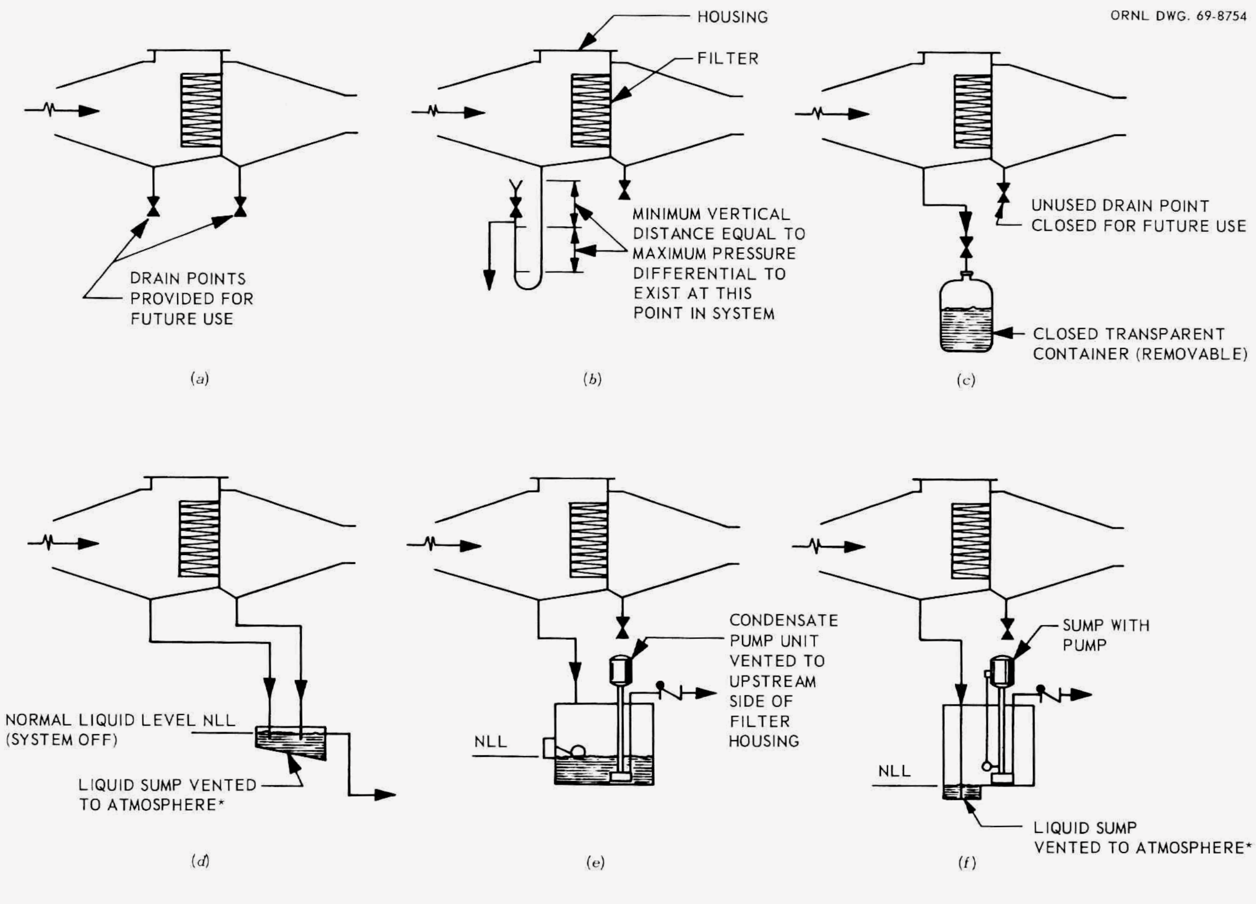


Fig. 5.19. A poor installation of a single-HEPA-filter system located outdoors. This arrangement is not recommended. Courtesy Oak Ridge National Laboratory.



*WITH NEGATIVE PRESSURE IN HOUSING, THE VOLUME OF LIQUID IN SUMP ABOVE THE END OF EITHER SUBMERGED TUBE MUST EXCEED THE VOLUME DRAWN IN ALL TUBES PLUS AT LEAST 2 in. MORE TO ACCOUNT FOR PULSATIONS AND WAVES IN SUMP.

Fig. 5.20. Methods of draining condensate from single-filter compartments.

5.7 MAINTENANCE

Maintenance and filter changing operations for single-filter systems should be performed by manual methods when permissible. Remote handling should be used only when radiation fields created by the particles collected on the filter could cause overexposure of maintenance personnel. The complications and expense of remote handling equipment and the use of heavy shielding should be avoided when more frequent filter changes will reduce radiation levels and permit the use of partial shielding and direct handling procedures.

When a filter is used to collect particles that emit penetrating radiation (beta, gamma, or neutrons), it must be changed often enough to keep radiation from exceeding the exposure limits set for workers. The exposure a person will receive is determined by the product of the intensity of the radiation field and the time required to change the filter; therefore the filter change procedure should be planned to minimize the number of persons required and their total exposure. The tasks to be performed in the radiation field may be divided so that only one worker is exposed at a time. Easy filter access and simplicity of changing operations will minimize the required time.

After a filter collects particles having high toxicity, such as alpha contamination, it may be desirable to use a bagging procedure to change the filter. The steps required to change a filter in a housing by bagging are illustrated in Fig. 5.2.

Regardless of the procedure used to change filters, adequate space must be provided around the housing for removal and replacement of the filter. As is discussed in Sect. 2.5, locating a filter in an unfloored attic space, behind other runs of duct or pipe, near a ceiling, or beyond convenient reach is likely to result in neglect. The poor installation shown in Fig. 5.21 makes it necessary to insert the filter from the top between adjoining duct flanges. In this instance, the worker has no secure place to stand and will probably brace himself against the suspended duct nearby. A dirty filter dropped in this area could contaminate the entire attic area, and complete cleanup would be costly and difficult. The less-desired practice of using flanged connections on the ends of the ducts to match the gasketed faces of the filter is also illustrated in Fig. 5.21. Spillage of moisture or dust when the flanges are separated for filter change is certain to spread contaminating particles. Since operating costs (material and labor) are 65% or more of the total cost of a system,[10] it is imperative that adequate space for filter handling be provided to reduce service time and risk of accidental spillage of contamination. Work aisles 40 in. wide are needed for convenient handling of 24-in.-wide filters, and the width of the access space should never be less than 30 in.

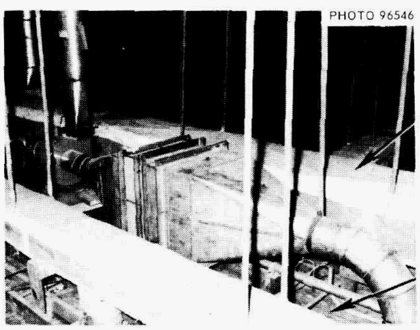


Fig. 5.21. Example of a poor single-filter installation showing lack of access. Courtesy Oak Ridge National Laboratory.

5.7.1 Mechanical Changers

Mechanical devices have been used with single-filter systems to aid the filter change operation. Their primary purpose is to help contain particles and gases that would be harmful if they were released by the opening of the filter enclosure for maintenance, and they make it possible to continue system air flow during filter change. However, such devices are special, and there are no standard designs for mechanical filter changers.

A mechanical filter changer built prior to 1963 is shown in Fig. 5.22. This filter system has a mechanical loader to displace the used filter by sliding it into a container, usually a filter carton in a plastic bag, on the opposite side as a new filter is slid into operating position by the force of the loader. Two stages of 24 × 24 × 11½ in. open-faced HEPA filters are used in series in this system, and the removable portion of the mechanical loader is usable on either stage. Half-round gaskets on the edges of the new HEPA filter casing are lubricated with silicone grease, allowing the filter to slide with less friction as the new filter displaces the used filter out the opposite side. The DOP connection upstream of the first-stage filter was added when routine DOP in-place tests were initiated after the 1963 installation of the system. The filter stages are situated very close together, and good sampling conditions are

[10] M. W. First and L. Silverman, "Cost and Effectiveness of Air-Cleaning Systems," *Nucl. Safety* 4(1), 61–66 (September 1962).

not possible. Without good mixing of the air stream leaving the first HEPA filter a single DOP sample is not representative; therefore probing must be used to search for leaks. Also, because the two HEPA filters are so close together (approx 12 in.) there is no convenient space to introduce DOP aerosol so that the second filter can be DOP leak tested separately from the first. This illustrates another reason for separating banks of HEPA filters other than improvements gained in fire protection.

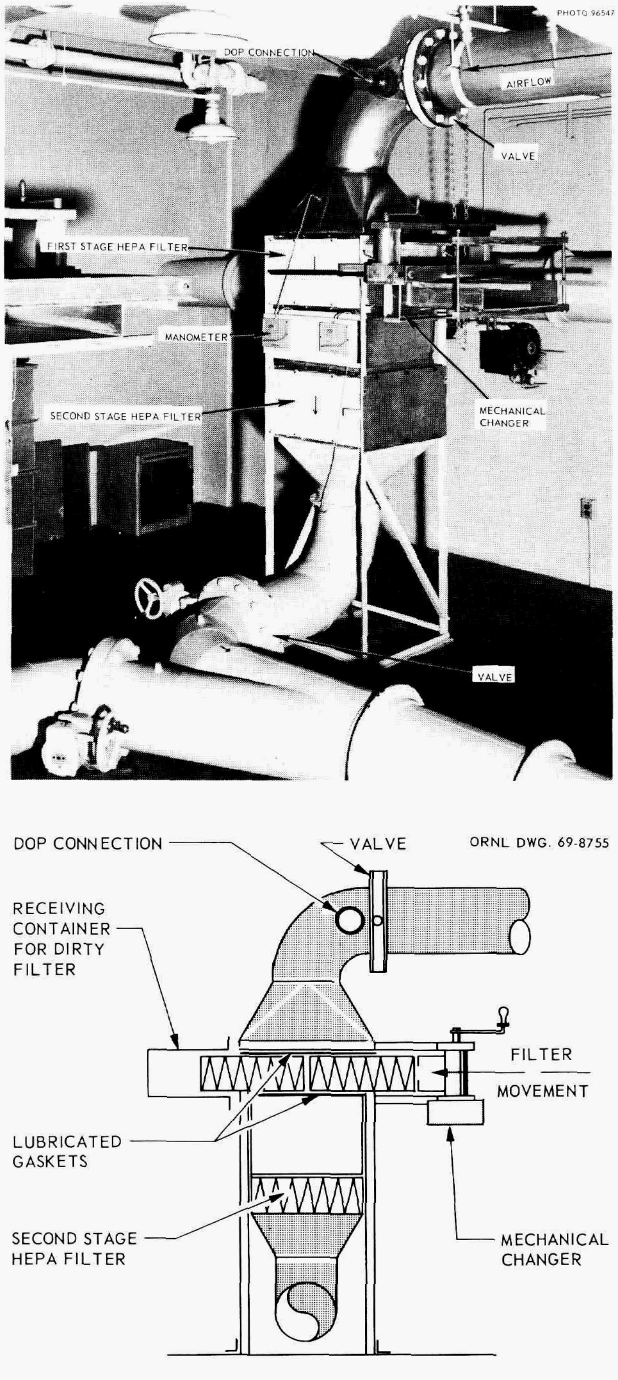


Fig. 5.22. Mechanical changer for HEPA filters. Courtesy Oak Ridge National Laboratory.

No radiation shielding is required for the system shown in Fig. 5.22, but tight enclosures are essential to retain alpha particles. If the collected particles also emit penetrating radiation, heavy protective shielding is needed around the source. The need for heavy shielding would necessitate different equipment for handling the filters remotely, as discussed in Chap. 7.

5.7.2 Bagging of Enclosed HEPA Filters

To provide better retention of the particles collected by an enclosed HEPA filter, the inlet (dirty) connection can be fitted with a sealing gland that permits bagging the filter. A 1000-cfm enclosed HEPA filter installed to permit bagging is shown in Fig. 5.23. This system has dampered inlet (the valve is shown in upper right portion of Fig. 5.23) and exhaust ducts to isolate a filter, one of four arranged in parallel, during a change and routine DOP testing. The DOP test connections are shown in the curved portion of the duct. The enclosed 1000-cfm HEPA filter, which weighs about 90 lb, in the plastic bag, rests on a roller-mounted tray on a positioning table. All of the apparatus needed to change the filter is situated in a heated, ventilated, and lighted space indoors, with adequate space provided on both sides of the positioning table for bagging and handling the filter. This equipment arrangement is not applicable for outdoor use or for an extreme indoor environment without changes.

To change a filter the side clamps are removed, the inlet-side sealing gland separated, and the bagging deflated by opening the small valved suction tube to the upstream side of the inlet-side main isolating valve. The bagging over the separated joint is grouped and cut by a heated knife that seals both ends (Fig. 5.24). Then the filter may be disjointed on the downstream end, and the bagging is cut and sealed with the hot knife and rolled out of position in preparation for the new filter to be "bagged in." The bagged dirty filter is fitted and sealed into a protective carton for transportation to a contaminated-waste burial site.

The special end connection used on the inlet or dirty end of the enclosed HEPA filter is a molded sealing gland of soft solid neoprene, 15 to 20 durometer, that provides peripheral sealing in two separate areas of the gland, as shown in Fig. 5.25. The gland remains on the

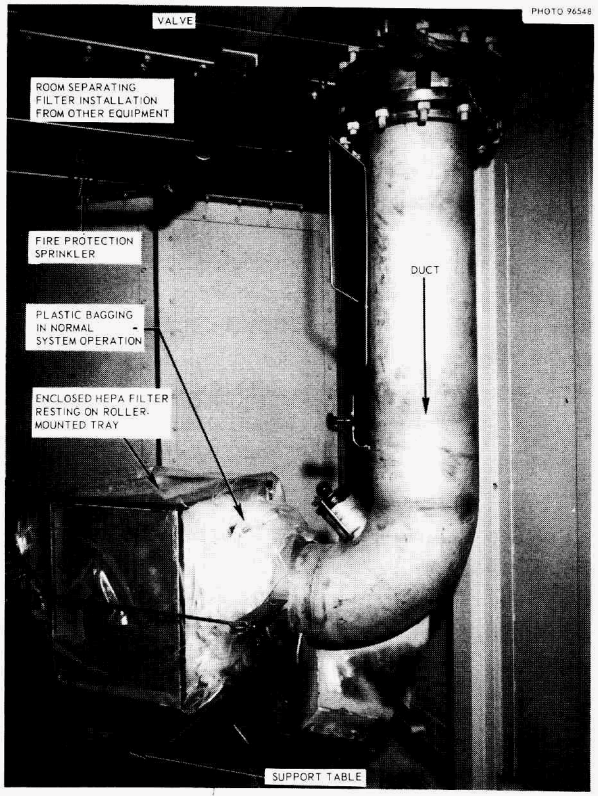


Fig. 5.23. Installation of enclosed HEPA filter for filter changes by the bagging method. Courtesy Oak Ridge National Laboratory.

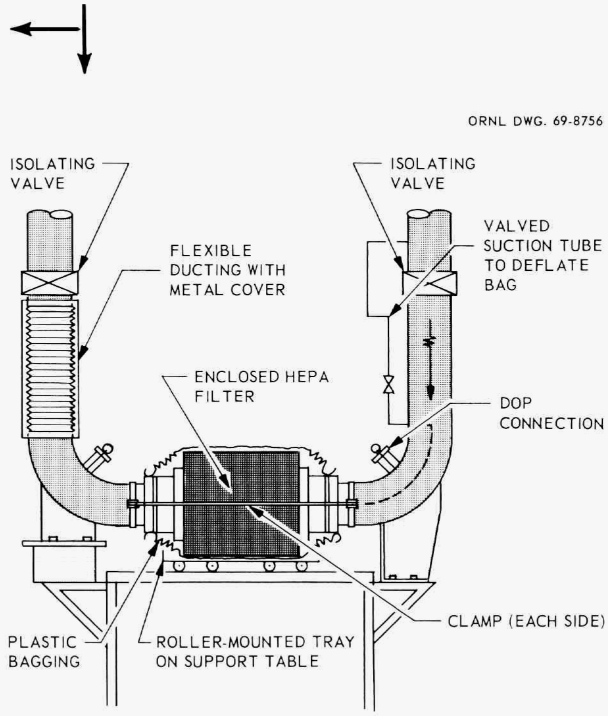


Fig. 5.24. Heat sealing a bag around an enclosed HEPA filter during filter changing operations. Courtesy Oak Ridge National Laboratory.

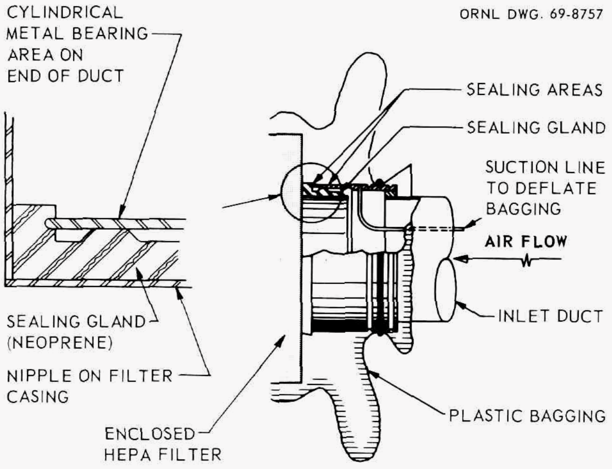


Fig. 5.25. Special sealing gland for inlet connection on enclosed HEPA filter to permit bagging.

end connection of the dirty filter and is discarded with the filter. A lubricant used sparingly on the outer bearing surface of the replacement gland reduces sliding friction during insertion and withdrawal. Vaseline has proved to be the best lubricant because it does not interfere with heat sealing of the plastic bag, as silicone and fluorcarbon compounds do.

5.8 SPECIAL APPLICATIONS

Single HEPA filters installed in moist and corrosive environments such as are encountered in fume hood service require special consideration. The single-HEPA-filter system is often used for emergency situations, and a single HEPA filter may also be used as a cleanup device when it is not actually required as an operational safety item.

5.8.1 Fume Hood Filtration

The wide variety of chemical agents used in laboratory fume hoods makes the selection of HEPA filters to be used in hood exhausts difficult and uncertain. Corrosive fumes damage the filter and mounting frame, and moisture and heat from hood operations accelerate chemical actions to shorten filter and framing life even more. Operations producing steam or moisture are particularly damaging to filters. Moisture condensation must be controlled so that droplets will not be conveyed to the filter pack, where they can clog the filter, or accumulate so that drainage will pass through the bottom region of the filter pack, causing deterioration (e.g., swelling of the wood casing), or wash collected contaminants through. The HEPA filter should be protected from these operations by condensers or moisture separators that keep the exhaust stream less than fully saturated.

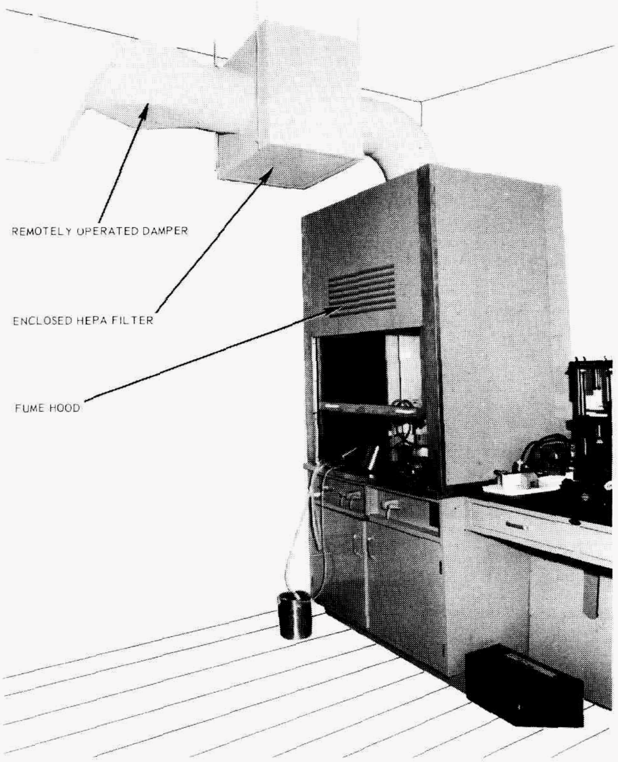


Fig. 5.26. Enclosed HEPA filter installed in fume hood exhaust stream. This arrangement is not recommended. Courtesy Oak Ridge National Laboratory.

An enclosed HEPA filter installed immediately downstream of a fume hood within a laboratory is shown in Fig. 5.26. This arrangement will allow warm vapor from the hood to condense in the duct and filter casing because of cooler room temperatures. Locating the fume hood exhaust filter outside the laboratory proper in a maintenance area will offer fewer condensation problems because the amount of vapor that can condense and damage the filter is limited by placing the filter farther downstream. In addition, inspection, DOP testing, and filter change operations can be performed without disrupting laboratory activities. It is preferable to have the HEPA filter arranged in a service space immediately adjoining the hood location, so that ducting can be short and direct. When long runs of ducting are mandatory, it is advisable to evaluate locating the filter in the upper part of the hood, thus reducing the amount of contaminated ductwork between hood and filter. The designer must not underestimate the inconvenience that can be created by having an HEPA filter situated near or in a fume hood that is used routinely.

Exhaust filters serving laboratory fume hoods in frequent use often have to be replaced because of excessive penetration brought about by chemical attack on the medium rather than because the maximum dust deposition has occurred. Since the supply systems of most modern laboratories provide good dust filtration, the airborne dust load in hood exhaust streams is lowered significantly. Unless operations within the hood generate a lot of coarse dust, there is seldom need for a particle prefilter in a hood exhaust stream. In fact, deterioration of an unsuitable prefilter from chemical attack can make it a detriment.

The inclusion of washdown systems in fume hoods and ducts is a common practice when corrosive fumes or hazardous condensates, such as from using perchloric acid, are released. Therefore a device to separate moisture droplets from the air stream is needed in the exhaust of hoods when a washdown system is used or when other sources of moisture are present. Moisture should be collected and conveyed to a hood drain rather than being allowed to drop back into the working area of the hood or onto the filter. All devices for separating airborne droplets from the air stream must be accessible and convenient for cleaning and inspection. The moisture separators described in Sect. 3.5.2 are applicable for use in hood exhausts when adequate space requirements, accessibility for inspection and cleaning, flow resistance, and gas velocity are designed into the system properly. A distinction must be made between moisture separators and wet chemical scrubbers in this application. Scrubbers usually create droplets and require the use of moisture separators in their outlet gas streams to protect downstream filters.

Equipment to neutralize volatilized chemicals should be considered for permanent hood installations that discharge corrosive agents. The efficiency of this equipment should be high enough to make the life of exhaust ducts and filter housing equal to that of the fume hood itself. This is usually ten years or more. HEPA filters used in fume hood exhausts from laboratories that are free of coarse dusts and corrosive fumes frequently last two years or more, but when corrosive chemicals attack the filter, effective life can be reduced to hours, and replacement costs of HEPA filters become prohibitively high.

When moisture and/or chemical attack is not a problem, the use of an effective spark arrester in a fume hood exhaust is of value to protect the HEPA filter from incendiary particles that might be generated within the hood. An easily cleaned and effective spark arrester is a removable 40-square-mesh metal cloth. As is discussed in Sect. 5.1.5, this cloth should be located 5 ft or more upstream of the filter to create a zone where small particles of debris that may pass the arrester can finish burning and cool down before reaching the filter.[3]

Heat sources and open flames are common in fume hoods, and an uncontrolled fire is a possibility that must be planned for in the design of the exhaust system. Extended lengths of duct between the hood and the exhaust filter can be used as a cooling zone,[3] but this length must be more than 100 ft to be completely effective. This is impractical for fume hood service in most cases. Therefore the recommended method of fire control for single filters installed in fume hood exhausts is the same as for the open-faced HEPA filter systems discussed in Sect. 5.1.5. Recommended methods for mounting, clamping, and sealing filters in fume hood exhaust systems are the same as those discussed in Sects. 5.1.2 and 5.1.3.

5.8.2 Filtering Systems for Emergency Use

Single HEPA filters are frequently incorporated in self-contained auxiliary systems for emergency ventilation, for cleanup uses, or to supplement flow in a disabled exhaust system. This requires that the HEPA filter and its mounting frame be portable and be capable of being put in service quickly, often after being in storage for long periods. The need for portability and readiness must not compromise operating performance. The requirements for portable HEPA filter systems are the same as those stated in Sect. 5.1 for stationary installations. Particular attention must be given to storage and protection so that the unit retains its readiness for an emergency. Storage should be indoors in a dry area, clean of debris and free from external loading that may strain the framing or casing. Emergency-use HEPA filter installations require the same periodic inspection and in-place leak testing as the stationary system where they are expected to see use.

The rough handling and vibration experienced in transport require that framing be rigid and able to absorb shocks without straining the HEPA filter or its mounting frame.

A skid-mounted emergency system that incorporates a fan unit is shown in Fig. 5.27. A wheel-mounted emergency system manufactured by Nuclear Safety Systems, Inc., is shown in Fig. 5.28. This unit has two SGN Caissons arranged for horizontal series flow. Both of these systems require portable ducts and electrical power sources for their operation. All standby systems must be tested routinely to ensure reliability and readiness for emergency use.

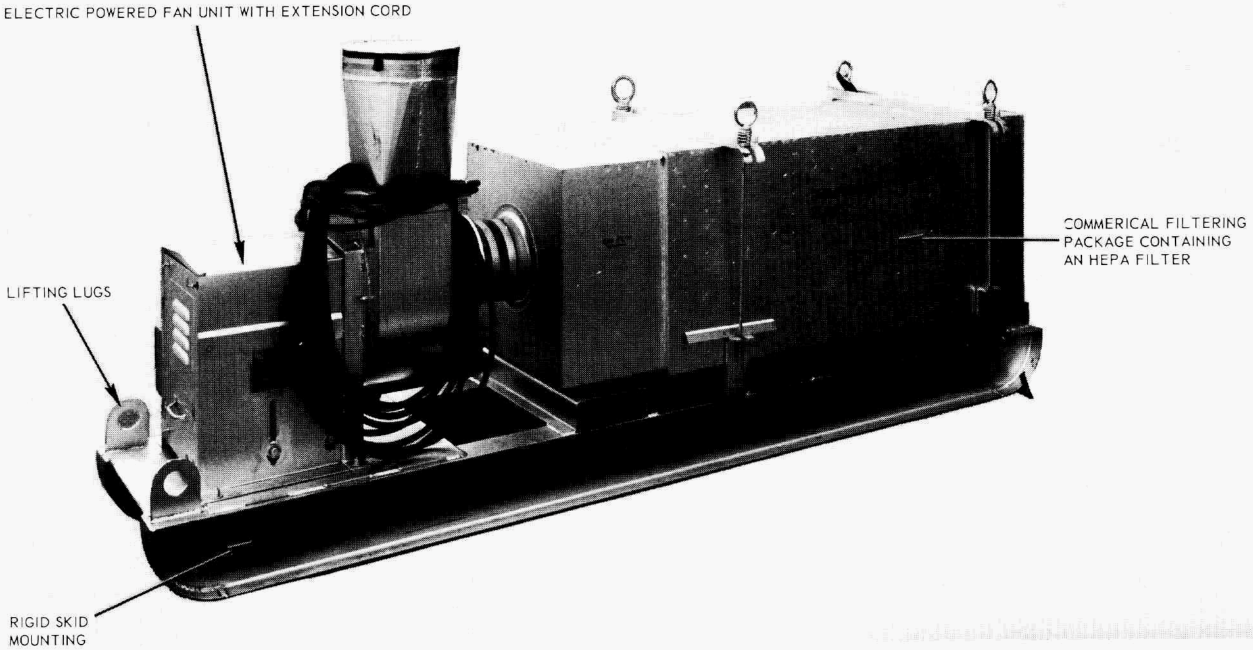


Fig. 5.27. A recommended skid-mounted emergency filtration and exhaust ventilating system. Courtesy Lawrence Radiation Laboratory.

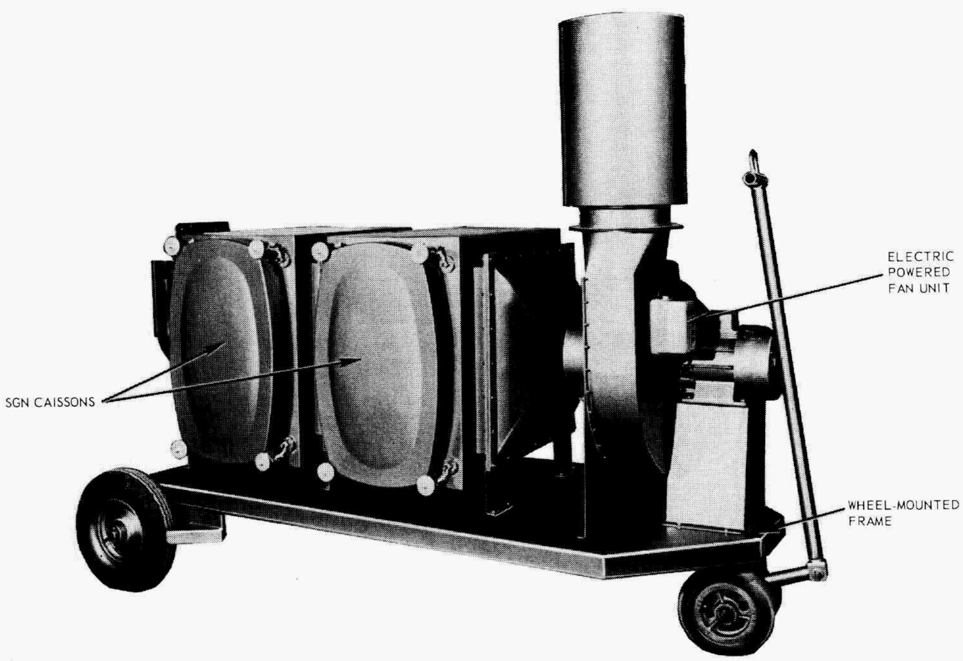


Fig. 5.28. An approved wheel-mounted emergency filtration and exhaust ventilating system. Courtesy Nuclear Safety Systems, Inc. (S.G.N.).

5.8.3 Temporary Cleanup Systems

There are occasions when a single HEPA filter can be used for a cleanup on a temporary exhuast hood that does not require a permanent installation. Portable fume hoods or plastic enclosures sometimes need good filtration for a short period of time, and when the job is completed they will be discarded, filter and all. A single use does not warrant the expense of a heavy mounting frame or permanent-type housing. A single HEPA filter installed in a light sheet metal mounting device with a flexible duct connection is shown in Fig. 5.29. This device can be attached to a central filtered exhaust system and used to ventilate occupied spaces, such as a manhole, tank, vault, etc., during maintenance periods. The filter collects contamination locally, and the flexible duct or hose remains clean for possible reuse. The filter is sealed in place with pressure-sensitive tape or fire-resistant sealant to limit the cost of mounting when maximum filter efficiency is not required. Should the unit become badly contaminated, it can be discarded as a throwaway item and replaced at moderate cost.

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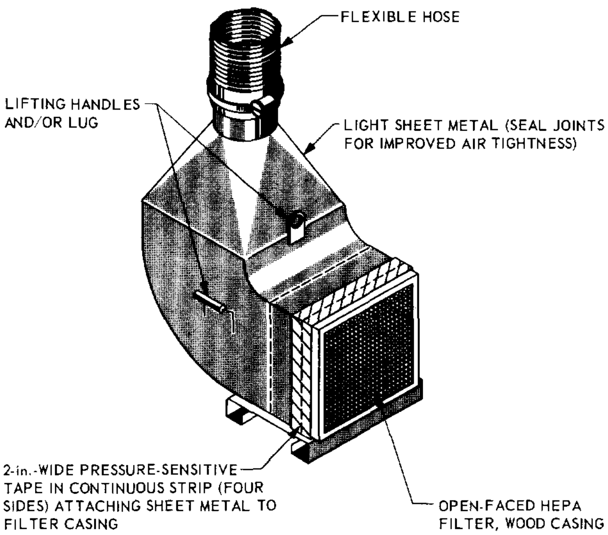

Fig. 5.29. Single HEPA filter in a light sheet metal mounting with flexible duct connection for one-time use.

6. Gloved Box and Enclosure Filtration

A gloved box is a sealed, or low leakage, enclosure equipped with one or more airtight flexible gloves for access and manipulation inside the enclosure. This chapter discusses the filtration of air or other gases associated with the ventilation of such specialized enclosures.

There is no commercial standard covering the construction of gloved boxes. As a result many different types and designs exist. Fabricators in the United States build and sell gloved boxes and related equipment either of their own design or to customer specifications. However, few items are interchangeable from one fabricator to another. Even though some standardization has resulted from the repetitive needs of single users, few features of gloved box design are widely accepted. Clear evidence of a difference in need and opinion on this subject is given in the USAEC *Report on Glove Boxes and Containment Enclosures,*[1] in which many design and operational data are documented.

It is imperative that ventilation and filtration requirements be specified clearly and completely when designing and purchasing commercial gloved boxes. The receipt of certified dimensional layouts and detailed data from the manufacturer will permit the buyer to evaluate the equipment before purchase and avoid any misunderstanding of terminology. New commercial equipment should be evaluated to determine its compatibility with existing requirements, components on hand, space needs and service connections, and existing stocked items such as filters, gaskets, and connecting hardware. Specific items that require close attention include:

1. the capacity, type, and number of filters in series to be used in the inlet and exhaust air streams;
2. air flow (purge) rates required to meet operating conditions;
3. the suction pressure required to achieve the air flow requirements of item 2 with the control equipment being used;
4. the capability of the ventilating system, including filters, to meet emergency conditions of air flow, abnormal temperature and pressure, and high particle concentrations;
5. the procedure for changing and testing filters.

In the absence of specific rules that establish limits for filter dirtiness, that is, filter resistance to air flow, initially one should consider maximum dirty-filter resistance three times clean-filter resistance for HEPA filters and two times clean-filter resistance for prefilters. The size of HEPA filter used inside a gloved box is usually 12 × 12 in. or less. Larger sizes are impractical because they cannot be safely handled without special inside equipment.

6.1 FACTORS INFLUENCING DESIGN OF FILTRATION SYSTEMS

Design factors that must be considered for effective and safe gloved box air filtration systems include: single vs double filtration, single vs multiple exhaust connections, maximum air flow requirements, maintenance of negative pressure, fire protection, fume dilution for fire safety and corrosion control, heat dissipation, protective atmospheres, monitoring system conditions, human limitations (e.g., reach, hearing in-box sounds), and equipment limitations like tools with sharp edges that damage gloves.

High efficiency and reliability of a filter system are the results of thorough planning of operation and maintenance during the design phase. For example, convenient regulation of gas flow through a filter requires not only an effective damper but instruments to observe the changes being made while adjusting dampers. Complete evaluation of the conditions of an operating filter is dependent upon two basic items of information: gas flow rate through the filter and the

[1] N. B. Garden, editor, "Report on Glove Boxes and Containment Enclosures," USAEC Report TID-16020, Health and Safety, June 20, 1962.

pressure drop across the filter at the time of flow measurement. One is of no real value without knowing the other. Safe gloved box operation is usually dependent upon the continued maintenance of negative pressure on the box to confine toxic materials; but, also, a gas flow through the box can be equally necessary to eliminate an unsafe accumulation of gas or particles.

6.1.1 Double Filtration

Arranging two HEPA filters in series is one method of assuring more reliable filtration for a containment-type ventilation system (i.e., a system required to ventilate a gloved box without release of hazardous or valuable particles). The second (backup) filter is positioned in series to collect particles that penetrate or bypass the initial filter stage during filter change or upon failure of the first filter stage. Two or more HEPA filters in series provide very little more collection of particles than one.[2] The principal advantage of two is the greater number of containing barriers for hazardous particles; hence double filtration is a safety measure rather than a means for providing significant improvement in the collection of particles from the airstream.

When corrosive gases or vapors are conveyed in the airstream, all filters in a series are exposed. Each stage that contains filters of identical construction with the first stage may be affected to almost the same degree as the first. Therefore a widely held impression that the operating life expectancy of a group of HEPA filters arranged in series is directly proportional to the number of filters in the series can be false when chemical or heat degradation occurs. Under these conditions, when the first stage fails, others fail from the same cause. Corrosive gases or particles from vats, scrubbers, and similar equipment must be neutralized before they reach the HEPA filters.

The full benefit of two or more filter stages cannot be realized unless each stage is kept in serviceable condition. Therefore each stage of HEPA filters must have built-in provisions for routine in-place testing. Testing with DOP aerosol is the best leak check known, whereas leak detection of damaged filters by changes in air resistance is insensitive and ineffective.

6.1.2 Single vs Multiple Exhaust Connections

A single filtered exhaust path may be acceptable when gloved box work does not include highly toxic particles and does not require continuous cooling or dilution of vapors. Requirements for continuous air flow make it mandatory that there be more than one exhaust connection to avoid interruption of exhaust flow during filter change and to afford a standby should sudden filter clogging occur during operations. The purpose of multiple exhaust connections is lost if all filtered paths are not kept in serviceable condition so that a standby connection is always ready for use during an emergency. Single and multiple filtered exhaust connections for a gloved box are illustrated in Fig. 6.1.

The safety value of multiple filtered exhaust connections can be realized easily in an interconnected line of gloved boxes or in a large box (enclosure) with several compartmented work areas. Compartmenting doors between work areas or between single boxes in an interconnected line must not isolate a work area with only one filtered exhaust connection. The several filtered exhaust points required to handle total air flow in an interconnected line of boxes are normally sufficient in number, but they must be sized for maximum flow and valved individually for flow control, as shown in Fig. 6.1.

6.1.3 Maximum Air Flow Requirements

The maximum required air flow rate for a gloved box determines the air flow capacity of the filters as well as the entire downstream ventilation system. Operating personnel can often assist the designer to establish realistic requirements, particularly when an existing system is being duplicated or revised, and industrial hygienists and radiation protection specialists at the site can suggest safety factors from experience. The types and quantity of material to be used inside the box, their toxicity, and form (wet slurry, dry powder, etc.) require consideration for safe handling of hazardous materials.[3]

The maximum rate of exhaust flow from an air-ventilated gloved box is usually based on the required inlet flow to safely contain in-box contaminants when an access port is opened or a glove ruptures. The exhaust air path must remain sufficiently free of air flow resistance so that the *maximum* insertion or pumping of gloves will not cause more than *momentary* conditions of positive pressure, preferably none at all.

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[2]R. E. Adams, J. S. Gill, *et al.*, pp. 27–28 in "ORNL Nuclear Safety Research and Development Program Bimonthly Report for March–April 1967," USAEC Report ORNL-TM-1864, Oak Ridge National Laboratory, May 10, 1967.

[3]Ad Hoc Committee: C. E. Guthrie, E. E. Beauchamp, L. T. Corbin, T. J. Burnett, and T. A. Archart, "Operating Guide for Radiochemical Laboratories at Various Activity Levels," USAEC Report ORNL-TM-626, Oak Ridge National Laboratory, April 1963.

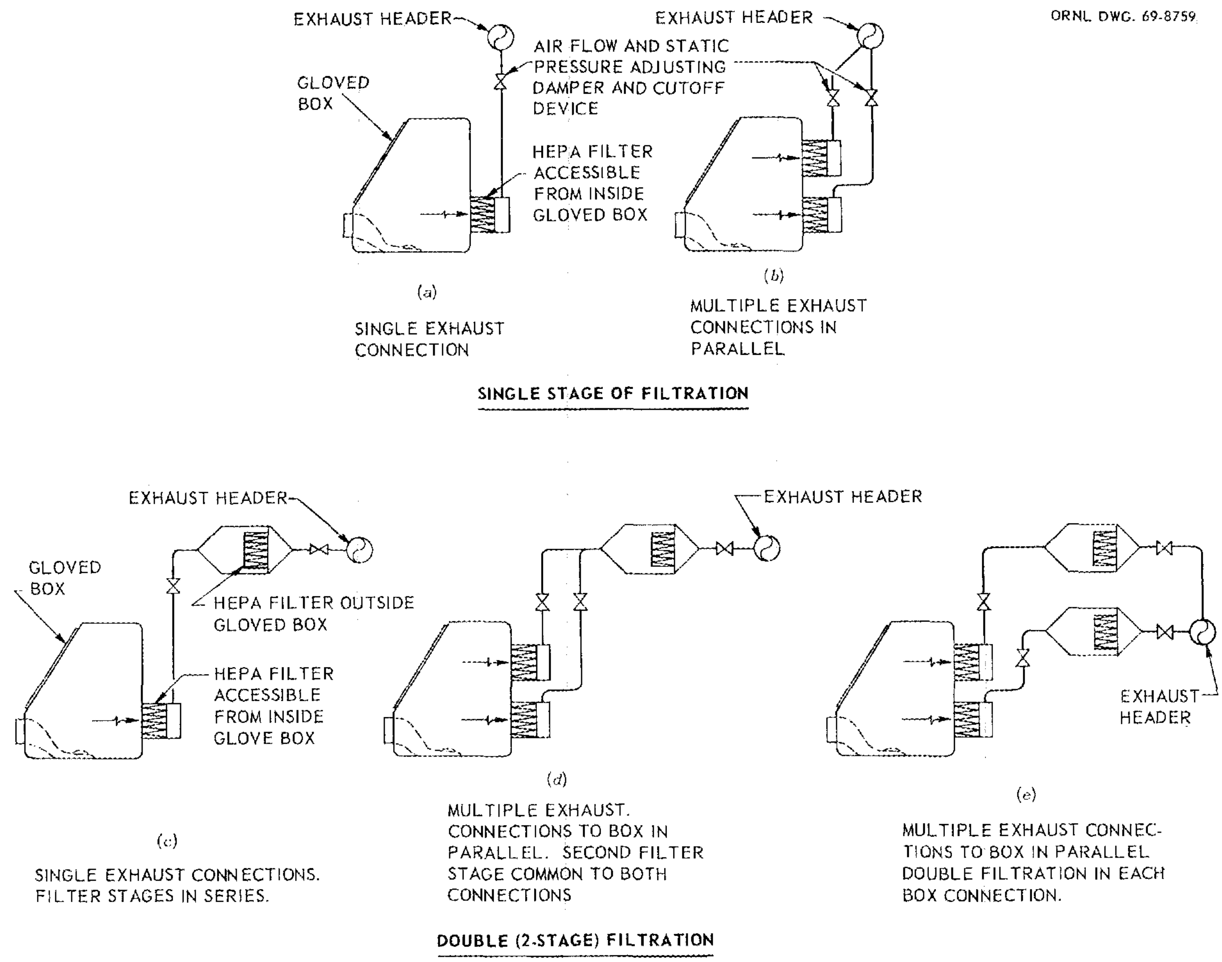

Fig. 6.1. Approved arrangements for single- and multiple-filtered exhaust connections for gloved boxes.

Frequently used flow rates for air-ventilated gloved boxes are tabulated below.

Condition	Flow Range
Normal air flow	2 to 15 cfm per 3-ft-long box module containing one pair of gloves
Maximum emergency air flow	35 cfm (minimum) per 3-ft-long box module. This rate corresponds to approximately 100 fpm air flow velocity through one open 8-in.-diam glove port.

Maximum emergency flow rates for filters in gloved boxes filled with inert atmospheres are different from those for air-ventilated gloved boxes. Inert atmospheres are used to exclude air, moisture, or contaminants from the interior of the box, and the admission of air during an emergency, like a ruptured glove, may not afford the safest condition for the gloved box. If the inert atmosphere in the gloved box is diluted by oxygen in an incoming emergency air stream, pyrophoric materials like plutonium metal can be ignited and cause an emergency far more serious than the ruptured glove. Where inert atmospheres are involved, specific criteria for emergencies must be determined by responsible persons to suit a particular situation.

6.1.4 Maintenance of Negative Pressure

Gloved boxes used to contain toxic materials are maintained at a negative pressure with respect to the room where they are located. This differential pressure is most often within the range of 0.30 to 0.70 in. H_2O.

Fast inward movement of the gloves can cause pressure pulsations in a small box that overcome pressure differentials as slight as −0.30 in. H_2O, whereas a large pressure differential will cause gloves to be stiff and tiring to use.

Good contamination control is more easily achieved in a gloved box having low air leakage. Leak-tightness is dictated by the degree of containment required for controlling hazardous materials or the need for excluding air or moisture rather than negative pressure requirements. Gloved box construction features are described in USAEC report TID-16020[1] and other publications.[4–6] When high-purity gases such as argon, helium, or nitrogen are used in gloved boxes, construction requirements affecting leakage and pressure regulation are much more critical than when boxes are ventilated with room air.

6.1.5 Fire Protection

Although the greatest hazards associated with gloved box work are explosion and fire, there are no nationally approved fire protection systems for gloved boxes or enclosures. Gloved box fires occur under various circumstances, and this makes the setting of design criteria very difficult. Gloved box fire safety is discussed in a Factory Mutual Research Corporation document.[7] The technology of gloved box fire detection and control systems has changed rapidly in recent years, and further improvements are expected. Fire extinguishing systems using gases such as Halon 1301 or FE 1301 [8] (bromotrifluoromethane) in small enclosures have proven very effective for many types of fires (Classes A, B, and C). Fire protection systems using Halon 1301 have been designed for use with enclosures for several years.[9] A proposed tentative standard on Halogenated Fire Extinguishing Agent Systems – Halon 1301 (NFPA No. 12A-T-1968) documents general information and requirements for such systems.

As the designer has no accepted standards to follow for providing protection against fires, empirical data that have proven successful should be used. A feature that has been accepted universally is the use of fire-resistant HEPA filters. Although their use reduces the amount of fuel contributed to a fire, there is no assurance that the filter will remain operable during and following exposure to fire, smoke, or burning debris. The temperatures reached during a fire, the quantity and density of smoke released, and the duration of the fire determine the destructive effects on prefilters and HEPA units. HEPA filters constructed for high-temperature service can withstand 750°F for periods up to 5 min without serious penetration of particles, but the same filter cannot withstand indefinite exposure to temperatures higher than 275°F (Tables 3.4 and 3.5). Longer filter life and more reliable service can be obtained when normal operating temperatures are below 200°F and high temperature extremes are avoided.

The selection and arrangement of HEPA filters on, in, or near gloved boxes and similar enclosures are limited by the type of fire control equipment used, because HEPA filters and most prefilters are not compatible with all types of fire extinguishing systems. Dry chemical extinguishing agents are finely divided solids that will be collected by the filters and may clog them, resulting in reduced air flow. Ideally, the discharge point of dry chemical agents will be selected to blanket the fire zone effectively without affecting the exhaust filters adversely.

When large amounts of carbon dioxide (CO_2) are released from a cylinder, moisture in a gloved box may form ice crystals that will clog the filters in only minutes of operation. Should this happen, further introduction of CO_2 is likely to pressurize the box relative to the room. Carbon dioxide is rated as a poor fire extinguishing agent for gloved boxes because of its tendency to promote clogging of exhaust filters and reduce air flow, as well as obscuring vision, when moisture is present.

When foaming agents or spray droplets from fire extinguishment systems reach a filter, it clogs quickly if free moisture cannot be evaporated into the air passing through the filter. This limits the use of foam generators and water fogs to ventilating systems where emergency devices are actuated and controlled manually, or where continuous air flow through the filter (or filters) during an emergency is not a necessity. A

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[4] P. A. F. White and S. E. Smith, *Inert Atmospheres*, Butterworths, Washington, D.C., 1962.

[5] C. J. Barton, "Glove Box Techniques," *Technique of Inorganic Chemistry*, vol. III, Interscience, New York, 1963.

[6] G. N. Walton *et al., Glove Boxes and Shielded Cells*, Butterworths, London, 1958.

[7] "Glove Box Fire Safety, a Guide for Safe Practices in Design, Protection, and Operation," USAEC TID-24236, Health and Safety, prepared by Factory Mutual Research Corporation for the USAEC, 1967.

[8] Trade name of E. I. du Pont de Nemours and Co., Inc.

[9] T. E. Franck and C. H. Youngquist, "Fire Protection in Chemistry Hot Cells by Use of Halon-1301," *Transactions of the American Nuclear Society, 1967 Winter Meeting*, vol. 10, November 1967.

tentative standard for High Expansion Foam Systems was published in 1968 by the National Fire Protection Association (NFPA No. 11A-T-1968) and revised in 1969 (NFPA No. 11A-TR-1969).

At the present time, better fire prevention in gloved boxes can be achieved by using oxygen-free atmospheres than by placing dependence upon fire extinguishing systems. However, oxygen must be reduced below 1% before it fails to support the burning of some pyrophoric metals.[7] Various inert gases, such as argon, nitrogen, and helium, can be used to purge and fill gloved boxes. The use of dry air (relative humidity less than 20%) reduces the hazard of pyrophoric metal fires but does not eliminate it. Moisture in the presence of heated pyrophoric metals, such as finely divided plutonium particles, increases the hazard of explosion and fire by generating flammable hydrogen. The suitability of an inert gas for the process and its cost are significant factors when selecting this type of fire control system. Systems of this type normally have low gas flow rates, and low-capacity filters are frequently used.

Fire prevention in gloved boxes is aided greatly by good housekeeping practices, for example, limiting the amount of combustible materials kept in the box, safer operating practices, like using high-frequency (induction) furnaces for low total heat input instead of open-flame burners, and frequent filter replacements, since a clean filter has more fire resistance value than one containing combustible collected dusts.

6.1.6 Dilution of Combustible Gases, Vapors, and Aerosols

The method normally used to dilute fumes generated in an air-ventilated gloved box is to increase the air flow through the box. This action purges the space and rids it of objectionable fumes or vapors. When evolved gases, vapors, and particles are not flammable, toxic, or corrosive, gas flow rates are regulated to maintain negative pressure in the box, to improve vision, to accelerate drying, or to control some other operating conditions. But when fumes or vapors are hazardous (toxic, explosive, flammable, or corrosive), the box ventilation rate and the dilution of the evolved substances must be adequate to provide safe operation of the box and to ensure the safety of operating personnel. When designing a gloved box ventilation system and filter, the maximum generation rate of hazardous substances must be determined to establish minimum air flow rates needed for dilution. When the incoming air is free of contributing fumes, the following equation[10] can be used to determine the minimum safe air flow rate for each vapor generation rate:

$$\text{cfm} = \frac{403\,(\text{sp gr})\,(\text{pints evaporated/min})\,(100)\,(C)}{(\text{mol. wt})\,(\text{lel})\,(B)}\,, \tag{6.1}$$

where

cfm = minimum inflow for dilution, cubic feet per minute;

sp gr = specific gravity of hazardous material;

C = factor of safety (4 is used for uniform evaporation);

mol. wt = molecular weight of hazardous material;

lel = lower explosive limit, *in percent*;

B = correction for elevated temperatures where lel is lowered (B = 1 at 70°F, =0.95 at 100°F, =0.7 at 250°F).

A handbook (e.g., *Dangerous Properties of Industrial Materials,*[11] *Industrial Ventilation,*[12] or *Fire Protection Guide on Hazardous Materials,* NFPA[13]) should be consulted to determine the lower explosive limits for hazardous materials.

6.1.7 Heat Dissipation

Many gloved box operations release heat. High temperatures within the box cause a worker's gloved hands and arms to perspire heavily, lowering his efficiency. When sufficient room air is circulated through the box to limit inside temperature to 15°F above room temperature, the worker's comfort will be maintained. When this air flow rate exceeds one air change per minute, consideration should be given to supplementary methods of cooling (e.g., better isolation of heat sources, recirculating coolers, chill blocks for hot materials) or decreasing the generation of heat by intermittent operation of the equipment. There are practical limits to the amount of convection cooling that can be accomplished by air flow, since high rates create disturbing drafts that may be incompatible with

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[10] Adapted from *Dangerous Properties of Industrial Materials,* 3d ed., 1968, p. 42 (ref. 11).

[11] N. I. Sax, pp. 42, 43 in *Dangerous Properties of Industrial Materials,* 3d ed., New York, Reinhold, 1968.

[12] *Industrial Ventilation,* American Conference of Governmental Industrial Hygienists, Ann Arbor, Michigan (latest edition).

[13] *Fire Protection Guide on Hazardous Materials,* National Fire Protection Association, 1st ed., Boston, 1966.

delicate work such as weighing, dispensing liquids by dropper, handling light powders, etc. Where possible, operators should be protected from objectionable sources of radiant heat by using reflective shields or jackets that conduct the heat. Exhaust streams may be routed through the shield to permit the maximum pickup of convected heat before leaving the box.

When heat transfer rates to the box atmosphere have been determined, the required cooling air rate to dilute the hot gases can be calculated by using the following equation:

$$Q = \frac{H}{1.08(t_2 - t_1)}\,, \qquad (6.2)$$

where

Q = air flow, cfm,

H = heat emission (by convection), Btu/hr (1 w = 3.41 Btu/hr),

t_1 = temperature of entering air, °F,

t_2 = desired average temperature inside box (higher than t_1), °F.

The operation of high heat producing equipment may cause damage to the filters, and the deterioration of gaskets, sealants, and other filter materials is increased when operating temperatures are elevated (see Tables 3.4 and 3.5).

6.1.8 Protective Atmospheres

Filter installation requirements in gloved boxes operated with inert atmospheres are more stringent than for air-ventilated boxes because acceptable leakage rates are generally less than 0.0005 box volume per hour.[4] To attain this standard, joints and fastenings between items of equipment and materials (gaskets and seals) must have low gas permeability. Full-welded joints are preferred for all permanent fixtures, as leakage can be eliminated by this means. Gasketed joints may deteriorate in service, and this imposes continuing costs for periodic testing and, when required, repair.

Low-leak systems require quality construction for all components including boxes, filters, and associated ducts. Gloved boxes for work with radioactive materials are normally kept at a negative pressure of at least 0.30 in. H_2O gage relative to the work space, and when a high-purity recirculating inert atmosphere is used, any inleakage associated with the filter mounting or connecting duct will adversely affect the quality of inert atmosphere that can be maintained in the box. Penetrations must be minimized in both number and size, and the use of smaller HEPA filters will allow smaller ports for maintenance. An 8 × 8 in. HEPA filter requires a round port 10 in. in diameter or a rectangular opening 6½ × 8½ in. for passage into and out of a gloved box. Filter changes should be planned for the times when other maintenance procedures (routine or special) are taking place inside the box to reduce interruptions to operations and to reduce the quantity of inert gases or time required to recondition the box spaces.

A less rigorous type of protective atmosphere (containing no more than 1 to 2% of oxygen) may be provided to prevent some types of fires, as mentioned in Sect. 6.1.5. In other systems, water vapor or hydrocarbons may be excluded to produce a working environment suitable for a particular task. In all of these systems, low leakage is required in order to reduce the size of the gas purification equipment and to minimize the amount of gas needed to maintain the desired atmosphere. Therefore the designer must arrange filter installations that will not jeopardize system leak-tightness.

6.1.9 Monitoring System Conditions

For safety and high-quality work, gloved box operators need reliable information about system pressure and gas purity, readiness of alarm devices, and at times, recorders are needed to show the operating status of a gloved box and its main supporting ventilating system. Day-to-day assessment of filter status can be made by observing the pressure drop across the filter and the air (gas) flow rate. When operator attendance is not continuous and when air flow reductions result in unsafe conditions, automatic alarm devices must be provided. Controls to automatically correct faulty operation may be included in a system if a single simple action, such as operating a solenoid valve in a parallel exhaust line, is adequate, but the use of an array of intricate control devices should be discouraged because they represent more of a detriment than an improvement in safety.

6.1.10 Human Limitations

The designer of equipment to be used inside and around gloved boxes and enclosures must understand and respect the limitations of the human body. Past experience indicates a lack of coordination in planning in-box equipment arrangements that would ensure continued access to filters in and around gloved boxes after other equipment has been installed. Tasks beyond the worker's reach or out of sight or objects too heavy

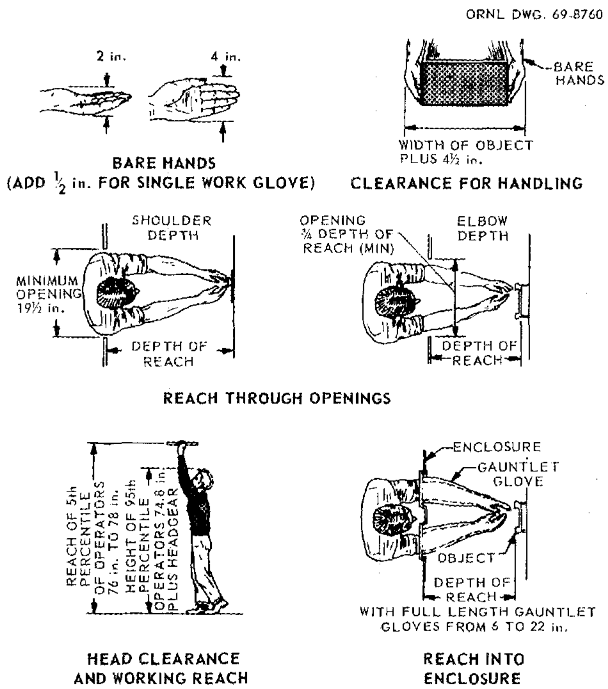

Fig. 6.2. Dimensional guide of critical work limits for male operators in and around gloved boxes.

to lift impose unrealistic requirements and lead to neglect of items that are difficult to maintain. Working within an enclosure with full-length flexible gloves imposes unnatural limits on body senses, and the depth of reach into an enclosure should be limited to between 6 and 22 in., as shown in Fig. 6.2. A depth of reach less than 6 in. is awkward for the hands, from 22 to 29 in. is difficult and tiring, and a depth over 29 in. is impossible to reach with both hands. A depth of 25 in. is the nominal limit for both hands. Other critical work limits for operators in and around gloved box equipment are shown in Fig. 6.2; the data are based in part on information given in *Human Engineering Guide to Equipment Design,*[14] where the values are those convenient for 95% of adult males.

6.1.11 Equipment Limitations

Coupled with human limitations are other limitations on the type of equipment that can be used inside gloved boxes or enclosures. The limited box space hampers the use of bulky power tools for filter maintenance just as it does for process operations. Small self-contained (battery powered) tools can be used for in-box work as long as they do not discharge harmful sparks, fumes, oil mists, or debris inside the enclosure. These tools should be enclosed in plastic film, if possible, to limit box contamination. Sharp cornered or pointed objects, such as drills and cutting blades, must be used with extreme caution to protect gloves and bagging materials. Simple hand tools such as reversible ratchet sockets, box-end wrenches, adjustable-end wrenches, and even a vise modified for wrench tightening are adaptable for use inside gloved boxes. When tools used for process work inside the enclosure are available, they may be used for filter maintenance also.

[14] Morgan, Cook, Chapanis, and Lund, editors, *Human Engineering Guide to Equipment Design,* McGraw-Hill, New York, 1963.

6.2 SELECTION OF FILTERS

6.2.1 Limitations of HEPA Filters

Open-faced HEPA filters are least costly and should be given first consideration for use in gloved box filtration systems. However, no single type of construction can meet all filtration requirements. Open-faced and enclosed HEPA filters with hose connections have the following *undesirable* features for gloved box use:

1. Exposed-medium open-faced filters are subject to damage during handling and storage.
2. Lack of a handle or gripping area for ease of transport.
3. Lack of visible means of detecting damage to the medium.
4. Insufficient holding capacity for large amounts of dust unless a prefilter is used.
5. Chemical fumes, such as hydrofluoric acid mist, can destroy filter medium and adhesives rapidly.
6. It is difficult to replace damaged face gaskets.
7. Sharp edges on metal casings can damage protective bagging.
8. In dry atmospheres (<2% relative humidity) the plywood in wood-cased HEPA filters will shrink and delaminate, causing eventual failure of the filter. This is an acute problem in inert atmospheres, where very low moisture levels (e.g., <50 ppm) may be maintained. In such inert systems, metal (steel) cased HEPA filters must be used.

Enclosed HEPA filters are affected adversely by these additional factors:

1. Currently this type of HEPA filter lacks UL certification.
2. Reeding (induced vibration of separators caused by air motion) at high flow rates is worse than in open-faced filters because the entering air impinges on a smaller area of the filter pack.
3. Greater weight than open-face filters (see Table 3.2 for comparison).
4. Greater cost than open-face filters of equal flow capacity.
5. Greater space required because they are longer than open-faced units.

The types and sizes of HEPA filters used at an installation should be minimized for operating economy. All HEPA filters should be of fire-resistant construction (of verified UL construction, where possible) for better system safety. The features of different HEPA filters are discussed in Sect. 3.2. The sizes most often used in gloved box systems are 8 X 8 X $3^1/_{16}$ in., 8 X 8 X $5^7/_8$ in., and 12 X 12 X $5^7/_8$ in. The size and number of filters required for a gloved box are determined by the maximum flow requirements and the suction pressure available to overcome air resistance. HEPA filters are customarily operated at flow rates below the manufacturer's rating. Reduced filtering efficiency of larger particles can be a limitation at low flow rates in the same manner as the pinhole effect.[15,16]

Since gloved boxes may require normal gas flow rates that are less than 10% of maximum, it is desirable to test filters in place for leakage at both rates. The USAEC Quality Assurance Stations (QAS) routinely test aerosol penetration levels for small filters (<100 cfm) only at rated flows, so other checks must be conducted. For example, when small filters are to be used in hazardous systems where any casing leakage is intolerable, they must be given encapsulation tests to evaluate all portions of the casing rather than just the upstream or downstream portion, as is done normally. Encapsulation testing is performed by immersing the exterior of the filter casing and the upstream face of the medium in an air stream enriched with DOP and sampling the downstream flow to detect leakage of either medium or casing. This procedure is described in more detail in Chap. 7. Multiple-flow testing and complete encapsulation testing for casing leakage require specific instructions both to the manufacturer and to QAS. The procurement of these HEPA filters to such specification will be at an increased cost. Test apparatus now in use at QAS locations may not be capable of conducting individual filter encapsulation testing. A prospective user needing this type of test service should investigate current conditions at his QAS location before finalizing design.

6.2.2 Flow-Pressure Relationship for HEPA Filters

A most crucial relationship in gloved box ventilation design and operation is air flow, box tightness, and the suction capability of the blower or main system. Box tightness is primarily dependent upon the leakage that can be allowed in or out of the enclosure, a subject apart from filtration. For this the designer is referred to publications on gloved box and enclosure construction.[1,4,6] Figure 6.3 gives approximate air flow vs pressure drop relationships that are representative of clean open-faced HEPA filters. Beyond an air flow rate approximately twice standard capacity, laminar flow gives way to a turbulent condition, causing the pressure drop to rise rapidly. Immediately after installation, while filters are still clean, the measured pressure drop across the HEPA filter can be used to establish the air flow to a good degree of accuracy by proportioning the measured drop to that stamped on the filter case (as

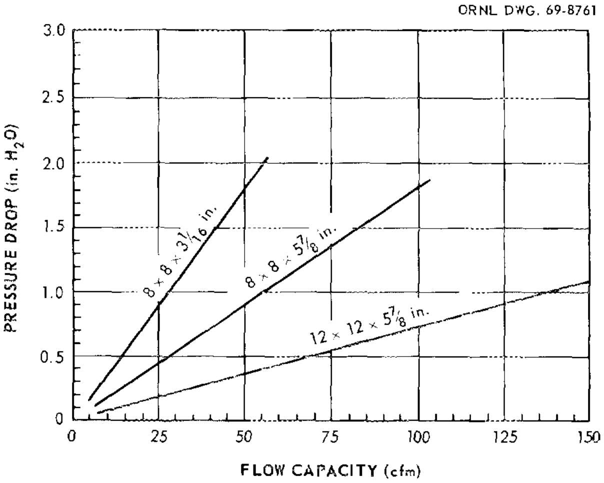

Fig. 6.3. Flow vs pressure drop relationship for small clean open-faced HEPA filters. Based on medium velocity of 5 fpm at rated air flow for filter.

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[15] R. H. Knuth, "Performance of Defective High-Efficiency Filters," *American Industrial Hygiene Association Journal*, vol. 26, November–December 1965.

[16] F. E. Adley and D. E. Anderson, The Effect of Holes in the Performance Characteristics of High-Efficiency Filters, HW-77912 Rev. (September 1963).

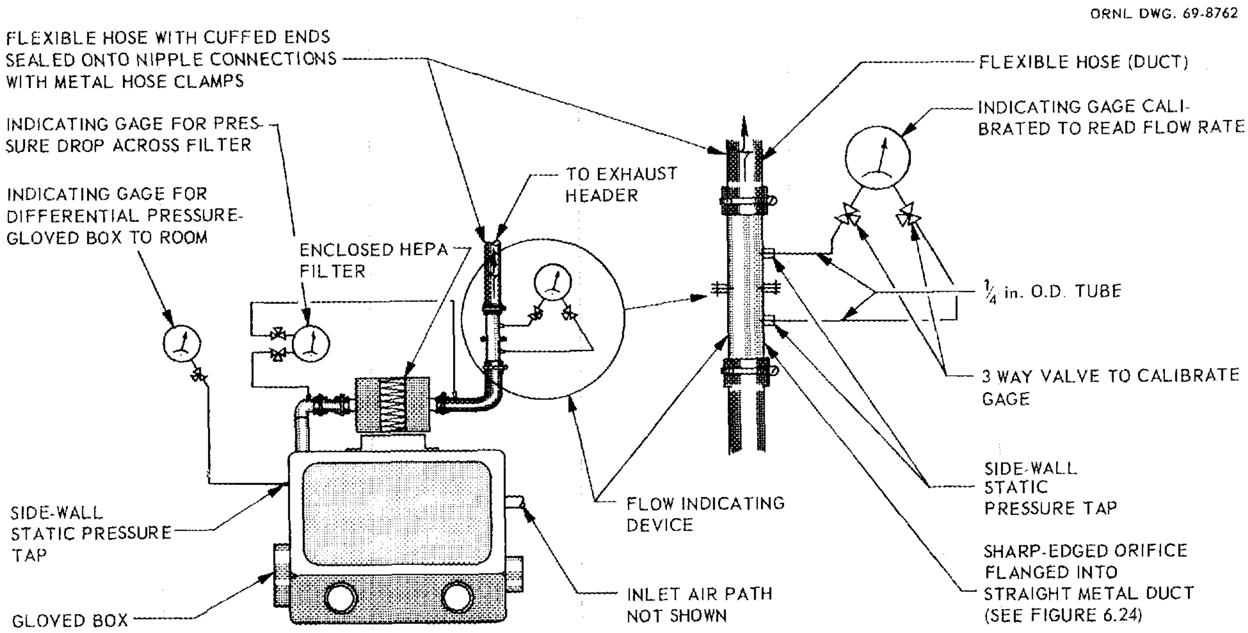

Fig. 6.4. An instrumented enclosed HEPA filter in exhaust duct outside gloved box with flow indicating device downstream.

measured at rated air flow) at the time of inspection. After HEPA filters have accumulated dust, the pressure drop across the filter is no longer a dependable indication of gas flow rate. Therefore, after a filter is in service it is necessary to measure both the pressure drop across the filter and the air flow through it to evaluate its status and relation to the whole ventilation system. Air flow instrumentation, such as that shown in Fig. 6.4, must be installed to measure flow.

6.2.3 HEPA Filters for Inlet Air Service

The work performed within gloved boxes frequently requires that interior spaces be kept free of particles from outside the box. Inlet air filters help maintain clean conditions inside and, when chosen properly, serve two other useful functions: (1) The service life of the exhaust filter may be greatly extended when inert dirt loading alone (i.e., pressure rise) controls replacement time. (2) The expulsion of airborne particles from the inlet is minimized by the inlet filter should the gloved box become pressurized from a fire, explosion, gas release, etc. When not limited by a backflow restrictive device such as a backflow damper, the inlet air channel is a direct relief path to the room for pressure in the gloved box. When explosion, fire, or the sudden pulsing of gloves in a limited box volume can pressurize a box containing hazardous materials, the use of an HEPA filter (with or without a prefilter) in the inlet is recommended. One approved method of application is shown in Fig. 6.5. Note that although no prefilter is shown upstream of the HEPA filter in this example, its use is recommended when airborne particles would shorten the life of the inlet HEPA filter appreciably.

Inlet air filters are much easier to maintain than HEPA filters in the gloved box exhaust. Although inlet filters collect more dirt in normal use, they collect far less of the contaminated material within the box than exhaust filters do, and ideally they should collect none. Therefore they provide fewer problems and less risk during changes. Whether inlet air filters are mounted inside or outside the gloved box (outside mounting is preferred) the same high quality of mounting, clamping, and sealing is required.

There are no objections to the use of a wood-cased fire-resistant (UL labeled) HEPA filter on the inlet to a gloved box. Such a filter should be DOP tested in the same manner as any HEPA filter in a protective system.

6.2.4 HEPA Filters in Exhaust Service

Choosing the appropriate size and construction of HEPA filters for gloved box exhaust service is difficult because accurate operating conditions are difficult to determine in advance. A knowledge of the filter limitations discussed in Sect. 6.2.1 helps the designer avoid obvious mistakes but does not help him make the

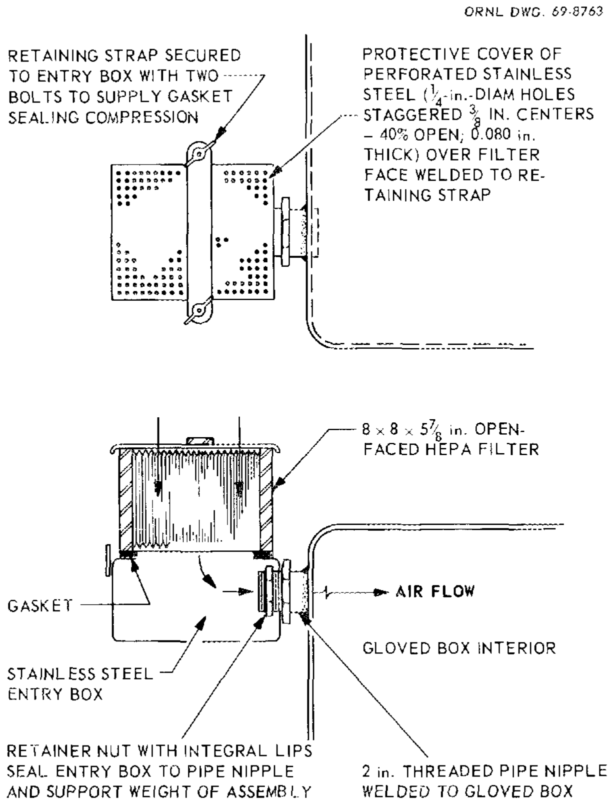

Fig. 6.5. Gloved box air inlet with HEPA filter.

best choice. A detailed discussion on filter performance and construction materials is in Sect. 3.2. Operational experience with a particular system remains the only reliable measure for selecting the best HEPA filter. For new and untried systems the initial choice should be limited to standard types (Sect. 3.2). Adopting new types of HEPA filters having special features, size, or materials is no guarantee of the most economical or reliable system operation. If exhaust streams are kept chemically neutral, as they should be for reliable exhaust system operation, HEPA filters of standard construction will afford the most economical filter choice.

6.2.5 Prefilters

As in larger systems, prefilters may be used in both the inlet and exhaust air streams to extend the life of the HEPA filters used in gloved box filtration systems. Prefilters are sacrificial items whose use is primarily intended to extend the life of HEPA filters situated immediately adjacent or downstream, and the decision to use them requires that the designer evaluate the advantage of longer HEPA filter life against the problems of limited space and the need for increased fire safety frequently encountered in gloved box systems. This type of service often requires that filters inside gloved boxes be subjected to periods of high temperature, moisture, dust, and corrosive agents that shorten the effective life of filters and mounting accessories.

Experience with prefilters in gloved box ventilation systems has shown the use of filters with metal media to be impractical. Without viscous coatings, their filtering efficiency is poor, and they are almost impossible to clean and decontaminate. Adhesives and oil coatings that improve filtering efficiency interfere with in-box cleanliness and lessen fire resistance. The experience of gloved box users where toxic materials are handled also clearly indicates that it is not practical to use conventional types of prefilters that require cleaning and/or decontamination of parts before reuse. Throwaway items with simple installation methods are preferred, and after use the units are discarded as contaminated waste unless the collected materials must be reclaimed. Users have preferred fiber glass or synthetic fibrous or porous media for in-box prefilters because their serviceability is good, costs are low, and combustible content is small.

Inlet air streams having HEPA filters require prefilters when using atmospheric air. However, when the room air has been cleaned of the bulk of its airborne dust by building air supply systems and when local room activities do not generate dust that is drawn into the inlet to the box, there is no need for a prefilter ahead of an inlet HEPA filter because it will not improve the life of the HEPA filter significantly. A perforated metal face guard (e.g., $\frac{1}{4}$-in.-diam holes staggered on $\frac{3}{8}$-in. centers – 40% open) to protect the HEPA filter, as shown in Fig. 6.5, is useful.

Where work involves radioactive contamination inside gloved boxes, a typical method of prefiltering is to use a thin pad of filter medium on both the inlet and exhaust air streams, as shown in Fig. 6.6. The pad is cut to fit the face of the HEPA filter and is clipped onto the HEPA filter retainer. This method of attachment permits easy removal of the prefilter pad without disturbing the seal of the HEPA filter. Normal usage will require that the prefilter pads be replaced frequently, because thin pads, $\frac{1}{4}$ in. thick or less, of fiber glass media do not have much dirt holding capacity and house dust and linters can clog them quickly. Therefore convenient and separate methods of attaching the prefilter pads are essential. Frequent replacement of prefilter pads with the resulting lighter dust loading assures that

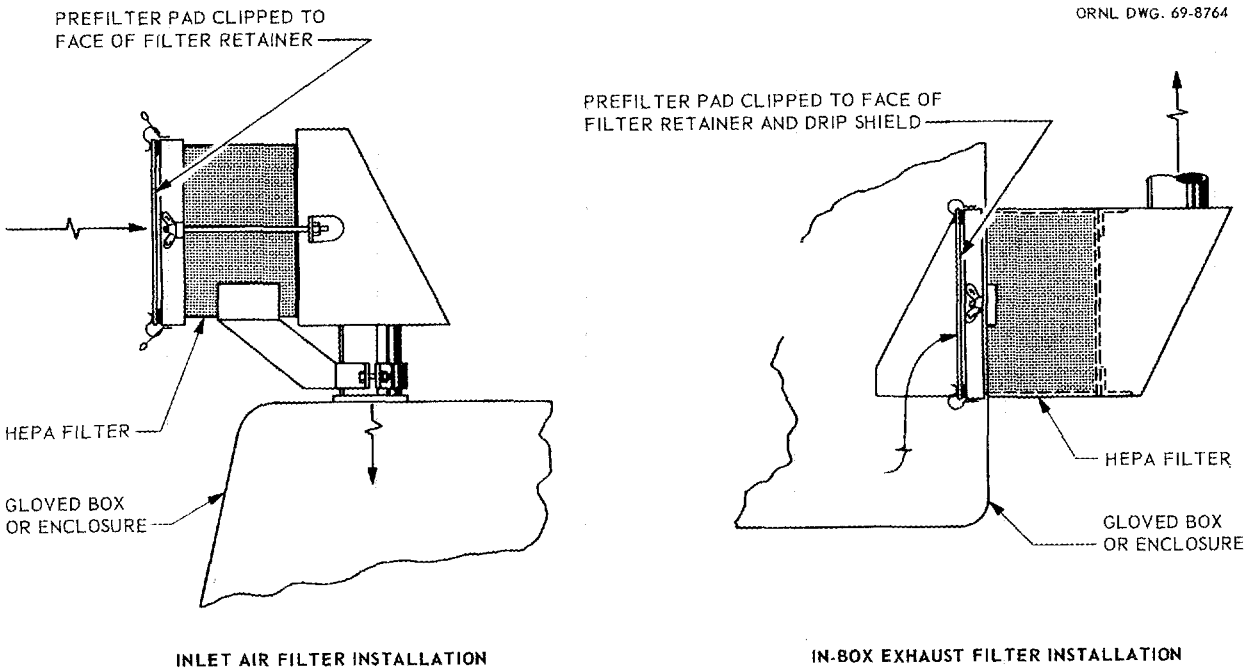

Fig. 6.6. Typical installations of prefilter pads on face of HEPA filters.

Table 6.1. Media Usable as Prefilter Pad

Medium	Thickness (in.)	Initial Pressure Drop (in. H_2O)	Velocity (fpm)	Collection Efficiency NBS[a]	Collection Efficiency AFI[b]	Remarks
Owens-Corning Fiberglas Corp., RE-1	3/16	0.05	35	20%		
American Air Filter Co.						
Type G Airmat	3/32	0.03	35		87.5%	Class 1 Underwriters' rating
No. 12 Airmat	1/4	0.09	35		95%	Class 1 Underwriters' rating

[a]Clean efficiency – National Bureau of Standard test method using atmospheric dust.
[b]Average arrestance – Air Filter Institute Code test method.

1. air resistance (pressure drop) through the exhaust path does not change rapidly, thereby allowing air flows to remain nearly constant without frequent manipulation of dampers;
2. the accumulation of combustible dust in the exhaust path is less, thereby providing better fire protection for the HEPA filter downstream;
3. the exhaust path can pass greater air flow rates in relieving an emergency condition, for example, clearing smoke quickly during an in-box fire so that vision may be restored.

Fiber-glass pads 1/4 in. thick or less can provide collection efficiencies up to 20% NBS[17] with low air flow resistance. Thin (1/4 in. thick or less) clean fiber-glass pads used at air velocities of ~35 fpm will create an initial pressure drop in the range of 0.03 to 0.15 in. H_2O. Table 6.1 lists several types of medium that can be used as prefilter pads.

For applications where long-term continuous processes hamper regular maintenance of in-box filters the

[17]Clean efficiency – National Bureau of Standard test method using atmospheric dust.

designer must include

1. provision for greater suction pressure (up to the safe limit that will not implode the box or gloves), controlled by damper, to allow for longer use of prefilters;
2. provision for more prefilter area; or
3. selection of a prefilter with less initial resistance to permit longer use, even though compromising collection efficiency.

6.3 INSTALLATION OF FILTERS

Common locations for HEPA filters near or inside gloved boxes are schematically diagramed in Fig. 6.7. Type *2C* shows inlet and exhaust filters inside the gloved box.

All operations inside gloved boxes are required to be convenient and safe for the operator. The designer must thoroughly study the planned location and operation of process equipment in order to be certain that in-box filters will be well arranged. Locations for filters must permit convenient maintenance, testing, and inspection. Choosing a position that is naturally shielded or protected from splashing liquids, flying missiles, or areas of greater fire potential are additional considerations in determining filter locations.

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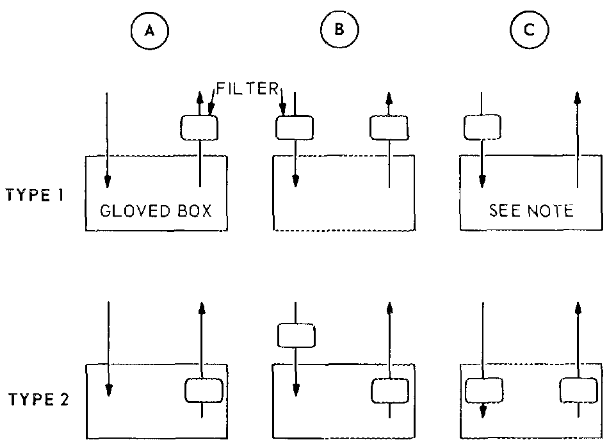

NOTE: TYPE IC IS NOT SUITED FOR CONTAINMENT OF RADIOACTIVE MATERIALS WITHIN THE GLOVED BOX BUT IS APPLICABLE WHERE THE INTENT IS TO EXCLUDE AIRBORNE PARTICLES FROM THE GLOVED BOX SPACE.

Fig. 6.7. Possible arrangements of filters near or inside gloved boxes.

Generally, filters are spoken of as inside and outside the gloved box, meaning that they are accessible from either the inside or the outside of the box rather than how they appear to be positioned. The materials of construction used for filter mounting devices and associated hardware inside the gloved box must provide an operating life comparable with that of the box itself. Stainless steel should be used for those inside pieces of equipment that will be subjected to corrosion and/or abrasion. The construction tolerances for dimensions and sealing faces of filter mounting devices used for gloved boxes should be equal to those for mounting frames in multiple-filter systems given in Table 4.2. Where the mounting is an integral part of the gloved box, the construction tolerances must be consistent with those of the box but never more lax than those values given in Table 4.2 if high-efficiency performance is to be attained.

6.3.1 Mounting Devices

There is a limited choice of commercially available prefabricated filter mounting devices suitable for gloved-box operations. One example is the Mini-Caisson housing shown in Fig. 6.8, which is marketed by the Nuclear Safety System Corporation. This housing normally uses open-faced HEPA filters with dimensions of 8 × 8 × 5⅞ in., and a larger size uses 12 × 12 × 5⅞ in. filters. This unit is located outside the gloved box, connected to the ducts, and is adaptable to the bagging method of filter change. However, this mounting device used alone is not sufficient for systems containing materials of high radiotoxicity (Tables 2.2 and 2.3) because it can allow leakage of particles to the downstream side during filter change, and therefore must be supplemented with additional high-efficiency filters downstream, or by other means of radioactivity confinement. To prevent leakage of contaminated air during a filter change, this housing must be provided with a tight sealing air damper (valve in the downstream side of the duct) as shown in Fig. 6.9. Although not essential for most gloved box service, a second damper may be desirable on the upstream side to relieve any suction that hampers filter bagging caused by other exhaust connections serving the same gloved box (multiple connections) or gloved box line.

Total costs for using a commercial housing that employs open-face HEPA filters are greater than costs for mounting devices made integrally with a box such as illustrated by Fig. 6.6. Therefore the designer planning an installation should make a complete cost evaluation to determine the most economical method of mounting

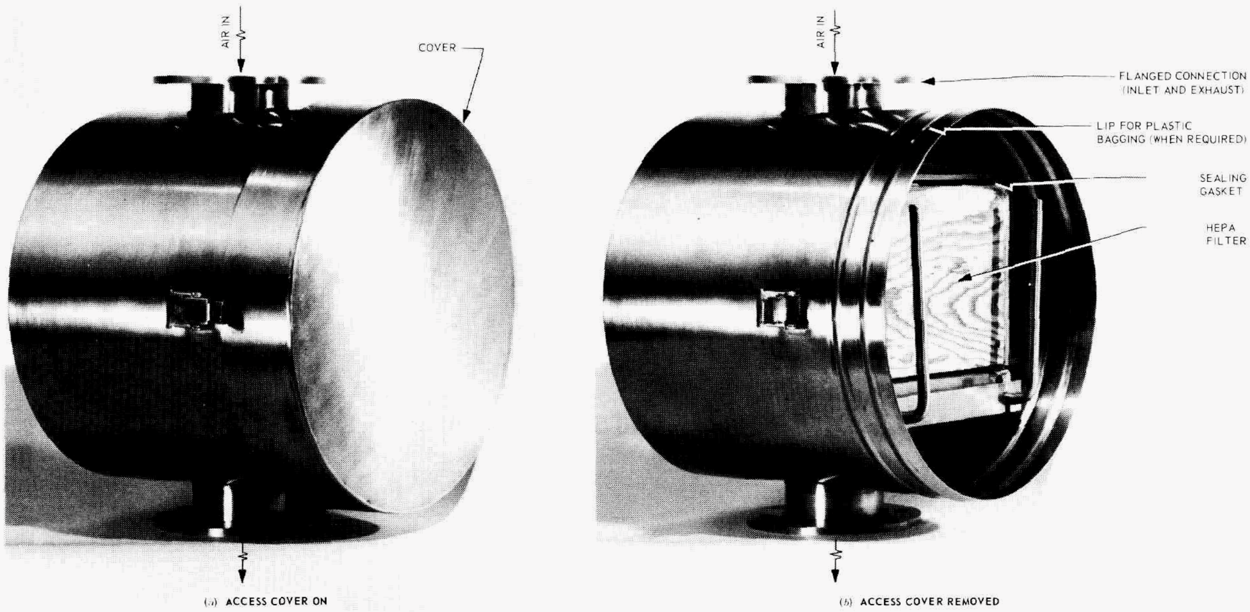

Fig. 6.8. Mini-Caisson housing for open-face HEPA filters. Courtesy Nuclear Safety Systems, Inc. (S.G.N.).

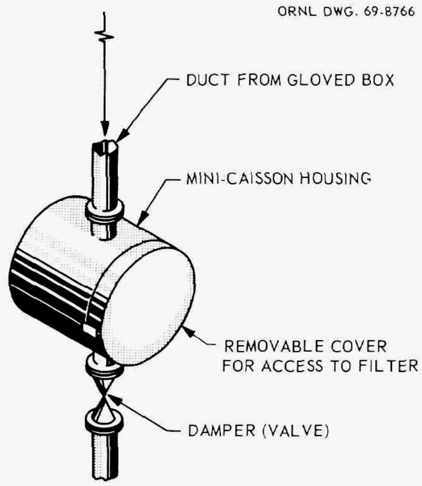

Fig. 6.9. Typical connections for a Mini-Caisson housing.

filters that will achieve the desired performance. There is little opportunity to realize cost savings through the use of prefabricated devices (housings) in installations designed for one, two, or three years of service as may be true for those designed for long-term service (>5 years). Another factor that must be considered is the number of filter mounting devices that may be required. Manufacturers vary widely in experience and shop capability for making gloved boxes and accessories like filter mounting devices. To obtain realistic comparisons, cost analyses of two or more design arrangements must be made by the same estimating source, because estimators may assign significantly different values to fabrication features such as quality welding and leak-testing welds. Lower costs can be obtained when designs remain within the limits of shop capability of prospective suppliers.

Equipment costs for the commercial housing shown in Fig. 6.9 installed in a duct outside a gloved box are compared with costs for the enclosed filter installation shown in Fig. 6.4 in the following tabulation. Only filter equipment costs are included.

Commercial housing	
Estimated cost of stainless steel housing	$300
Cost of first open-face wood-cased HEPA filter (8 × 8 × 5⅞ in.)	20
Subtotal	$320
Enclosed filter	
Cost of 50-cfm steel-cased enclosed HEPA filter	$ 50
Difference in first costs	$270
HEPA filter replacement costs	
Enclosed filter	$ 50
Open-face filter	20
Difference, per change	$ 30

Number of filter changes after initial installation required to equalize equipment costs = 270/30 = 9

Since economy is dependent upon the frequency of filter change and the life of the installation, the designer must estimate time factors to make the comparison accurately. Experience at many installations indicates that the majority of HEPA filters used in gloved box systems will last longer than 6 months of continuous operation and often longer than 18 months, when conditions are unusually clean or use is intermittent. Using a filter change frequency of six months, the cost comparison above indicates no equipment cost advantage for use of a housing costing $300 or more unless the life expectancy of the installation is more than five years of continuous use.

The preceding cost comparison does not include installation or maintenance costs. A close analysis indicates that under ordinary circumstances installation costs using either a prefabricated or a custom-built housing exceed those for installations using an enclosed HEPA filter with hose connections. Although more difficult to separate and estimate, total costs (installation and operation) for HEPA filters installed inside gloved boxes are less than those for installation using exterior filter housings. However, total costs for in-box filter installations (using standard-size filters) are about equal to those for installations using enclosed HEPA filters in ducting outside the gloved box. The cost advantages for any type of installation can easily be outweighed by operational requirements or if the lack of space makes the desired scheme impractical.

6.3.2 Mounting HEPA Filters Inside Gloved Boxes

Access to filters mounted inside a gloved box (also termed in-box) is a major concern after the internal process equipment has been installed. When mounting an inside filter, space needed for permanent equipment or items too delicate to move must be respected. Certain dimensional limitations on inside filter arrangements are set by human reach limits, as shown in Fig. 6.2, since gloves on the box must be used to change the filter. The tasks that must be performed to change the filter must therefore be kept as simple as possible, and the mounting equipment must have smooth surfaces with rounded corners to prevent damage to the gloves.

One approved or recommended mounting arrangement for an open-face HEPA exhaust filter in the back or side wall of a gloved box is shown in Fig. 6.10. A perforated plate retainer guards the open face of the filter, and no prefilter is used unless coarse particles are made airborne in the box. The wall of the box serves as the sealing face for the gasket. Flatness and dimensional

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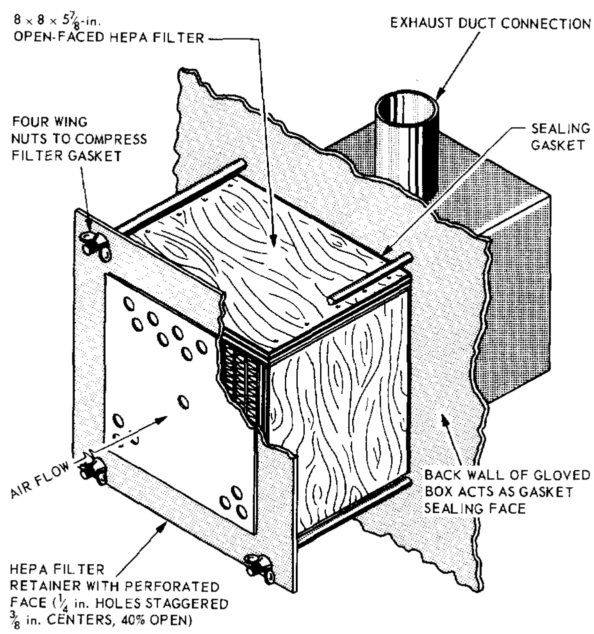
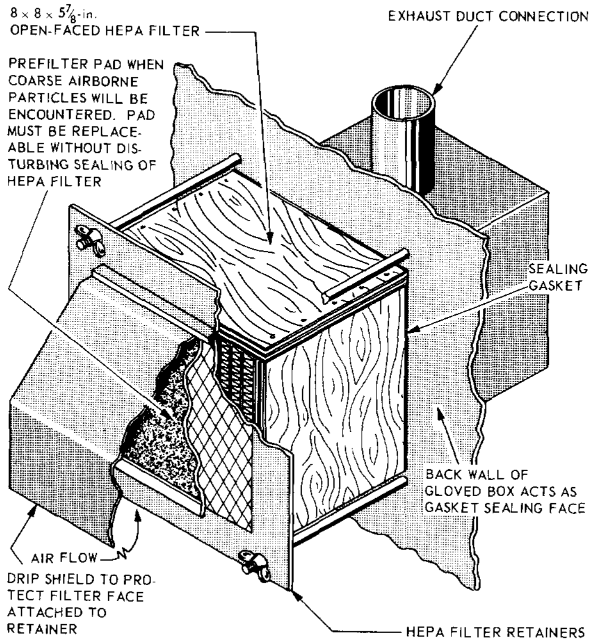


(*a*) WITHOUT DRIP SHIELD

CAUTION: AREA OF PREFILTER MUST BE KEPT SUFFICIENTLY LARGE SO MAXIMUM AIR FLOW RATES CAN BE ACHIEVED WITHIN AVAILABLE PRESSURE DROP LIMITS.



(*b*) WITH DRIP SHIELD AND PROVISION FOR PREFILTER

Fig. 6.10. Recommended methods for mounting open-faced HEPA exhaust filter inside gloved box (in-box).

stability are needed to ensure good gasket seating. To change the filter in this arrangement, the operator, using the box gloves, removes the four wing nuts and the perforated face plate retainer to free the filter. If the four wing nuts are not large enough for gloved-hand operation, a tool is required. When a filter is mounted against the back wall of a gloved box, it reduces available work space, especially when the filter is located directly opposite a glove station. Less work space is lost if the filter mounting is situated to the immediate right or left of the glove station. Adding an extra glove can improve access even more, further reducing the use of prime space for the filter.

Another acceptable method of mounting an open-faced HEPA exhaust filter inside a gloved box is shown in Fig. 6.11. By having a separable exit box, this style of inside mounting permits the filter assembly to be removed or rotated to accommodate changes in box use. The assembly is supported by the 2-in. pipe that protrudes through the wall of the gloved box. However, the filter sealing gasket is not completely visible for inspection in this arrangement. This particular mounting method has a companion inlet air filter mounting arrangement, shown in Fig. 6.5, external to the gloved box, which uses accessories of identical design. This practice reduces the number of different parts that must be kept on hand.

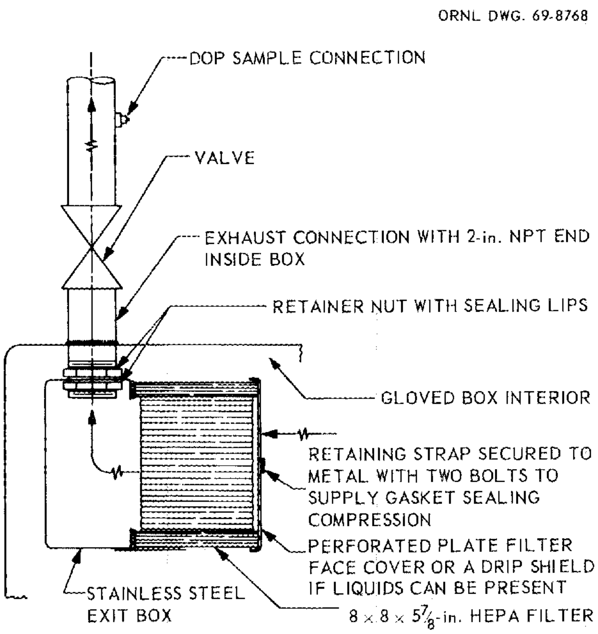


Fig. 6.11. Open-faced HEPA filter with exit box mounted inside gloved box (in-box) for exhaust service.

Fireproof adhesive tape has been used to seal in-box wood-cased filters when there are other HEPA filters downstream. Gaskets are not used when filters are taped in position, because no means is provided for their compression. The weight of the filter is supported by a ledge or niche on the box wall, while the tape provides the seal. This sealing method does not assure maximum particle collection efficiency and can leak seriously when subjected to fire (heat) or displaced tape. Taping HEPA filters in place should be limited to low-level contamination systems where leakage can be tolerated and fire potential is nil. One method of taping an open-face HEPA filter inside a gloved box is shown in Fig. 6.12. The opening (niche) in the back wall of the box has a protruding lip on all four sides to receive approximately half the 2-in.-wide sealing tape. The other half width must adhere to the sides of the filter case. This type of seal rules out the use of metal-cased filters, because they do not have smooth surfaces at corners.

Several pertinent features of an in-box filter mounting are illustrated in Fig. 6.13. The desirable features of this arrangement include

1. the use of a standard size HEPA filter located in the back or end wall of the gloved box,
2. the use of less inside box space by partially recessing the filter in the wall,
3. a simple clamping method with no removable pieces that is operable with a gloved hand by actuating a spring-loaded (snap-over-center) easily replaceable cam latch on each side of the filter,

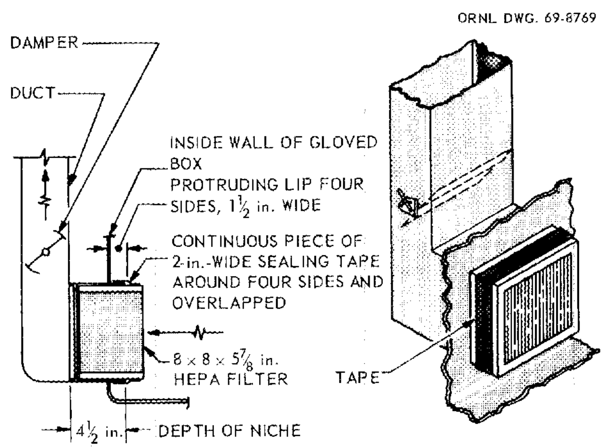


Fig. 6.12. Open-face wood-cased HEPA filter inside gloved box (in-box) with tape seal.

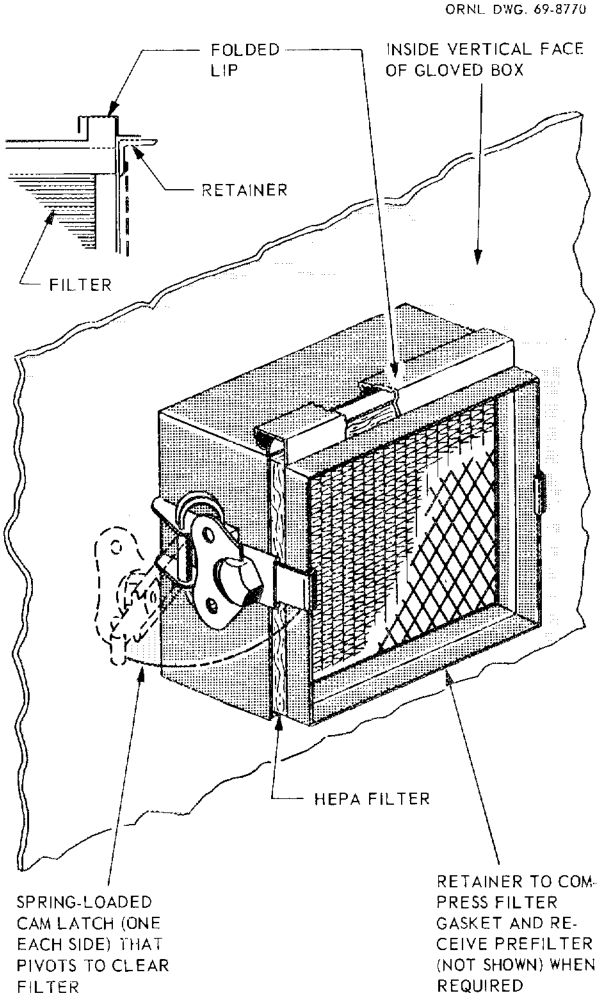


Fig. 6.13. Inside gloved box open-face HEPA filter mounting arrangement with cam latches.

4. a retainer that serves as a face shield for the filter, that permits attachment of a prefilter pad via flexible magnetic strip (accessible from the front), and that remains in position after being unclamped because of the folded lip at top.

A drawback to this arrangement is the inability to inspect gasket and sealing face area while the filter is in place. There could be other drawbacks for specific applications. There is no single mounting arrangement with no disadvantages, and an intelligent compromise must be made for each application.

6.3.3 Mounting HEPA Filters Outside Gloved Boxes

The use of valuable space inside gloved boxes for mounting filters is not always acceptable in spite of the in-box mounting advantages of easier control of containment and faster filter change. The advantages of outside filter mounting include the opportunity for better fire protection for the filters by being more displaced from the box, conservation of in-box space, and the possibility of lower cost. All outside filter mountings do not automatically provide these advantages; a poor mounting job can create serious handling problems as well as compromise the containment features of the box.

Two commonly used methods of outside gloved-box filter mounting are shown in Fig. 6.14. These two methods are *inadequate* for operations involving toxic or radioactive materials at any but the lowest level (e.g., Class 4 – Table 2.3). Although simple in appearance, and certainly cheaper than filter housings, these methods make filter replacement a very tedious and delicate operation if spillage of contaminants is to be prevented. Being outside and nearby the gloved box, the risk of contaminating the local area is higher than for housings that enclose the filter, or the use of enclosed HEPA filters as shown in Fig. 6.4. The use of tools to remove bolts makes it necessary for the filter to be located within convenient reach, preferably from the floor. High locations (Fig. 6.14*b*) that require ladders for access make handling less safe both for filter handling and for the gloved boxes nearby.

When outside filters are sandwiched between two flanged faces, precise alignment of gasket seating surfaces is essential to ensure uniform gasket compression.

Misalignment of surfaces will not only cause nonuniform gasket compression but further the chance of

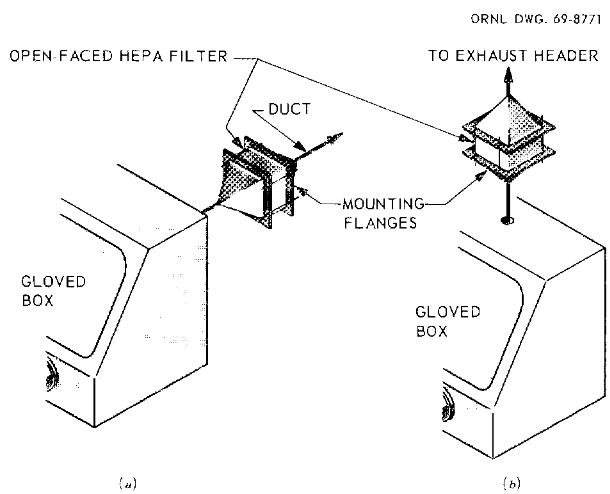


Fig. 6.14. Two examples of methods of mounting HEPA filters outside gloved boxes that are not recommended.

leakage both for particles and for condensed moisture at the gasket surfaces. Rigid ducting can cause bolt pull-up forces to strain the wall of the gloved box or joints in the ducting itself. The designer must remain aware that pull-up forces for double-gasket mountings are significantly more than for single-sealing-gasket mountings. A short section of cuffed flexible hose on the downstream side of the filter is one method of relieving strains, but this does nothing to lessen the gasket sealing forces. Though data on filter casing strength are inconclusive, experience has clearly shown that both wood and steel filter casings can be ruptured by unlimited pull-up.

Much operating experience has been gained relevant to the use of enclosed HEPA filters outside gloved boxes. Typical examples of this type of installation are shown in Figs. 6.4 and 6.15. Both flanged and nipple-end enclosed filters have been used, but the nipple-end enclosed filters are more common and easier to install. The integral casing caps help enclose the dirty filter medium and make filter changing a less difficult and risky task than with open-faced filters. As shown in Fig. 6.15, the exhaust ducts are flexible hoses with cuffed ends sized to suit the duct nipples on the enclosed filter. Initial installation costs for enclosed HEPA filters mounted outside gloved boxes (Fig. 6.15) are always less than for adequate filter housings outside gloved boxes.

Important features of a filter installed outside a gloved box in which the filter can be bagged in and out

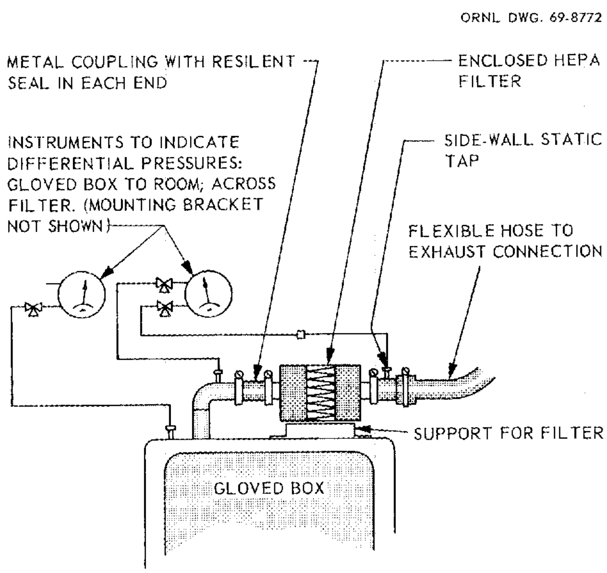


Fig. 6.15. Acceptable enclosed HEPA filter installed in exhaust outside gloved box.

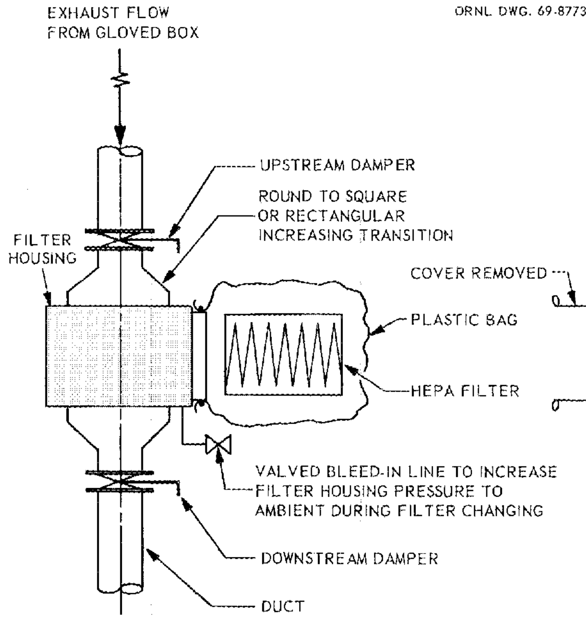


Fig. 6.16. Typical connection for a single-filter housing in a gloved box exhaust stream.

are shown in Fig. 6.16. If filter change by bagging is not necessary for containment, the operation can be simplified by direct handling methods, and the valved bleed-in line will not be needed. The arrangement for the Mini-Caisson housing shown in Fig. 6.9 is comparable with the arrangement shown in Fig. 6.16 except for the valved bleed-in line and the dampers required to stop air flow and isolate the housing from the ducts. For applications requiring filters to be bagged in and out the procedure is like that discussed in Sect. 5.1.1 with the aid of Fig. 5.2.

6.4 FILTER MAINTENANCE

Various maintenance methods can be used for gloved box filters. Those installed inside the box must be accessible by use of the gloves on the enclosure. When the total activity of contaminants is high, protective measures must be employed during filter changing to lessen worker exposure and loss of contaminants to the environment outside the gloved box. One method of controlling the spread of contamination, while preserving the integrity of the closed box and the system, is bagging the used filter out and the new replacement filter into the contaminated zone. The plastic bagging materials used are discussed in Sect. 5.7, and the changing procedure for a gloved box is illustrated in Fig. 6.17. This technique (Fig. 6.17) is used when total

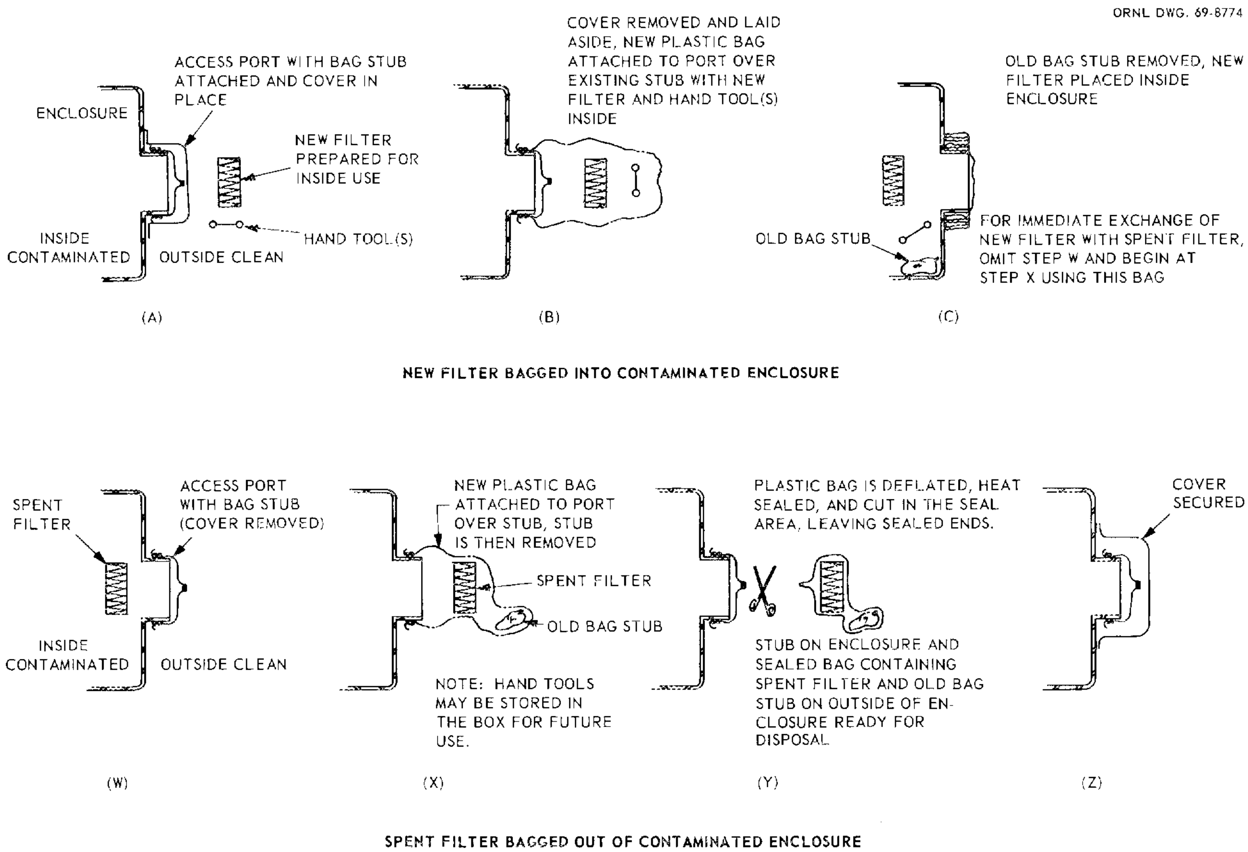


Fig. 6.17. Technique for changing filters used inside contaminated enclosures.

containment is necessary, that is, where even minute leakage to the room cannot be permitted. When inert atmospheres or oxygen-free environments are used inside the gloved box, stringent provisions may be required to prevent air leakage into the box, and bagging may still be needed to prevent the escape of toxic materials.

Replacement of an HEPA filter inside an air-ventilated box entails many steps that must be performed sequentially. Each step must be carefully completed in a methodical manner to ensure continuous closure of the system. A filter change must be planned by maintenance personnel with those in charge of gloved box operations to establish a mutually satisfactory date and time of change, to identify the boxes and systems involved, to procure the needed items, and to schedule operating and maintenance personnel for the work. The health and safety requirements of the industrial hygienist, health physicist, or safety officer must be established, and he should be available to assist. After the necessary materials and tools have been readied and on hand and all personnel have been instructed in their specific duties, final permission must be secured from the responsible operator to alter air flow and replace filters. Then the required safety clothing and gear should be donned as directed by the health and safety supervisor. The steps required to change a filter and place a box back in service are as follows.

1. Cease all gloved box operations, and store unsafe materials in suitable containers.
2. Cut off gas flow to the filter to be replaced, and adjust flow through the remaining branches to restore a safe negative pressure or flow rate for the box.
3. Bag in (*a*) a clean replacement filter (and prefilter if used), with gaskets in position and adhesive dry, (*b*) a small clear plastic bag with sufficient tape to hold the spent filter and prefilter, and (*c*) hand tools required, as shown in steps *A*, *B*, and *C* of Fig.

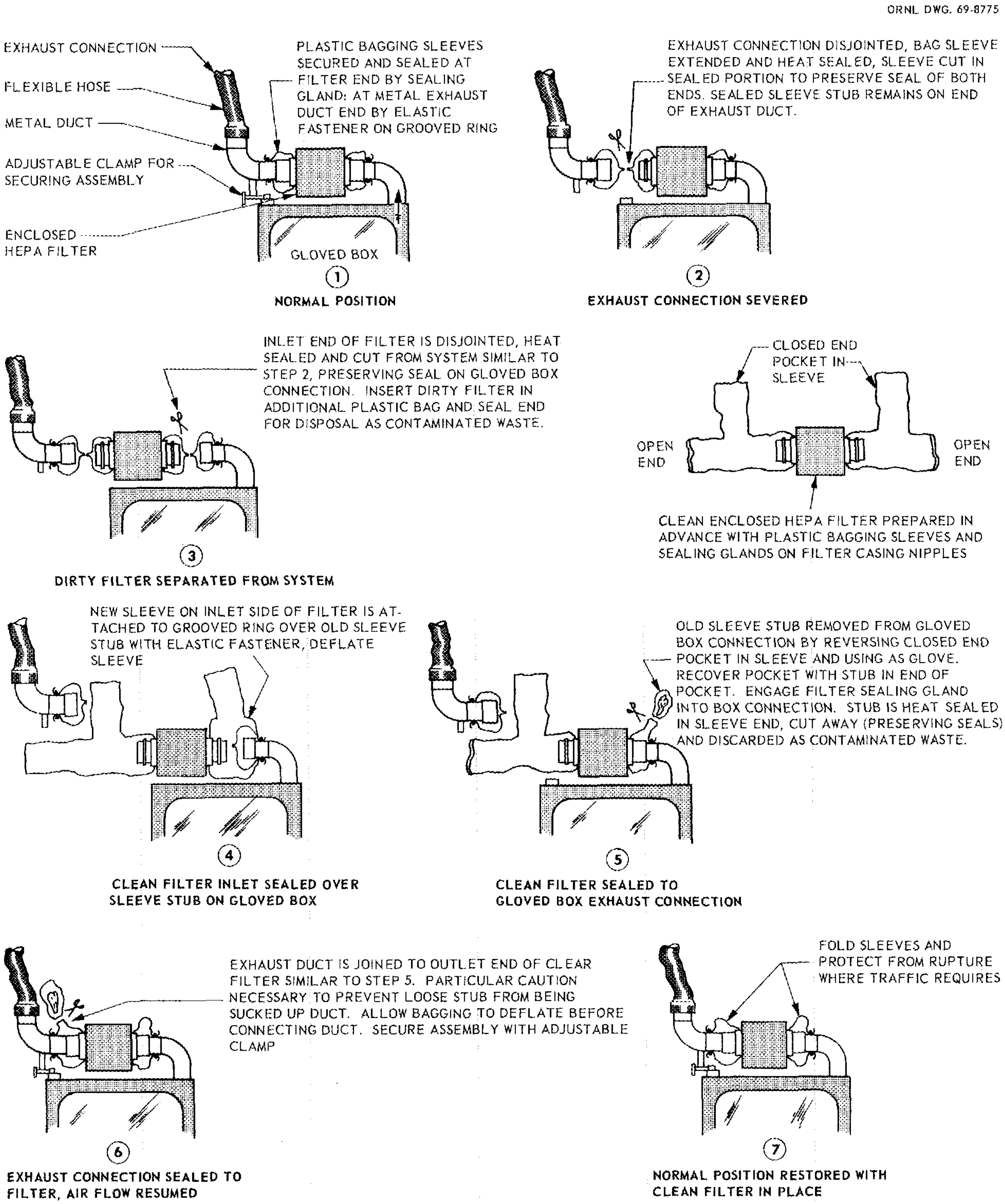


Fig. 6.18. Bagging technique for enclosed HEPA filter located outside the gloved box.

6.17. Hand tools needed for filter changing are introduced during the first change operation and are left in the gloved box for subsequent use if space and environment permit. Decontamination is more costly than replacement for many hand tools.

4. Using the gloves on the box, remove the dirty filter and prefilter from their mounting frame. Exhaust flow through this path must be completely stopped if unfiltered leakage is to be prevented.

5. Insert the dirty filter and prefilter into the empty clear plastic bag, slowly expel excess air from the bag, and seal it with tape.

6. After sealing the dirty filter, inspect the gasket sealing face of the mounting frame, and clean it if necessary. Place the replacement filter in position, and secure the clamping devices. Place the prefilter in position and secure it.

7. Remove the dirty filters and all debris from the gloved box, as shown in steps *W, X, Y,* and *Z* of Fig. 6.17, and place the removed items in a container for contaminated-waste disposal.

8. Restore air flow through the filter, and regulate flow or negative pressure throughout the system.

9. Before gloved box operations are resumed, test the newly installed HEPA filter with DOP, using the permanent test connections on the housing. If the test result is not satisfactory, stop the flow and inspect the filter for damage. If no damage is apparent, reposition the filter, restore the flow, and retest the filter. If the second DOP test is unsatisfactory, the filter should be replaced and steps 3 through 9 repeated. Continued leakage suggests a failure of the mounting frame or a faulty test, and each possibility should be examined in detail until the fault is discovered and corrected.

10. After successful filter replacement, notify the responsible operator so that gloved box operations can be resumed.

Filters located outside a gloved box require convenient access for changing, and it will usually be necessary to interrupt air flow during the change. Being outside the gloved box, highly contaminated filters must be encapsulated during changing. The most

Fig. 6.19. Enclosed HEPA filter being removed from exhaust stream outside gloved box by bagging. Courtesy Oak Ridge National Laboratory.

common method of providing this protection is by using the bagging technique. Different bagging techniques provide different degrees of protection. The approved technique shown in Fig. 6.18 employs the principle of total containment for use when even minute leakage cannot be permitted. This bagging technique seals both ends of the air ducts, and no flow can occur downstream while the filter is removed. When uninterrupted air flow through a box is required, this method of filter change necessitates the use of multiple exhaust connections on the box. An out-of-box filter in the process of being removed from a system by the procedure illustrated in Fig. 6.18 (corresponding to step 3) is shown in Fig. 6.19.

For other methods where the bagging does not block the air flow path (e.g., the housings represented by Figs. 5.3 and 6.16) but merely encapsulates the filter being removed or replaced, there is a strong dependence on the valve in the duct to prevent blow-by (leakage) during filter changing. By close comparison it can be seen that the total containment method (Fig. 6.18) disconnects the exhaust duct and does not depend on valve tightness. The technique of bagging filters from housings (Figs. 5.3 and 6.16) offers protection only for local personnel and the service area where the filter mounting device is located. The side of the system downstream of the filter is protected not by the bagging but by leak-proof dampers and flawless handling of the dirty filter. Obviously, any dislodged particles will be swept downstream when air flow is restored. In instances where loss of contaminating particles can be damaging, additional downstream HEPA filters should be provided to intercept these particles.

6.5 INSTRUMENTATION

Instruments are required to indicate the operating status of gloved box filtration systems, and in some cases automatic devices are required to keep the system in proper operation. The most important indication is the differential pressure between the inside and the outside of the box. When inside pressure is negative relative to the outside, leakage will be inward, and airborne materials will not leak out. Maintenance of a strong differential pressure is not, by itself, sufficient to ensure safe working conditions for many gloved box operations. When a fire or explosion hazard exists from flammable gases or vapors released inside the box, an adequate flow rate for dilution and in-box distribution purposes is necessary to prevent explosive atmospheres, and there must be an instrument to indicate this flow.

Inert gas enclosures require differential pressure indication like air-ventilated boxes, but measurement of recirculated gas flow (throughput) does not indicate a safe concentration of gases in the box. Even with an oxygen-free atmosphere, airborne materials must not be permitted to accumulate when an unsafe condition can result from a ruptured glove, spill, etc. Through inleakage or internal releases it is possible for hazardous gases to accumulate in a recirculating inert gas system where conditions are expected to always remain safe from fire or explosion. Direct-reading monitors (with alarm devices) are employed to detect unsafe gas concentrations.

The minimum instrumentation for a gloved box ventilation system should include devices to indicate differential pressure on the box, filter resistance, and exhaust flow rate from the box. The arrangement of indicating devices in a gloved box ventilation system is diagrammed in Fig. 6.20. Those items shown above the double dashed line in Fig. 6.20 indicate common types of instruments used to supplement the minimum group to improve safety for a particular operation or circumstance. For example, when box operators are not in full-time attendance for a continuous process a sensor can be provided to monitor abnormal pressure or temperature and alarm at a remote point where an attendant is stationed.

6.5.1 Differential Pressure Gages

Figure 6.21 shows a typical mounting for an aneroid-type differential pressure gage on top of a gloved box, usually near eye level. The indicating face should always be located so that the operator has a clear view while manipulating the gloves. Sensing lines need to be short and sloped directly back to the box so that moisture will not be pocketed in the tube. Tubing should be at least $^3/_{16}$ in. ID to allow the instrument to respond quickly to rapid changes in pressure. Using a three-way vent valve at the gage permits easy calibration (zeroing) without disconnecting the sensing tube. Calibrating gloved box differential pressure gages should be a weekly routine.

Most users prefer a gage pressure range of 0 to 1 in. H_2O, but the instrument must have a proof pressure greater than that of the maximum system suction so that it will not become inoperable during a system malfunction. Liquid-filled devices are not recommended for use as gloved box pressure indicators. Liquids can be sucked into the box or filter if the safety traps on the manometer leak, as they often do under prolonged exposure to high pressure. The aneroid-type gage has a

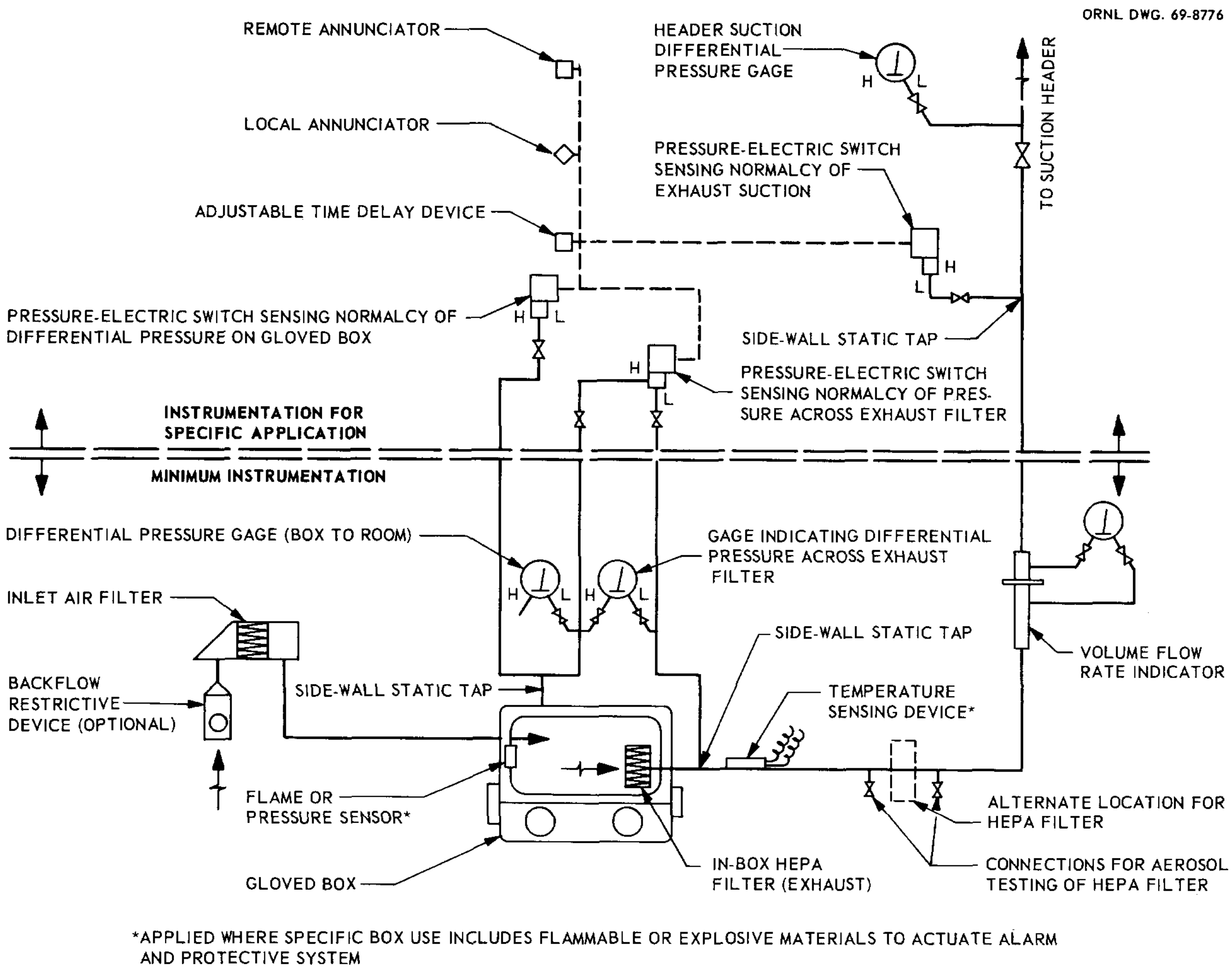


Fig. 6.20. Instruments in a gloved box ventilating system.

diaphragm that seals the path against contamination leakage.

Inlet air filters on air-ventilated gloved boxes do not require the use of differential pressure gages. The pressure drop across the filter approximates the differential pressure on the box space. Inlet flow rates can be measured with portable instruments, such as a portable thermal anemometer, with sufficient accuracy (±15%). When inlet filters become clogged enough to limit the inlet flow below that needed to serve the box, they must be changed.

For exhaust filters, a differential pressure gage to indicate filter resistance assists in predicting needed filter changes. Pressure-sensing connections can be provided that will permit the use of portable instruments. As shown in Fig. 6.20, a pressure switch can be used to actuate an alarm when a selected air resistance limit is exceeded and to announce a loss of suction when the switch is a high-low (dual) pressure device.

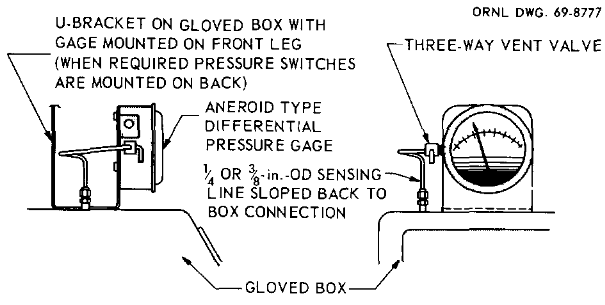


Fig. 6.21. Aneroid-type gage to indicate differential pressure on gloved box.

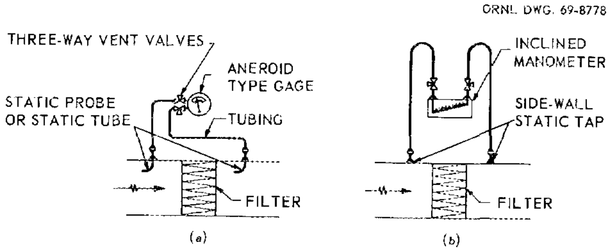


Fig. 6.22. Two methods of indicating pressure drop created by air flow through a filter.

Alarms or controls that must function on small pressure differentials (less than or equal to 0.25 in. H_2O) can be difficult to keep in proper calibration and are often expensive. Two methods of indicating pressure drop created by air flow through a filter are diagrammed in Fig. 6.22.

6.5.2 Air Flow Indicator

Various methods can be employed to indicate air flow rates from gloved boxes using an orifice plate, venturi meter, flow nozzle, calibrated Pitot tube, etc. The aim is to apply a simple trouble-free method that gives reliable readings within ±15% accuracy. Where free moisture is not present, a center-line orifice plate with calibrated gage or inclined manometer will prove to be the cheapest and most adaptable for the small volume flow rates associated with gloved box ventilation. Figure 6.23 shows an arrangement which uses a round orifice in a straight section of metal duct. This method can be made to read the volume of flow directly on the gage, which is a simpler and more accurate operation than sensing the center-line velocity pressure, which must then be formulated into flow rate.

By using the proportions given in Fig. 6.24, a thin square-edge round (center-line) orifice size and arrangement can be determined with sufficient accuracy for ventilation system calculations by the following relation:

$$Q = 14.2 d_2^2 h^{1/2} \,, \tag{6.3}$$

where

Q = air flow, cfm,

d_2 = diameter orifice, in.,

h = pressure drop across orifice, in. H_2O.

Assumptions inherent in the use of the constant (14.2) are: Air at STP; flow coefficient for orifice = 0.65; and ratio of orifice to smooth duct diameter = $d_2/d_1 \cong 0.6$.

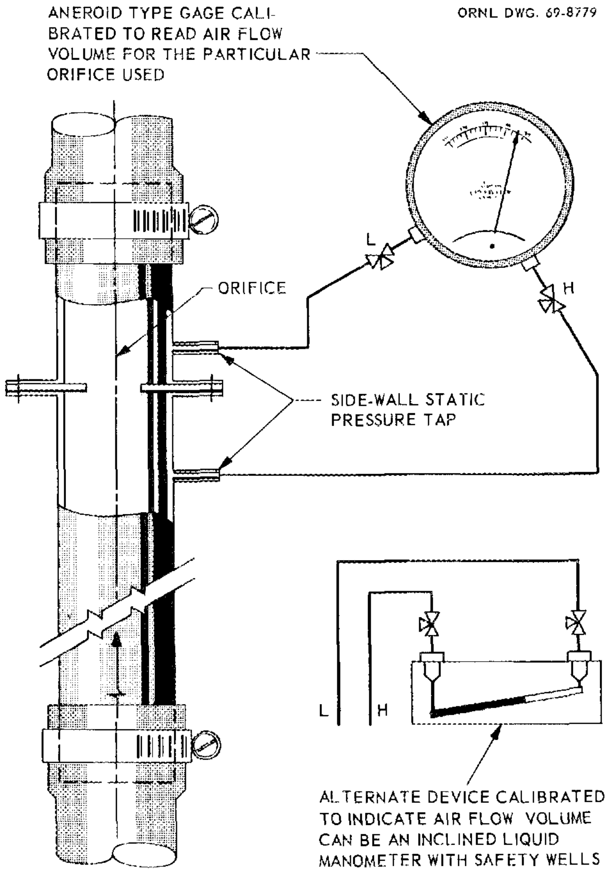


Fig. 6.23. Orifice meter method of measuring volume flow rate in small ducts.

The practical use of this formula can be shown by this example: Determine the orifice size necessary for a 20-cfm air flow rate that would give a reading near center of scale on a 0-to-0.50-in.-range gage or manometer.

$$Q = 14.2 d_2^2 h^{1/2}$$

$$Q = 20 \text{ cfm}$$

$$h = \frac{0.50}{2} = 0.25 \text{ in. } H_2O \text{ (desired reading)}$$

$$d_2 = \sqrt{\frac{Q}{14.2 h^{1/2}}} = \sqrt{\frac{20}{14.2(0.25)^{1/2}}}$$

$$= \sqrt{\frac{20}{14.2(0.50)}} = \sqrt{\frac{20}{7.1}} = \sqrt{2.82}$$

d_2 = 1.68 in. (diameter of orifice)

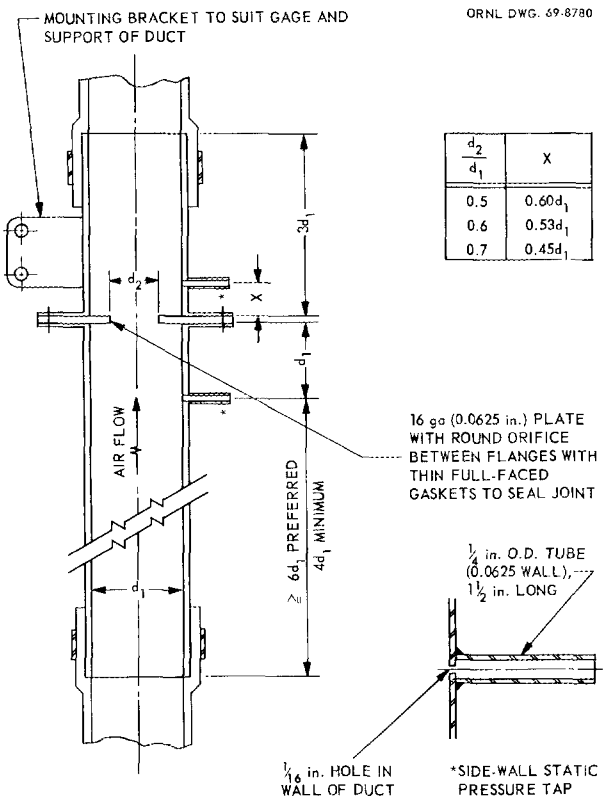


Fig. 6.24. Arrangement of thin sharp-edge round orifice in small metal duct.

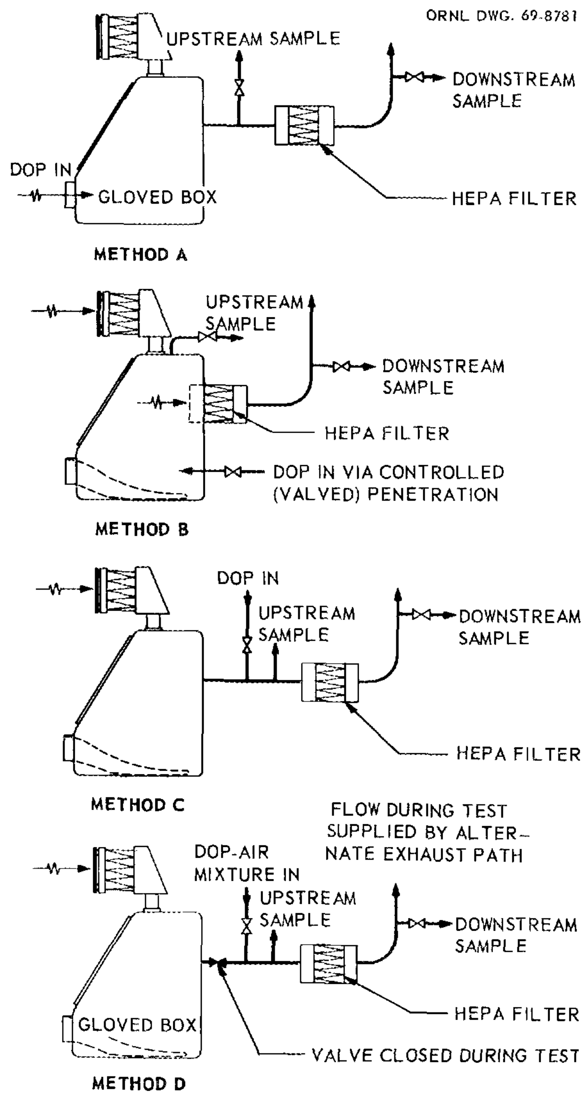


Fig. 6.25. Four methods of DOP testing HEPA filters in gloved box exhaust streams.

6.6 DOP TESTING OF GLOVED BOX FILTERS

In-place testing of HEPA filters of all sizes is a necessity for systems that must maintain a high degree of containment integrity. The principles of DOP testing of HEPA filters are given in Chap. 7. The HEPA filters used in gloved box systems are often inconvenient to test, because DOP is injected into the duct or box environment and then a sample is extracted for analysis. The usual methods of injecting DOP and extracting samples are shown in Fig. 6.25. DOP cannot be fed into the inlet of the box to test the exhaust-side filters if high-efficiency filters are used in the inlet. Methods *A* and *B* (Fig. 6.25) require DOP to be drawn into the gloved box by the suction of the exhaust system. However, when gloved boxes house apparatus with open or exposed optical lenses, highly polished surfaces, delicate balances, crystalline structures, sensitive conductors, or similar equipment or products, DOP should not be injected into the box. In such cases, the filter should be installed in the duct downstream of the gloved box so that the injected DOP aerosol will not back up into the gloved box proper. Then method *C* may be used for DOP testing the exhaust HEPA filter.

For circumstances where the new exhaust filter is not allowed to pass exhaust air from the box before the filter is DOP tested satisfactorily, method *D* should be used. Note in method *D* that the exhaust path from the gloved box is closed and that the DOP-air mixture for filter testing is drawn from a separate valved path. The side path is closed and sealed after testing is completed.

Gloved boxes with low flow rates (compared with the nominal rated capacity of the HEPA filters) will experience a more severe leak testing of the HEPA filter than those with higher flow rates. This is caused by the greater leakage effect of pinhole defects in the HEPA filter and mounting frame. Air-generated DOP injected into a system must become well mixed with the main air stream before the upstream sample is extracted. The downstream sample must also be thoroughly mixed to ensure that the sampled stream is representative of the total flow, or else single-point sampling can miss DOP that has penetrated. The size of the sample connection at gloved box filters may be small; a $^3/_8$-in.-ID tube is adequate. When air-diluted DOP must be injected into the system, as in method *D* of Fig. 6.25, the connection must be capable of admitting a flow that will afford convenient and reliable testing. The designer should plan for a DOP-air mixture flow rate through the filter under test that is at least 20% of the manufacturer's rating for the filter. This is equivalent to a flow of 1 fpm through the medium.

Methods *A* and *B* of Fig. 6.25 require DOP-air mixtures to be injected into the gloved box via some convenient opening. A glove port can be used if containment is not critical during testing. Otherwise, a connection can be prepared, as shown in Fig. 6.26, or an alternate method can be devised. Methods *C* and *D* of Fig. 6.25 do not require the introduction of DOP into the gloved box, but the DOP inlet connection must be sized to pass the DOP or DOP-air mixture. The connection for concentrated DOP in method *C* needs to admit 2 to 5 cfm, while the connection in method *D* must accommodate the total DOP-air mixture used for the test.

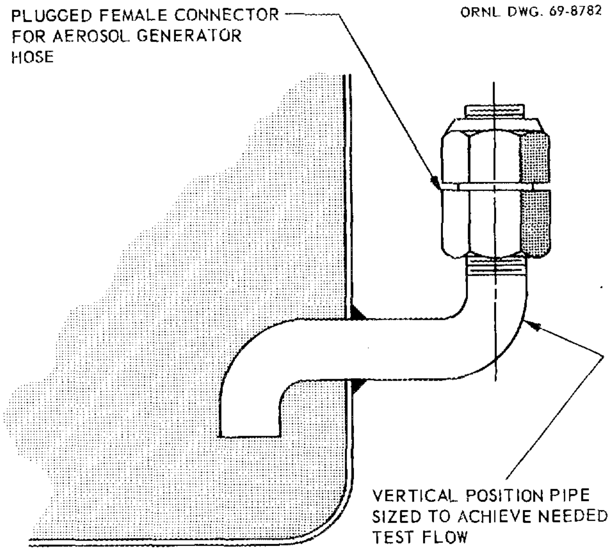


Fig. 6.26. Connection for introducing test DOP into gloved box.

7. Testing

7.1 INTRODUCTION

A basic principle of exhaust air-cleaning systems is that no credit can be taken for safety if the HEPA filters and adsorbers are not tested regularly. Although filters and adsorbers are tested by the manufacturer (and efficiency of HEPA filters may be confirmed by testing at an AEC Quality Assurance Station), testing after installation is essential because of damage that can take place during handling, shipping, and installation.

In-place tests of HEPA filter and adsorber systems should be made upon acceptance of a new system to ensure leak-tightness of construction and acceptability of the components furnished; after each filter or adsorber change to ensure proper installation of components; and at regular intervals after installation to detect deterioration of components, relaxation of gaskets or clamping devices, weld cracks, or other leaks that develop under service conditions. Regular in-place testing of both on-line and standby systems is necessary because of deterioration that can take place even when the systems are not being operated. Aside from actual component damage, frequently discovered causes of failure to meet in-place test requirements include loose clamping bolts, inadequately designed clamping devices, foreign material trapped between the filter and mounting frame, rough or warped mounting frame surfaces, cracked welds, unwelded joints in mounting frames, incorrectly installed components (e.g., HEPA filters installed with pleats horizontal, charcoal adsorbers installed with beds vertical), deteriorated caulked or duct-tape seals, inadequate seal between mounting frame and housing, inadequately designed mounting frames, and bypassing through or around conduits, ducts, or pipes that penetrate or go around the mounting frames. Initial in-place tests of 50 HEPA filter banks at one AEC installation revealed 31 banks (62%) that would not meet the specified efficiency of 99.95%.[1]

In-place tests of HEPA filters are made with a polydispersed aerosol of dioctyl phthalate (DOP) droplets having a light-scattering mean diameter of 0.7 μ (as opposed to quality assurance tests of these filters, which are made with a monodispersed DOP aerosol having a mean particle size of 0.3 μ). In-place tests of adsorbers are made with refrigerant R-112 (e.g., Freon[2] F-112) or radioactive-iodine-tagged elemental iodine or methyl iodide. Although test results are expressed as "percent efficiency," all of the in-place tests are basically leak tests. When the tests are made of components of known efficiency, the numbers give an indication of system efficiency.

7.2 FREQUENCY OF TESTING

The following schedule for both on-line and standby systems is recommended for systems built in accordance with this handbook:

All systems: before initial startup and after each filter or adsorber change.

Radiochemical plants, fuel reprocessing plants, laboratory fume hoods: semiannually or even quarterly where high moisture loadings or high temperatures are involved. In some systems, monthly testing may be required where the environment is particularly severe.

Laboratories and plants where filters are not exposed to extremely hostile environments: annually.

Reactor postaccident air-cleanup systems: semiannually.

For systems not designed in accordance with this handbook, the frequencies for radiochemical plants, fuel reprocessing plants, and laboratories should be

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[1]E. A. Parrish and R. W. Schneider, Review of Inspection and Testing of Installed High Efficiency Particulate Air Filters at ORNL, *Treatment of Airborne Radioactive Wastes*, International Atomic Energy Agency, Vienna, 1968.

[2]Registered trademark of E. I. du Pont de Nemours and Co., Inc.

halved until experience shows that greater intervals between tests are justified.

7.3 IN-PLACE TESTS OF HEPA FILTER SYSTEMS

The test is made by charging the upstream side of the filter or filter bank with DOP "smoke," then measuring and comparing the DOP concentration in samples of the filtered and unfiltered air, as shown in Fig. 7.1. If the system fails to meet the specified system efficiency, the downstream faces of the filters and mounting frame are scanned to locate localized high DOP concentrations which indicate leaks.

7.3.1 System Requirements

It is essential that the air-DOP mixture charged to the filters be thoroughly mixed so that the concentration entering all points of the filters is essentially uniform, and that the air-DOP mixtures at the upstream and downstream sample points be thoroughly mixed and representative of the concentrations at those points. Adequate mixing upstream usually can be obtained by introducing the DOP at least ten duct diameters upstream of the filters or by introducing it upstream of baffles or turning vanes in the duct. When neither of these is practicable, a Stairmand disk[3] located three to five duct diameters upstream will give satisfactory mixing. When arrangement of the duct makes it necessary to introduce the DOP directly into the filter

[3] An annular plate having a face area equal to ½ the cross-sectional area of the duct. To reduce pressure drop, the disc is usually pivoted so that it can be turned parallel to the axis of the duct when not in use (*Engineering* 152, 141 and 181 (1941).

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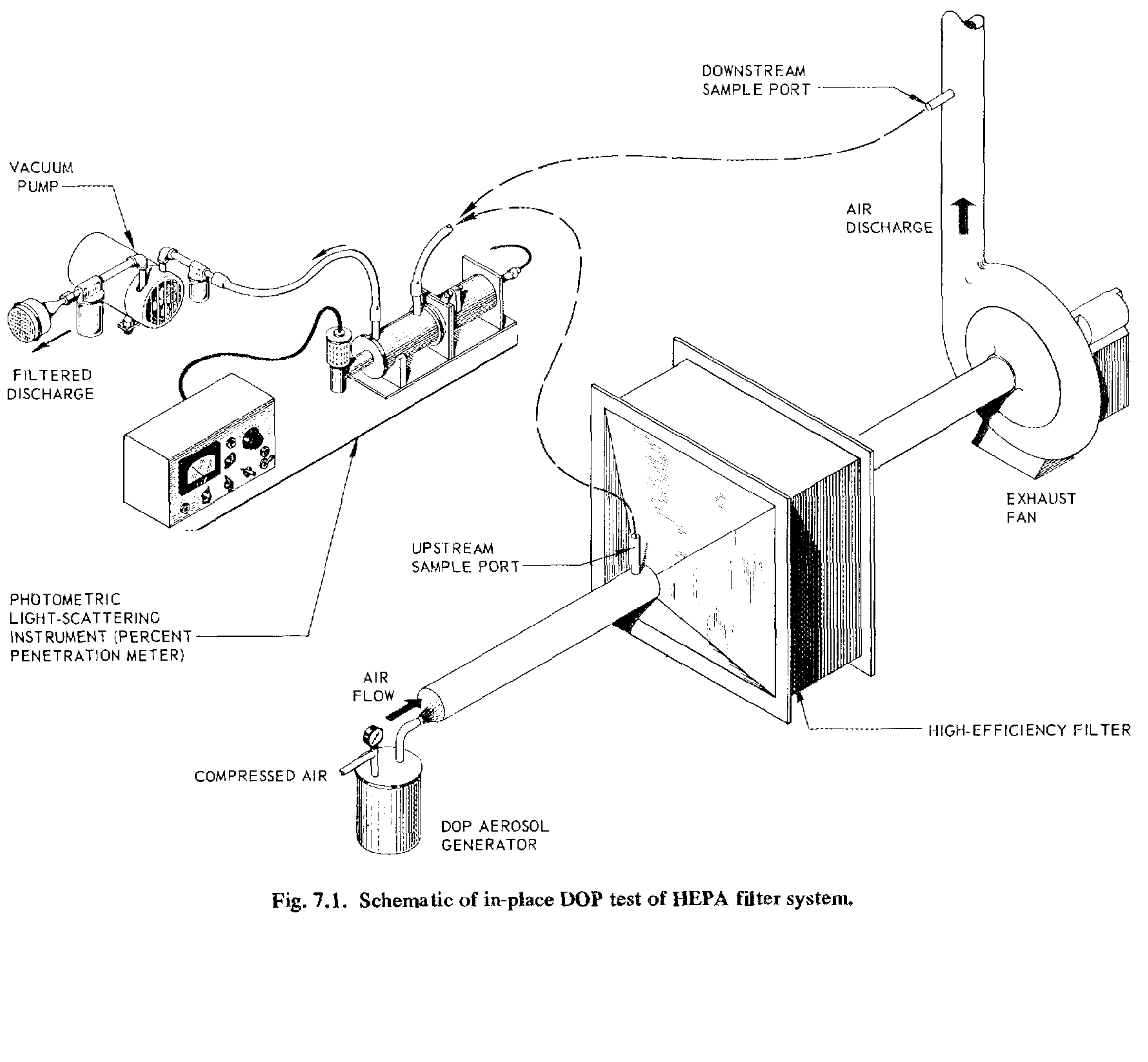

Fig. 7.1. Schematic of in-place DOP test of HEPA filter system.

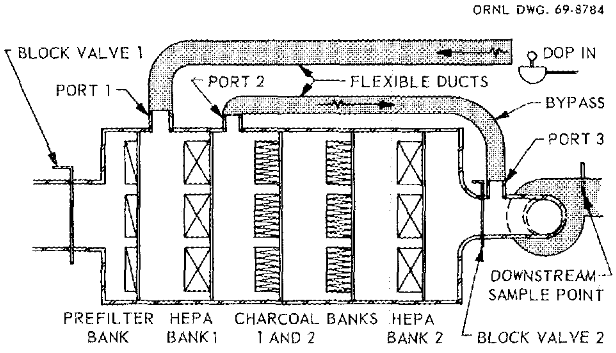

Fig. 7.2. Set-up for in-place testing of HEPA filter system when DOP is introduced directly into filter housing. System rigged to test HEPA bank 1. To test HEPA bank 2, the bypass is removed, ports 1 and 3 are closed, the DOP intake duct is connected to port 2, and block-valve 2 is opened. Upstream samples are taken from the housing immediately ahead of the bank of filters being tested.

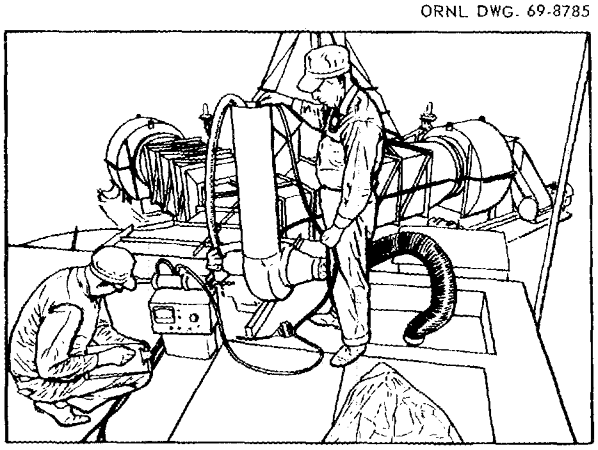

Fig. 7.3. Auxiliary blower used to establish air flow in system for in-place test where use of system fan is impracticable. Note permanent flexible duct connection.

housing or when high-efficiency prefilters are installed ahead of the HEPA filters, provision may have to be made for installing temporary ducts as shown in Fig. 7.2. Extraction of the downstream sample downstream of the fan usually provides a representative sample.

Fan-shaft seal leakage is usually not a problem in testing except when the fan is located in a dusty or smoky atmosphere which causes an objectionable downstream particle "background reading" on the instrument. This can be overcome by installing a temporary felt shaft seal to reduce dust inleakage during the test. The use of an auxiliary fan, as shown in Fig. 7.3, is sometimes required when side streams from other banks that cannot be valved off dilute the air from the system under test to the extent that representative samples cannot be obtained.

Because in-place tests must be made routinely, permanently installed aerosol injection and sample ports and careful planning of how tests are to be made are necessary in the original design in order to minimize testing costs. Figure 7.4 shows the injection and sample ports in a filter system for a radiochemical plant.[1] In Fig. 7.5, the configuration of the system and the side stream make it necessary to introduce balanced concentrations of DOP at more than one location to ensure a uniform air-DOP mixture at the filters. The upstream ducts are sampled separately, and aerosol concentrations in the two ducts are balanced by using different numbers of generators at the two locations and by adjusting the compressed air supply pressure to the generators. Other system adjustments are often necessary in practice, particularly when the testing procedure has not been carefully planned in the design of the filter system.

Access to the downstream side of the filter bank is essential for inspection of the filters and to permit leak probing. For most filter systems it is possible to select an overall filtration efficiency value which, if met, will satisfy safety and operating requirements. This value can be no higher than the minimum acceptable efficiency of the individual filter units (usually 99.97%) and is sometimes somewhat less (99.95%) to allow for minor system deficiencies.[1] When leaks that would result in inability to meet the specified system efficiency exist, they can often be located by visual inspection. In some cases, however, it is necessary to probe the downstream faces of the filters and mounting frame. This is a very sensitive technique, since the DOP aerosol that passes through a leak is sampled before it is substantially diluted. Direct personnel access is desirable, as shown in Fig. 7.6. Where this is impracticable, either because of system configuration or because of high radioactivity levels (as, for example, in a radiochemical plant filter system), sufficient probing ports (see sample ports above) must be provided in the downstream walls of the filter housing to provide access, using a long-handled probe, to the entire downstream area of the filters and mounting frame. Lights, with independent switches and bulbs replaceable from outside of the filter housing, should be provided on each side of the banks in housings large enough for personnel access. Wired-glass viewing windows should be provided in the access doors to permit visual inspection of the filters without entering the filter house. Compressed air

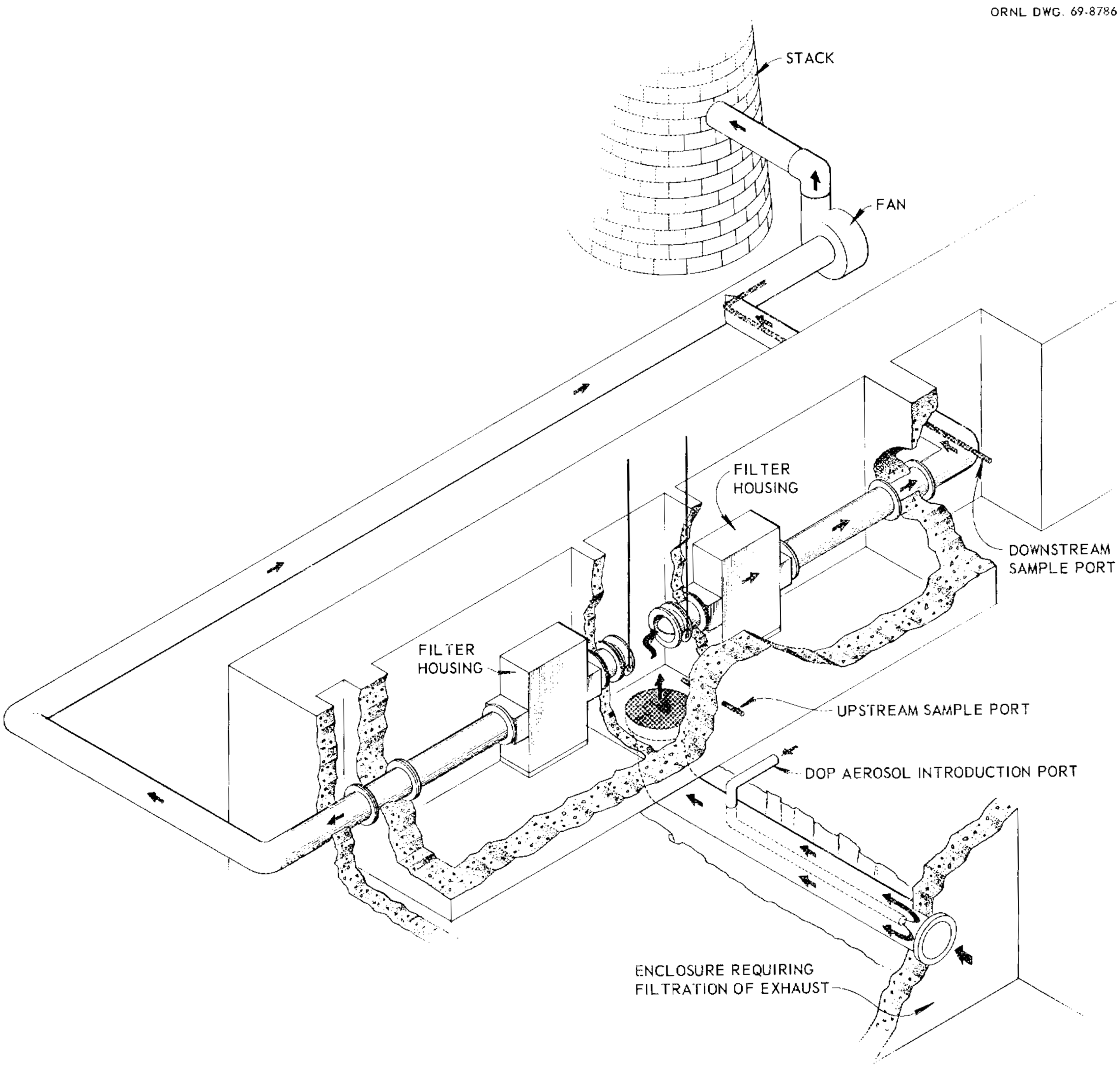

Fig. 7.4. Filter system with built-in DOP injection and sample ports. Courtesy Oak Ridge National Laboratory.

(50 psig minimum) and electrical (115 v, 15 amp) services should be provided close to the point where the test equipment will be set up (but not inside the housing).

7.3.2 Equipment

Basic equipment required for the in-place DOP test was shown in Fig. 7.1. The instrument is a Naval Research Laboratory (NRL) type linear-readout forward-light-scattering photometer or "percent penetration meter." An instrument having a threshold sensitivity of at least 10^{-3} μg liter for 0.3- to 1.0-μ particles and a sampling rate of at least 1 cfm is recommended.[4] The instrument should be capable of measuring concentrations of 10^5 times the threshold value. Although the ability to indicate absolute concentration values is desirable, it is not necessary if efficiency is calculated

[4] AACC Standard CS-2T, *Laminar Flow Clean Air Devices*, American Association for Contamination Control, Boston, 1968.

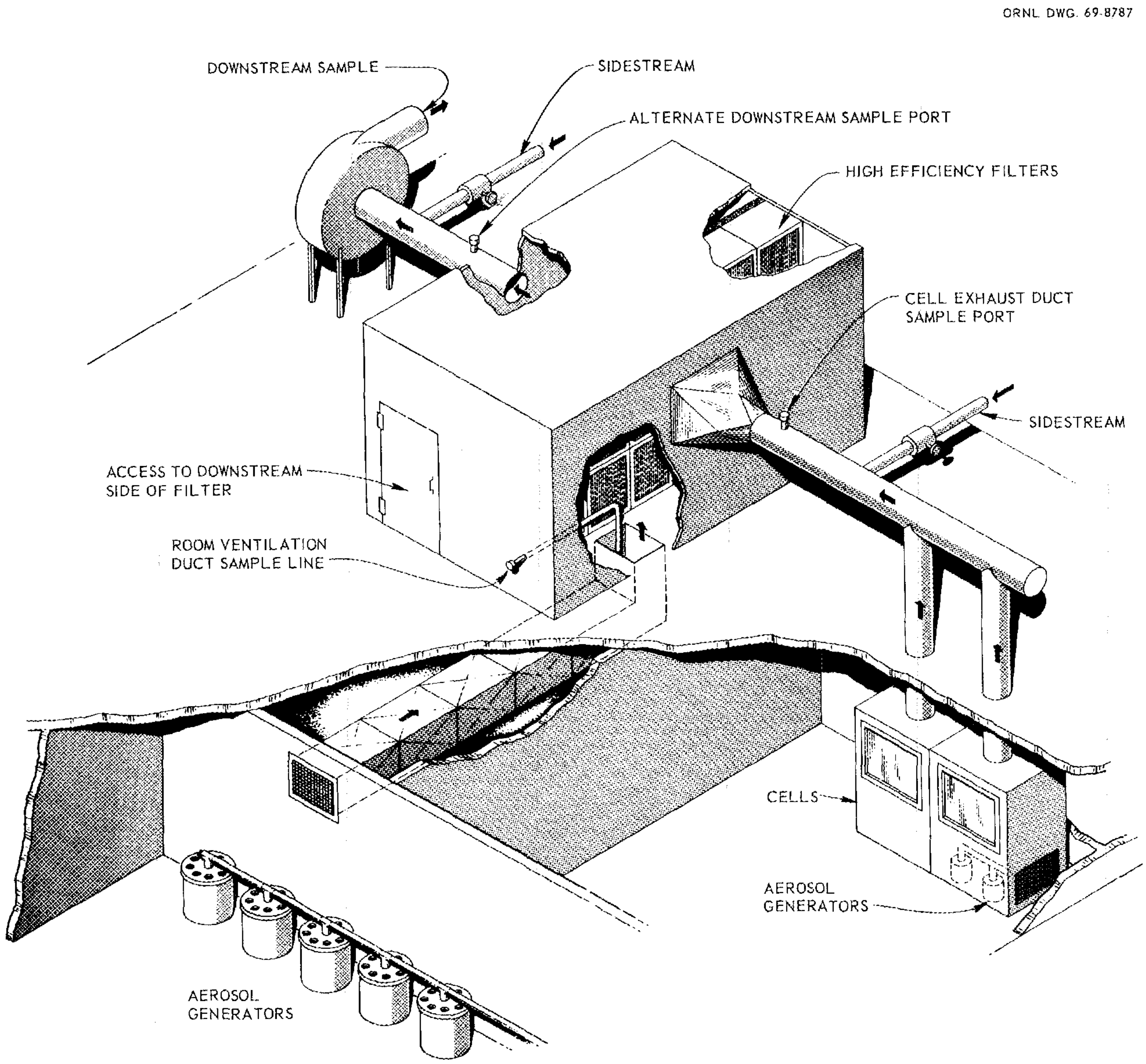

Fig. 7.5. Filter system with built-in DOP injection and sample ports.

from the relative concentrations of the upstream and downstream samples. A cabineted, self-contained instrument "package" is commercially available.

The DOP aerosol may be generated either thermally[5] or by compressed air. Compressed air generators are the most commonly used and are available or can be made in sizes from 1 to 24 nozzles. Details of a six-nozzle generator made from a paint bucket and of the Laskin nozzle used in all sizes are shown in Fig. 7.7. A rule of thumb for determining the generator capacity required is one nozzle per 500 cfm of installed filter capacity. Less DOP and less generator capacity can be used if a more sensitive photometer than recommended in the previous paragraph is used. The upstream concentration of DOP should be at least 2×10^4 times the threshold capacity of the instrument used. Compressed air requirements are approximately 1 cfm per nozzle at a

[5] R. H. Knuth, An Evaluation of Two Portable Thermal Aerosol Generators for In-Place Filter Testing, *Proceedings of the Ninth AEC Air Cleaning Conference,* USAEC Report CONF-660904, Harvard Air Cleaning Laboratory, 1967.

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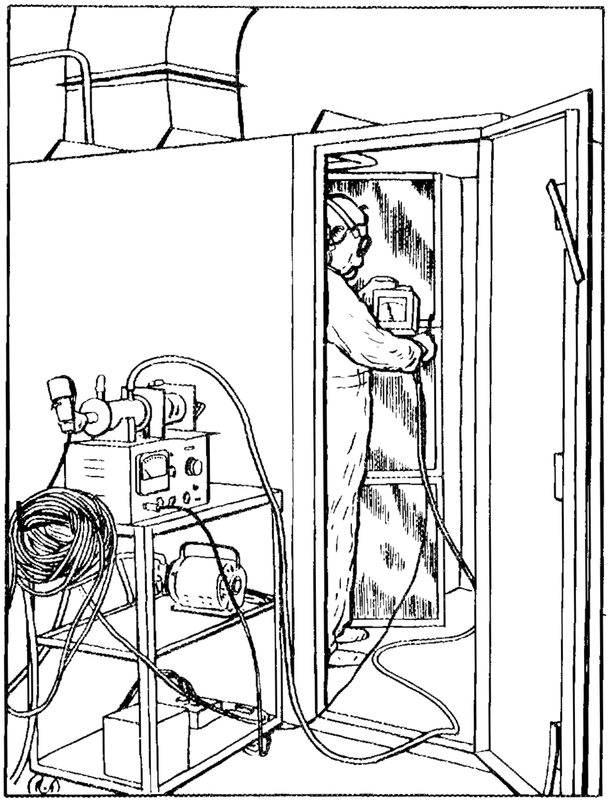

Fig. 7.6. Leak probing HEPA filter bank. Extension meter used to indicate a sharp increase in DOP that would indicate a leak.

pressure controllable from 2 to 20 psig (liquid carry-over may occur at pressures higher than 28 to 30 psig). A careful dimensional check of the radial-drilled holes of the generator nozzles should be made before placing a new generator in service. A properly operating generator will produce a DOP aerosol having a (light scattering) mean diameter of approximately 0.7 μ and having 95% of its droplets less than 1.5 μ in diameter.[4]

7.3.3 Test Procedure[4,6]

1. Visually inspect filters and mounting frames for obvious damage and defects; make necessary repairs or corrections.

2. Adjust system (or bypass) air flow. Actual air flow during the test may be lower than rated system air flow in some systems; in some systems, tests are made first at

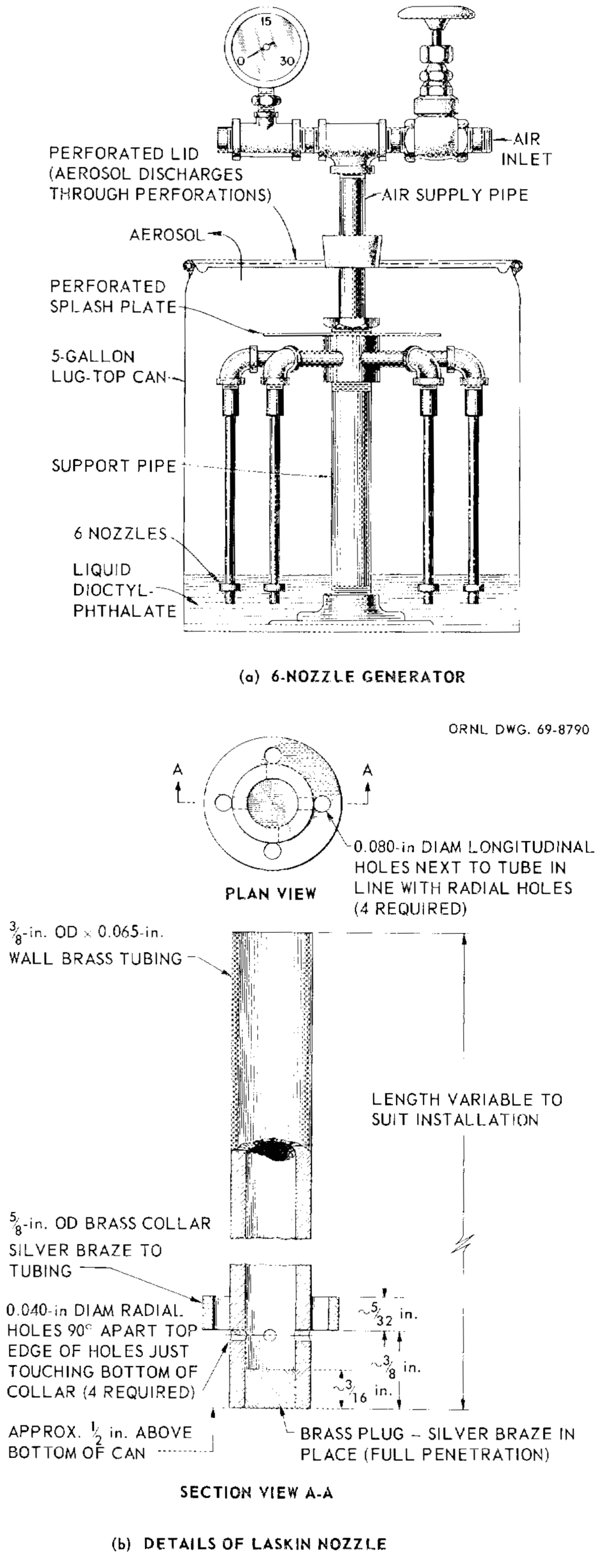

Fig. 7.7. Air-operated DOP generator.

[6]Proposed USA Standard for *Efficiency Testing of Air-Cleaning Systems Containing Devices for Removal of Particulates*, USA Standards Institute, New York, Draft 3.

rated flow, then at 20% of rated flow. The low-flow test gives a somewhat more sensitive test.

3. Calibrate or adjust photometer in accordance with manufacturer's instructions.

4. Turn on DOP generators; adjust air pressure.

5. Connect sample tube to upstream sample port; adjust instrument to read approximately 50% – adjust DOP generator if necessary.

6. Connect sample tube to downstream sample port, and leave until instrument stabilizes. Determine downstream concentration.

7. Reconnect sample tube to upstream sample port; recheck concentration. Recheck downstream concentration.

8. Calculate system efficiency from the formula:

$$E = 100 \left(1 - \frac{C_d}{C_u}\right) , \qquad (7.1)$$

where

E = system efficiency, percent,

C_d = downstream DOP concentration,

C_u = upstream DOP concentration.

9. Determine whether efficiency is within tolerance (some users require system efficiency to be the same as the efficiency of the filter units, that is, 99.97%; others permit system efficiency to be somewhat lower, usually 99.95%, to allow for minor system deficiencies).

a) If system efficiency is not within tolerance, visually inspect the filters and mounting frames and repair any defects; retest system. If system efficiency is still not within tolerance, scan the downstream sides of the filters and frames, holding the probe approximately 1 in. from the face of the filter or frame. Make a traverse first around the periphery of the filters, as this is where leaks are most likely to occur. Then probe the faces of the filters in slightly overlapping strokes until the entire faces are covered, noting where the leaks are located (Fig. 7.6).

b) Replace damaged filters, readjust filters, or repair mounting frames, as indicated. Repeat efficiency test. The probe used for scanning should have a head large enough that probe inlet velocity is approximately the same as system flow for best results. The probe should be moved at a rate of about 10 to 15 fpm.

10. If tests are to be made at two flows, reduce system flow, readjust DOP generators if necessary, and retest. Calculate and report efficiency at low flow.

An alternative procedure is to adjust the photometer so that the upstream concentration reads 100%, then calculate system efficiency from the formula:

$$E = 100 - C_d . \qquad (7.2)$$

The first procedure gives more satisfactory results.[7]

7.3.4 Special Requirements for Reactor Postaccident Cleanup Systems

Some reactor postaccident cleanup filters may be exposed to an initial rush of air at flow rates several times the nominal filter capacity. Although it is recommended that DOP tests be made at system flow rate where possible, the quantities of DOP required under such circumstances, and the deterioration that might take place in the filters because of the high overpressure, make this impractical. On the other hand, it is desirable, from the standpoint of system reliability, to know how the installed filters will react under these conditions. A way of obtaining the desired result is to remove a single filter unit, at random, from the bank at the time of the DOP test and test it individually, with DOP, at the maximum expected postaccident flow rate. This gives a sampling of the bank's efficiency at the high flow rate, while the total system test proves the leak integrity of the bank. A filter from a different location should be taken for the high-flow test each time. Filters removed for the high-flow test should be replaced with new filters. This high-flow test provides an indication of possible filter deterioration and may signal when all filters require replacement because of inability to withstand high flow. The test for record should be made after installation of the new filter that replaces the one removed for high-flow tests.

7.3.5 Special Requirements for Standby Filter Systems

Experience has shown that HEPA filters may deteriorate unless ventilated regularly. For this reason it is recommended that the fans in standby systems, postaccident cleanup systems that are not on line except in case of accident, and other systems which are not operated more or less continuously be operated for 15 to 30 min each week. This is in addition to routine DOP testing.

[7] E. A. Parrish, Oak Ridge National Laboratory, personal communication to C. A. Burchsted.

7.4 QUALITY ASSURANCE TESTING OF HEPA FILTERS

The in-place test should not be confused with predelivery acceptance tests made by the AEC Quality Assurance Stations. These tests and the tests by the filter manufacturer determine the efficiency of individual filter elements for a specific particle size, 0.3 μ. The test is made with monodisperse, thermally generated DOP. It is a go–no-go test — that is, there is no scanning or repair; if a filter does not meet the test, it is rejected. Tests by the manufacturer are made on similar equipment and according to the same procedures as those by the Quality Assurance Station.[8] The Quality Assurance Station test is a check on the manufacturer and on shipping procedures and damage; it has resulted in a significant improvement in filter quality and is recommended for all users who plan to use HEPA filters in nuclear applications. The test service is available to nongovernment operators at cost.[9]

7.5 IN-PLACE TESTING OF ADSORBERS

The effectiveness of activated carbon adsorbers may be impaired by poisoning (i.e., adsorption of or chemical reaction with paint, solvent, hydrocarbon, or chemical fumes), adsorption of water vapor, or settling of the charcoal due to vibration or improper installation (e.g., pleated-bed adsorbers installed with pleats vertical), in addition to the system defects mentioned in the discussion of in-place testing of HEPA filters (Sect. 7.1). There are three in-place tests for checking of adsorber systems: the Freon[10] test developed by the Savannah River Laboratory,[11] the radioactive tracer test for elemental iodine developed by the Oak Ridge National Laboratory,[12] and the radioactive tracer test for methyl iodide developed by the Oak Ridge National Laboratory.[13] The latter is applicable only to adsorbers containing charcoal impregnated for trapping of organic forms of radioiodine. All of the tests are basically leak tests rather than efficiency tests and must be supplemented with laboratory tests of charcoal samples taken from the adsorbers at the time of test to give a true measure of system efficiency and remaining capacity for iodine.

System efficiencies at 25°C, rated system air flow, and relative humidities up to 90% are usually specified as 99.9% for elemental iodine for 1 in. of charcoal. Reasonable system efficiencies for methyl iodide, at temperatures to 25°C and rated system air flow, are 95% for relative humidities of 85% and less, 90% for 90% relative humidity, for 2 in. of charcoal. System requirements (i.e., injection and sample ports, means for establishing proper mixing and system flow, etc.) are essentially the same as for in-place testing of HEPA filters.

7.5.1 Freon Test

Leaks in an adsorber system can be detected by charging the upstream sides of the beds with an adsorbable vapor, measuring the concentration upstream and downstream of the beds, and comparing the concentration ratios. If the test is made on a system containing charcoal of known iodine efficiency, it gives a measure of the system efficiency. As with the DOP test, basic items required are the sampling equipment and the generating equipment. The vapor used for the test is Freon[10] 112 (F-112) or equivalent fluorocarbon refrigerant.

The sampling system consists of a pump to draw upstream and downstream air samples from the adsorber system, two identical gas chromatographs with electron-capture detectors for measuring F-112 concentrations, a timer, and several rotameters for determining sample dilution factors. The chromatographs should have a linear range for detection of F-112 of about 1 to 100 ppb, by volume. Since the upstream concentration would exceed the linear range of the instrument, the upstream sample must be diluted with a known volume of air to bring it within the detection range of the chromatograph. The calibrated rotameters are used to determine the dilution factors. A transportable test

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[8] Military Standard MIL-STD-282, *Filter Units, Protective Clothing, Gas-Mask Components, and Related Products: Performance Test Methods,* 1956.

[9] Filter Unit Inspection and Testing Service, *Health and Safety Information Bulletin,* U.S. Atomic Energy Commission (issued annually).

[10] Registered trademark, E. I. du Pont de Nemours and Co., Inc.

[11] D. R. Muhlbaier, *Standardized Nondestructive Test of Carbon Beds for Reactor Confinement Applications,* USAEC Report DP-1082, Savannah River Laboratory, July 1967.

[12] R. E. Adams and W. E. Browning, Jr., *Iodine Vapor Adsorption Studies for the NS "Savannah" Project,* USAEC Report ORNL-3726, Oak Ridge National Laboratory, February 1965.

[13] J. H. Swanks, *In-Place Iodine Filter Tests at the High Flux Isotope Reactor,* USAEC Report ORNL-TM-1677, Oak Ridge National Laboratory, December 1966.

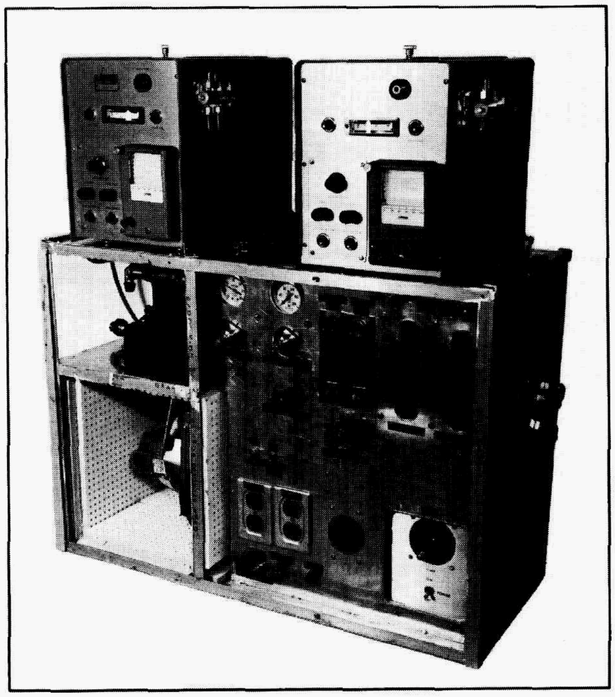


Fig. 7.8. **Sampling equipment for Freon test.** Gas chromatographs on top of cabinet, pump at left, timer and rotameters on right. Courtesy Savannah River Laboratory.

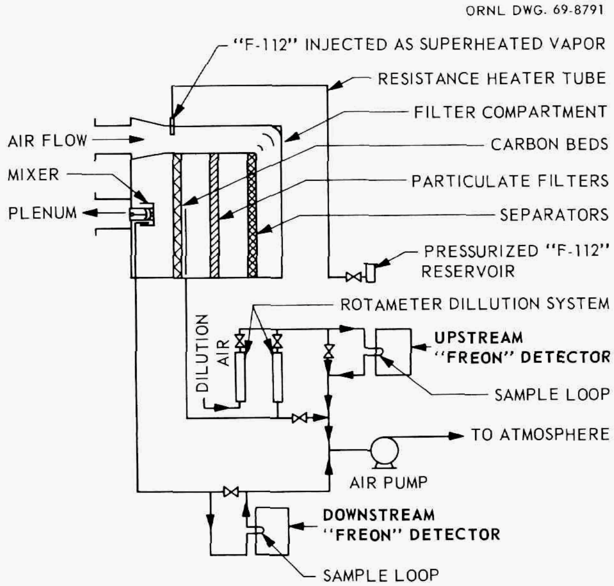


Fig. 7.9. Schematic of Freon test setup.

stand, containing all of the sampling equipment, is shown in Fig. 7.8.[14]

The F-112 generator consists of a reservoir with an immersion heater to preheat the F-112 (freezing point 23.8°C) to about 100°F, a stainless steel tube (3/32 in. OD by 0.010 in. wall by 45 ft) connecting the reservoir to the system, and an F-112 injector nozzle.[14] The stainless steel tube and injector nozzle serve as resistance heaters to vaporize and superheat the F-112 before it enters the filter housing. The reservoir is pressurized with nitrogen to force the liquid F-112 into the tube.

The test setup is shown schematically in Fig. 7.9, as used for testing the Savannah River Plant systems (see Fig. 8.3). It can be seen that the presence of prefilters and HEPA filters in the duct does not affect the Freon test. The test is relatively easy to conduct by persons experienced in the use of the gas chromatograph but must follow a careful procedure as given in USAEC report DP-1082.[11] Precise adjustment of the air flow rate, the F-112 injection rate, and the chromatographs is not required. Relative calibration of the two chromatographs is necessary for accurate results. The use of the mixer shown in Fig. 7.9 is not necessary if samples can be taken far enough downstream (approximately 10 duct diameters) to ensure good mixing. The test can be made with a single chromatograph, switching the instrument from upstream to downstream sample points as in in-place testing of HEPA filters. The results will not be as fast or accurate, however, since simultaneous readings cannot be made. The test cannot be made with currently available halogen leak detectors, which do not have the sensitivity required for this test.

Two days are required for the test, the first to condition the charcoal and to set up and check out equipment, the second to actually run the test. Heaters in the filter housing must be operated for about 24 hr before the start of the test to desorb moisture in the charcoal that might prejudice the results.

7.5.2 Radioactive Tracer Test for Elemental Iodine

Equipment requirements include an iodine injector tube (Fig. 7.10), two sampling units (Fig. 7.11), a sample extraction pump, and three calibrated rotameters for controlling the injection and sampling flows. The sampling units are filled with charcoal of known efficiency for elemental iodine. The sampling units shown in Fig. 7.11 are 1.5 and 14.5 cfm flow capacity, respectively, and were used for testing systems having rated flow capacities of 1000 and 12,000 cfm respectively. The test aerosol is $^{127}I_2$ containing $^{131}I_2$ tracer. A combination of injected activity (in microcuries), sampling rate, and counting technique (usually

[14]Drawings are available from the Clearinghouse of Federal Scientific and Technical Information.

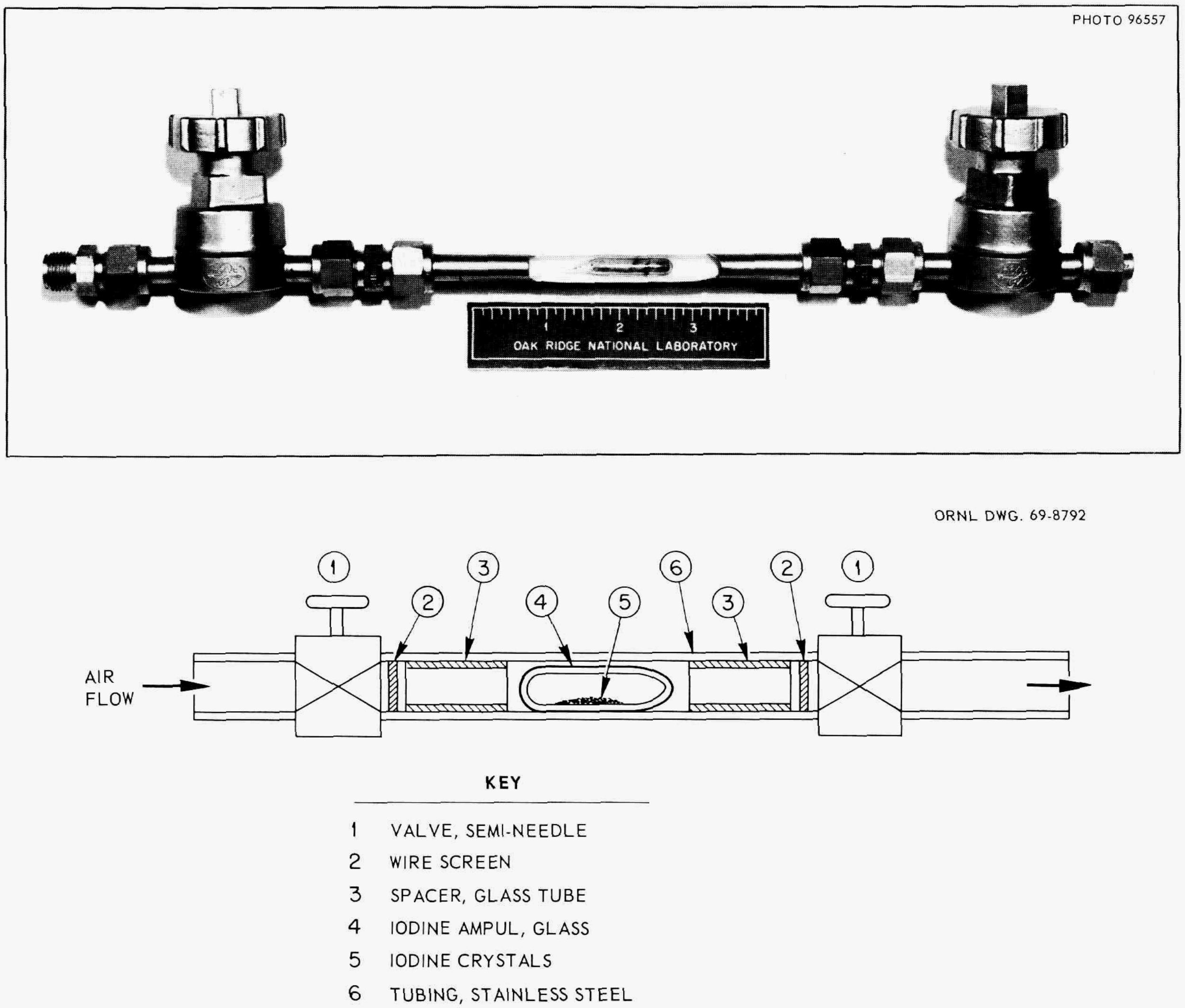
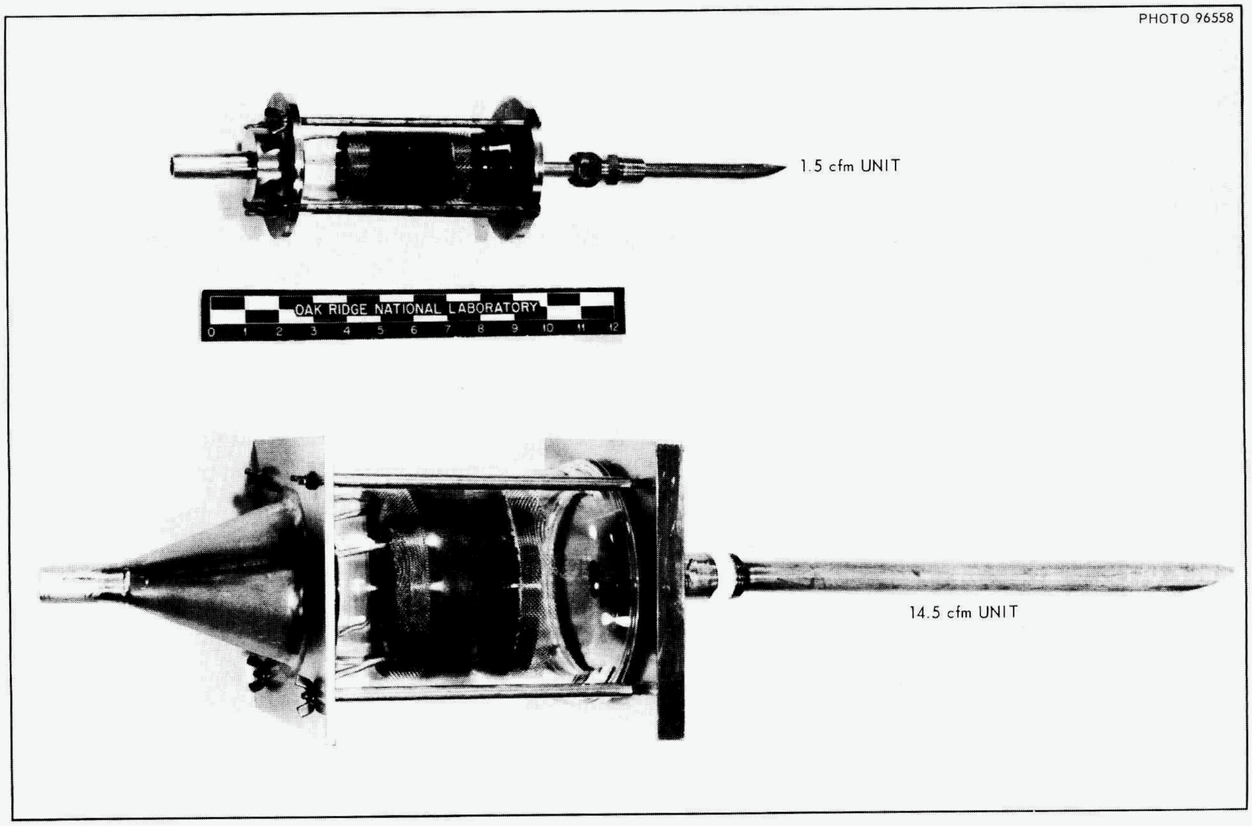
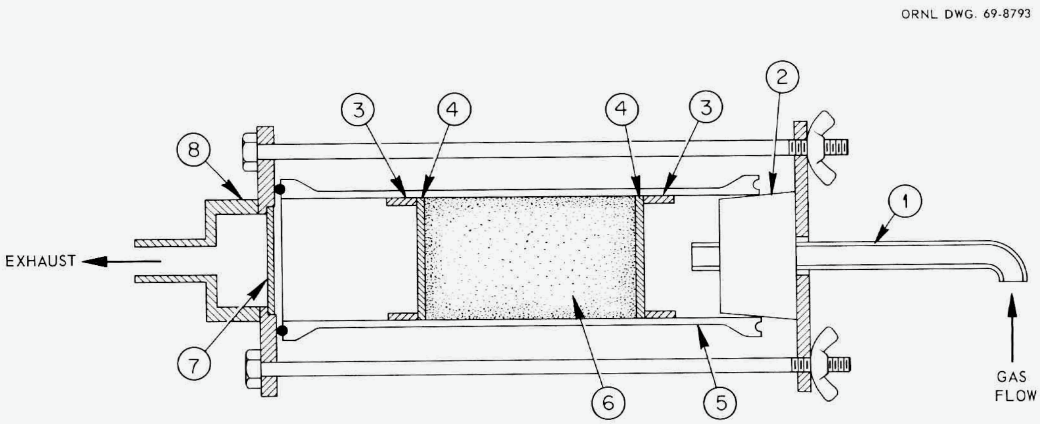


Fig. 7.10. Injector tube for iodine tests. Courtesy Oak Ridge National Laboratory.

dictated by the kind of counting equipment available) must be developed which will give the required test precision. At the Oak Ridge National Laboratory, a combination of sampling and injection rates is selected which, with the available counting equipment, will produce an upstream sampler activity count between 8×10^5 and 5×10^6 counts/min. These are not rigid limits but are convenient target values and have considerable latitude. Satisfactory tests have been made at sampling rates as low as 0.03% of the system flow rate, but sampling rates of about 1 cfm per 1000 cfm of rated adsorber capacity are suggested.[7-12]

The amount of iodine required and the size of the injector tube are not critical. The amount of $^{127}I_2$ is invariably 100 mg in the ORNL tests, although this may be doubled if plate-out in the upstream duct or housing is expected. The amount of $^{131}I_2$ tracer must be adjusted to give the activity count noted above. The radioactive iodine source is prepared by mixing the required quantities of ^{127}I and ^{131}I as NaI, precipitating the iodine content as PdI_2 by treatment with acidified $PdCl_2$, then decomposing the PdI_2 under vacuum. The liberated $^{127+131}I_2$ is collected in a liquid-nitrogen-cooled U-tube, then transferred to a glass ampul that is installed in the injector. The latter operations must be carried out in a laboratory equipped for handling radioactive materials. To inject iodine during the test, the injector tube is crushed, breaking





KEY

1 STAINLESS STEEL PROBE, ½ in. × 12 in.
2 RUBBER STOPPER
3 FLEXIBLE BAND RETAINER
4 SCREEN
5 GLASS PIPE, 2 in. ID
6 ACTIVATED CHARCOAL
7 HIGH-EFFICIENCY FILTER
8 END PIECE AND FILTER HOLDER

Fig. 7.11. Sampling units for iodine tests. Courtesy Oak Ridge National Laboratory.

the ampul and releasing the iodine vapor. Compressed air is flowed through the tube at a carefully controlled rate for a period of approximately 2 hr. During the final half hour of the injection period, heat is applied to the injection tube to drive out the remaining iodine.

A typical iodine test setup is shown in Fig. 7.12. After system flow is established, iodine is injected far enough upstream to ensure adequate mixing with the air, and samples are withdrawn simultaneously through the upstream and downstream sampling units. Injection of iodine is continued for approximately 2 hr; system air flow and downstream sampling are continued for another 2 hr in order to include the effect of any iodine that may desorb from the beds in addition to that which might immediately penetrate. Exhaust air from the sampling units is usually dumped back into the upstream side of the system.

After the completion of sampling, the sampling units are removed to and dismantled in a laboratory preparatory to analysis. The iodine content of the charcoal from the samplers is determined by direct gamma spectroscopy, and the efficiency is determined from the formula:

$$E = 100\left(1 - \frac{C_d}{C_u - B}\right), \qquad (7.3)$$

where

E = efficiency, percent;

C_d = iodine content of downstream unit, disintegrations per minute;

C_u = iodine content of upstream unit, disintegrations per minute;

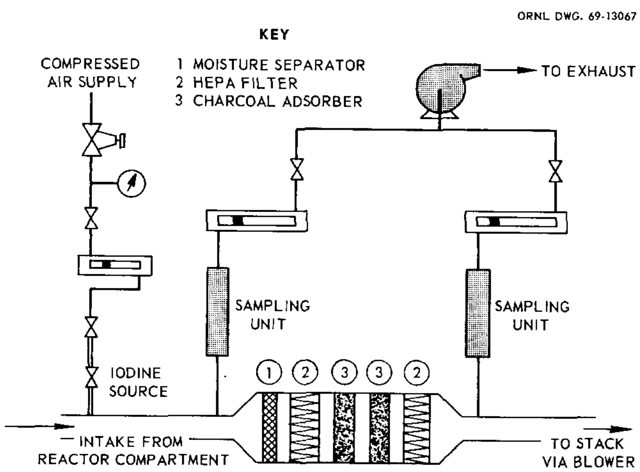


Fig. 7.12. Schematic of iodine test.

B = background due to impurity iodine in charcoal, disintegrations per minute.

7.5.3 Radioactive Tracer Test for Methyl Iodide

The methyl iodide test for determining the trapping efficiency of adsorbers for organic forms of radioiodine is similar to the test for elemental iodine and, except for the injector, uses the same equipment. The injector used for the methyl iodide test is a U-tube and vapor expansion chamber. Testing and analytical procedures are the same as for the elemental iodine test. The test aerosol is $CH_3{}^{127}I$ containing $CH_3{}^{131}I$ tracer. Sampling rates and amounts of test aerosol are the same as for the elemental iodine test. Because the methyl iodide test determines a different property of the charcoal and is dependent on a different mechanism, it cannot be used in place of the elemental iodine test, and both tests are required for a complete evaluation of impregnated charcoal adsorbers.

7.6 ACCEPTANCE TESTING

Acceptance testing of high-efficiency air cleaning systems should include a careful visual and dimensional check of the housing and mounting frames, a leak test of the housing(s), in-place tests of the HEPA filters and charcoal adsorbers (where required) after installation, and capacity tests of the fans, both with filters and adsorbers installed and with artificial resistance in the system to simulate dirty-filter pressure drop. Artificial resistance can be introduced by adjusting dampers or by blanking off filters, using plywood or polyethylene film taped to the spark-arrester screens (where provided), until the desired pressure drop is attained under maximum flow conditions. Confirmation of the fan's ability to provide the specified air flow under all operating conditions, up to maximum system resistance, is extremely important to reliable and economic performance of the system. The light level in the housing during visual inspection should be at least 150 to 200 ft-c, including general and supplementary lighting. Particular attention should be paid to the quality of welds and seating surfaces of the mounting frames and the attachments of the mounting frame to the housing.

Both acceptance testing and periodic testing of filter and adsorber systems often involve important safety considerations as well as contractual responsibilities and therefore must be completely objective. Since the outcome of tests is often of interest to a number of parties, including contractors, owner-operators, owner representatives such as architect-engineers, and licensing and regulatory agencies, the tests must be conducted by personnel of demonstrated competence who have no conflicting interests which could cast doubt on the objectivity of the reported results. Contract documents should explicitly describe the precise responsibilities of the owner, his agent, and the contractor.

7.6.1 Housing Leak Test

Seal openings of the housing (doors sealed only by their normal latching devices); alternately subject the housing to a positive and a negative pressure of at least 2 times the maximum total system resistance of 10 in. H_2O, whichever is greater, holding the pressure for at least 4 hr during each cycle. Housings for recirculating postaccident air cleanup systems that will be installed within the reactor containment should be pressurized to at least the maximum differential pressure that could exist across the walls of the housing during a design basis accident. After pressure cycling, connect an integrating wet-type flowmeter to the pressurizing line; pressurize the housing with air to 3.0 in. H_2O, and adjust the flowmeter so that this pressure is maintained within ±5% throughout the test. Continue the test for at least 8 hr. The permissible leakage, as determined by volumetric flow during the test, should be related to the relative hazard of the system (see Sect. 4.5.8). Since the filter housing can be considered as an extension of the space being ventilated, the permissible leak rate of the housing should be the same as that of the space being ventilated. For hot cells, the permissible leak rate is usually from 10^{-3} to 10^{-2} cell volume per minute at a negative pressure of 2 to 3 in. H_2O. For power reactors, the permissible leak rate may be as low as 0.1 to 0.5 of the housing or duct volume per 24 hr for external systems connected directly to the primary containment shell. The leak rate of ducts and housings for internal recirculating cleanup systems for power reactors is probably of little significance other than that inleakage during operation of the system would increase the number of cycles needed to reach a specified level of decontamination. Leaks in filter housings and ducts may be very difficult to locate, and soap-bubble techniques may not be sensitive enough to detect leaks in extremely low-leakage systems, necessitating the use of halogen or helium-mass-spectrometer leak detectors. When soap-bubble techniques are suitable, a solution of one part water, one part glycerin, and one part liquid dishwashing detergent has been found useful; cornstarch is sometimes added to give greater stability to the bubbles. Leak detection should be carried out at as high a positive pressure in the duct or housing as possible, and pressurization should be continued until all potential leak areas have been examined. Repairs should be by welding when possible; the use of silicone-base sealants is not recommended unless there is no other way of repairing the leak.

8. Remotely Maintained and Reactor Postaccident Cleanup Filtration Systems

8.1 INTRODUCTION

The preceding chapters have generally assumed that personnel have direct access to contaminated filter housings and components during a filter change. In some filter systems, however, radiation levels are so high, or could be so high following a major accident, that direct access is impossible, and resort must be made to remote maintenance. The basic design and construction requirements of remotely maintainable systems are the same as for direct-access systems but are complicated by the necessity for radiation shielding and the necessity to manipulate filter clamping devices and to handle components indirectly from a distance. Remote systems are found mostly in nuclear reactors, radiochemical and fuel-reprocessing operations, and hot cells. The first part of this chapter points out problems of these systems and shows how they have been met at a number of AEC plants. The second part of the chapter discusses special problems of reactor postaccident cleanup filter systems.

8.2 REMOTELY MAINTAINED FILTER SYSTEMS

The Code of Federal Regulations specifies a maximum radiation exposure to operating personnel of 3 rems in any three-month period.[1] Whenever radiation levels are or could be high enough that workmen receive or exceed this limit during a filter change, consideration must be given to a remotely maintainable filter system. Radiation exposure can be minimized by limiting the time of exposure, by attenuating the radiation by means of shielding, and by reducing the intensity of the radiation by keeping at a safe distance from the source (intensity decreases as the square of the distance from the source). A not uncommon practice in some low- to moderate-hazard systems is to limit the time of exposure by sending personnel into the contaminated filter housing in relays. Such procedures run the risk that all personnel will have received the maximum dose before the filter change can be completed, or that personnel will have received enough radiation that their availability for other work in contaminated areas of the plant is limited. In even such borderline cases, better personnel protection may be had by utilizing the factors of distance and shielding — this is the function of remotely maintainable systems.

Clamping devices and filters in remote systems are handled by special extended-reach tools, electromechanical manipulators, cranes, or other mechanical devices. In many systems, filters are installed on a removable mounting frame that is replaced as a complete assembly by means of a crane, and in at least two systems the entire housing is replaced. Housings for remote systems are in most cases concrete pits or enclosures with heavy concrete plugs to seal the access ports. Designers must recognize that workmen do not have the close control over movements that is possible in direct-access systems. Careful attention must be paid to filter withdrawal and handling space, and if alignment guides are not provided, access ports must be generously sized to permit easy passage of components when handled by a crane or manipulator. When filters are installed on a removable mounting frame, heavier construction is needed to prevent damage from inadvertent bumping of the removable frame against the stationary frame to which it seals or against the sides of the access port. In some systems the contaminated filters or filter assembly is withdrawn into a special carrier to permit safe transport through occupied areas of the building or plant to a disposal area. Building openings, areaways between buildings, and ground

[1] 10-CFR-20, Standards for Protection Against Radiation, *Code of Federal Regulation,* Title 10, Part 20, U.S. Government Printing Office, 1965.

clearance of power lines and other utilities must be adequate to permit easy passage of the heavy shielded carrier and the truck or trailer on which it is hauled. Underground pipelines along the route may have to be reinforced to prevent crushing under the load of the carrier and truck. For hot cells and caves where the filters are installed from inside the cell, provision must be made for access without interfering with process or experimental equipment in the cell.

It is often possible to design for semiremote maintenance — that is, to provide for direct access when radiation levels are low and for remote removal when radiation levels are high. This approach is particularly appropriate for nuclear reactor postaccident cleanup systems, where radiation levels during normal reactor operation are well within personnel tolerances but would be extremely high in the event of a major accident. The filters of a semiremotely maintained system are held to a removable mounting frame by means of nut-and-bolt or other conventional clamping devices. The removable mounting frame, in turn, is clamped to a stationary sealing frame by latches which can be operated from outside of the housing by means of extended-reach tools. Under normal circumstances, personnel enter the housing and replace filters using direct-access procedures. When direct access becomes impossible, the shielding blocks over the filters are removed, and the removable frame is released and hoisted from the housing. Construction of the removable and stationary frames must be precise to ensure a good seal under remote handling procedures, and frame members should be heavier than for direct-access systems to withstand the rough treatment that might be received during a remote filter change.

Each step of a remote filter removal and replacement procedure, from initial dressing of personnel in protective clothing to final disposal of the dirty filters and decontamination of the area, must be carefully planned before system design is frozen. Overlooking of any detail may complicate the actual procedure in the field and result in unduly high labor costs, personnel injury or overexposure, or contamination spread. Clearances, temporary storage of new and dirty filters and other removable items, clothing-change facilities, access routes to and from the filter housing, decontamination procedures, radiation monitoring, and handling facilities must all be carefully examined. It is often desirable to build a model or full-size mockup of the proposed filter housing to guide the planning of the change procedure and to ensure that all factors have been considered. The mockup can later be used for change-crew training.

The following examples are representative and illustrate a number of problems of remotely maintained systems.

8.2.1 Brookhaven Reactor Bypass Filter System[2]

This system is installed in an underground pit (Fig. 8.1) which has removable concrete shielding blocks in the ceiling to provide access to the filters. The filters and adsorbers are installed on 12 removable mounting frames, as shown in Fig. 8.2. To change filters remotely, the shielding blocks over the removable frame are removed, the latches which clamp the frame to the stationary seal frame are released from outside of the housing by means of extended-reach tools, and the frame, with the filters, is hoisted out by crane.

Radiation levels are low enough under normal operating conditions to permit direct access for filter changing. Figure 8.3 shows a detail of one of the clamping plate assemblies that hold the filters and adsorbers to the removable mounting frames. The plate is bolted to the frame after the filters and adsorbers have been placed in the support structures; then the clamping screws are tightened on the pressure distribution frames (see Fig. 4.25). This permits re-adjustment of individual

[2] R. O. McClintock, The Design, Test, and Use of the Brookhaven National Laboratory (BNL) Reactor Bypass Filter Facility, *Proceedings of the Ninth AEC Air Cleaning Conference*, USAEC Report CONF-660904, Harvard Air Cleaning Laboratory, January 1967.

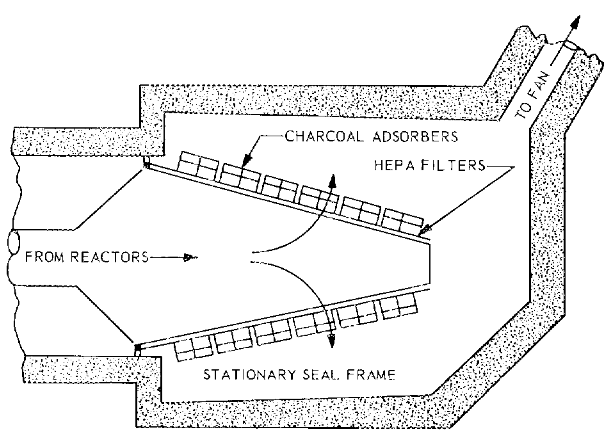


Fig. 8.1. Plan view of bypass filter pit at Brookhaven National Laboratory. Each stack of eight HEPA filters and charcoal adsorbers is clamped to a removable mounting frame that in turn is clamped to the stationary seal frame as shown in Fig. 8.2.

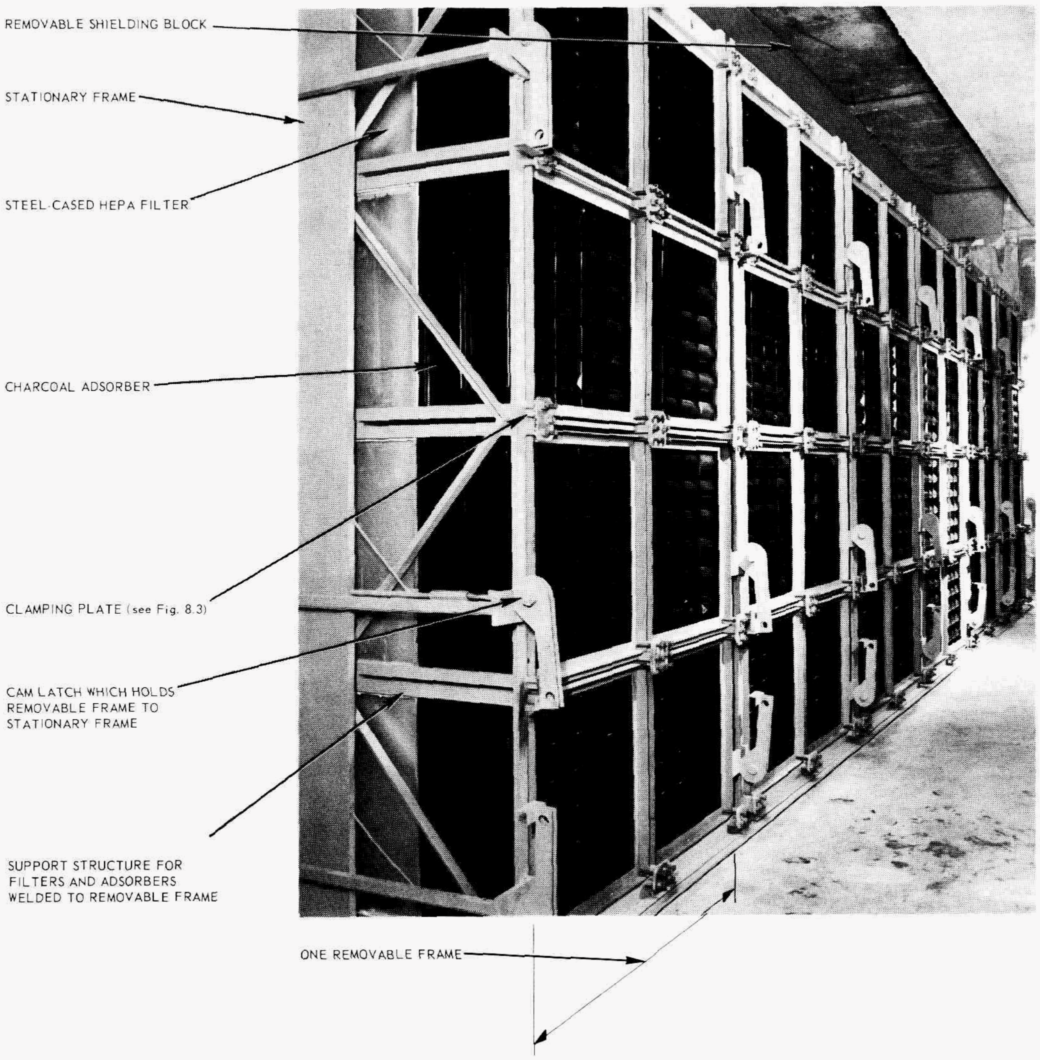


Fig. 8.2. General view of filter bank, Brookhaven bypass filter pit. Cam latches can be released from outside of pit by means of extended-reach tools, enabling frame assembly to be hoisted out by crane through opening in ceiling. Courtesy Brookhaven National Laboratory.

filters after installation but does not permit replacement without upsetting the seals of surrounding filters. The practice of clamping adsorbers to the HEPA filters as shown in Fig. 8.2 saves space and simplifies remote filter change procedures but makes it necessary to remove the adsorbers to change HEPA filters. Close coupling of filters and adsorbers risks losing both should a fire get started in either. This illustrates the type of compromises which sometimes must be made in remotely maintainable systems.

8.2.2 Hanford Reactor Filter System[3]

This is a remotely maintained system installed in an underground pit, as shown in Fig. 8.4. Each compartment has 36 moisture separators, 36 HEPA filters, and 36 pleated-bed charcoal adsorbers installed on removable frames, as shown in Fig. 8.5. The components are replaced by replacing the complete frame assembly, as shown in Figs. 8.5 through 8.14, which indicate some of the problems of handling, space, and contamination control encountered. Radiation levels during the change depicted were not high enough to prevent close contact with contaminated components or to require burial of the contaminated frame assembly. The operation was

[3]J. W. Green *et al.*, Hanford Experience with Reactor Confinement, *Proceedings of the Eighth AEC Air Cleaning Conference,* USAEC Report TID-7677, John Hopkins University, 1963.

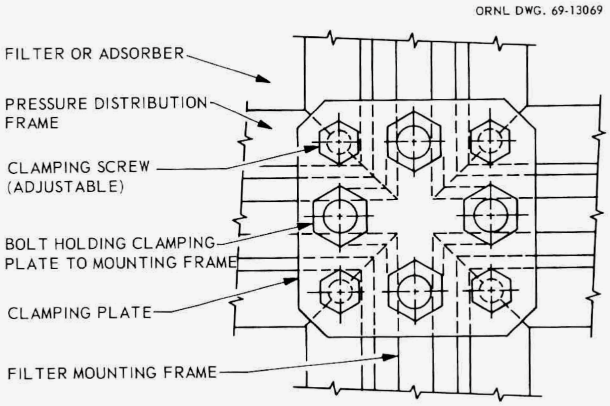


Fig. 8.3. Clamping plate assembly, Brookhaven bypass filter pit. Clamping pressure on individual filters is adjustable, but entire assembly must be removed to replace a filter.

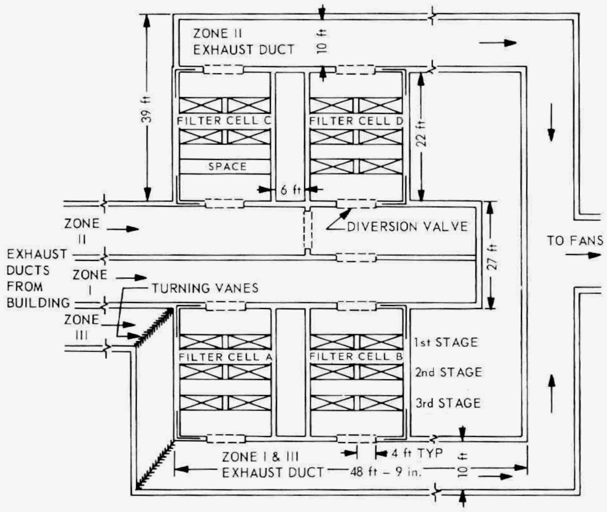


Fig. 8.4. Plan view of Hanford reactor filter system. First stage contains moisture separators, second stage contains HEPA filters, third stage contains pleated bed charcoal adsorbers. Cells A, B, and C are on-line, cell D is normally held in standby. Courtesy USAEC, Richland Operations Office.

Fig. 8.5. Remote filter change, Hanford production reactors. Loading new filters in removable mounting frame. Courtesy USAEC, Richland Operations Office.

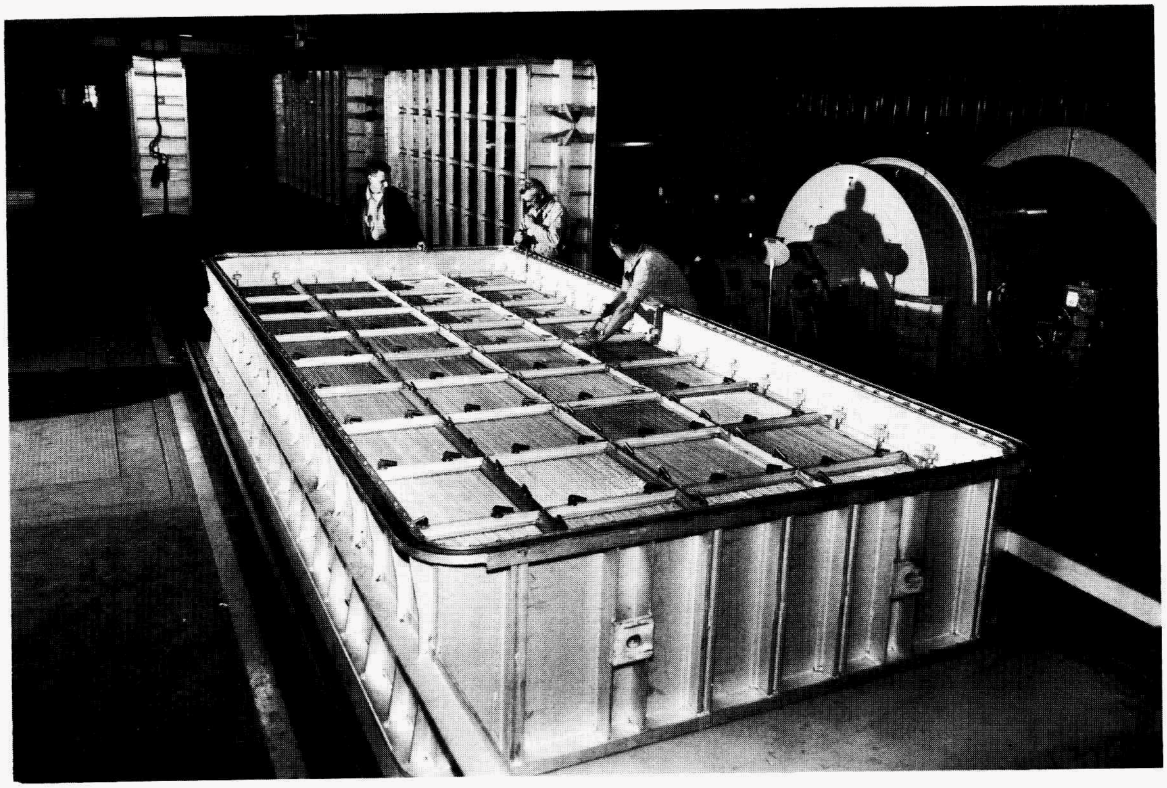


Fig. 8.6. Remote filter change, Hanford production reactors. Filter installation complete. Courtesy USAEC, Richland Operations Office.

Fig. 8.7. Remote filter change, Hanford production reactors. Delivering new frame assembly to installation site. Note special trailer, protective box, storage space required. Courtesy USAEC, Richland Operations Office.

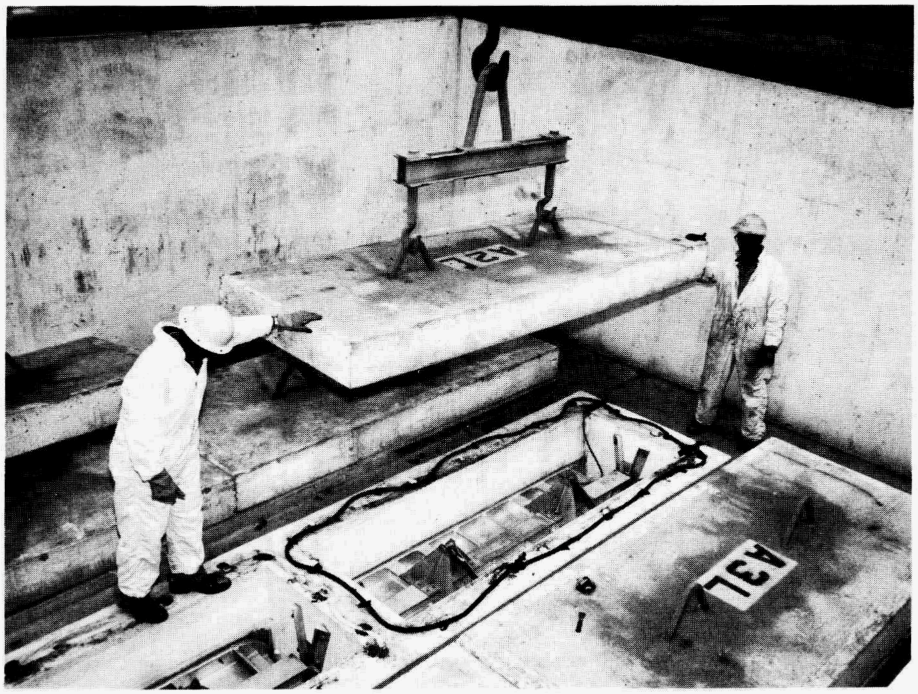


Fig. 8.8. Remote filter change, Hanford production reactors. Removing shielding blocks from filter pit. Note inflatable seal between block and pit. Courtesy USAEC, Richland Operations Office.

Fig. 8.9. Remote filter change, Hanford production reactors. Withdrawing contaminated frame assembly into plastic contamination shield. Courtesy USAEC, Richland Operations Office.

Fig. 8.10. Remote filter change, Hanford production reactors. Temporary storage of contaminated frame assembly. Note space required. Courtesy USAEC, Richland Operations Office.

Fig. 8.11. Remote filter change, Hanford production reactor. Positioning new frame assembly over filter pit opening. Note alignment pins. Courtesy USAEC, Richland Operations Office.

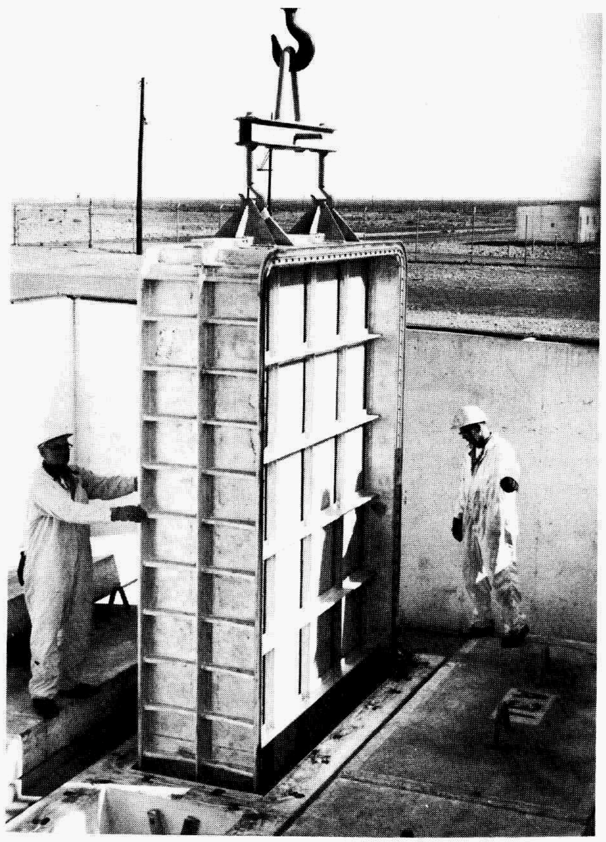


Fig. 8.12. Remote filter change, Hanford production reactor. Lowering new frame assembly into pit. Note lifting assembly. Courtesy USAEC, Richland Operations Office.

Fig. 8.13. Remote filter change, Hanford production reactor. Disassembling used frame assembly. Note radiation monitoring, protective clothing. Courtesy USAEC, Richland Operations Office.

Fig. 8.14. Remote filter change, Hanford production reactor. Cleaning used frame assembly. Note portable steam supply, protective clothing. This type of cleaning is permissible only when contamination levels are very low. Had the frame been badly contaminated, it would probably have had to be buried. Courtesy USAEC, Richland Operations Office.

constantly monitored (Fig. 8.13), and contaminated materials were bagged in plastic (Fig. 8.9 and 8.10) to minimize the spread of radioactive dust that might fall from the dirty filters or frame. Had this operation been done after a major reactor accident, personnel would not be allowed as close to the contaminated housing, frame, and filters, and the entire frame and filter assembly would probably have been buried. The size of the frame (approximately 22 X 9 X 3 ft) suggests the disposal problems that could be encountered.

8.2.3 HFIR Filter System[4]

Figure 8.15 shows the remotely maintained underground filter system of the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory. Two off-gas and two building-ventilation systems are on stream at all times, with the third on standby to permit maintenance without reducing system air flow or interfering with reactor operations and to provide backup protection if filters in either of the other compartments should fail. Components in the off-gas system are individual 1000-cfm units. Components in the building exhaust system are banded together in stacks of three with stainless steel strapping as shown in Fig. 8.16, using a commercially available banding device. There are four mounting frames abreast in each bank. A stack of filters is installed by forcing it against the mounting frame by means of the movable wedge which is installed between the back side of the filters and the stationary wedge; bottoming lugs on the stationary wedge prevent overpressurizing the filters. The stacks and wedges are handled with a crane.

This type of clamping system calls for a high degree of accuracy in construction and very close tolerances in the parallelism, planarity, and spacing of the stationary and movable parts. The mounting frame is made from square tubing and the wedges from $^3/_8$-in. plate. The flatness and parallelism of the mounting frame and the seating surfaces of the wedges must be within $\pm^1/_{16}$ in. and preferably within $\pm^1/_{32}$ in. The spacing between the mounting frame and the stationary wedge is critical and must be maintained within $\pm^1/_{32}$ in. of specified values at all points. Such tolerances are difficult to maintain during construction, and the mounting frame or stationary wedge can be knocked out of tolerance by careless handling during filter replacement.

[4]F. T. Binford and E. N. Cramer (eds.), *The High Flux Isotope Reactor,* USAEC Report ORNL-3572, vol. 1, May 1964.

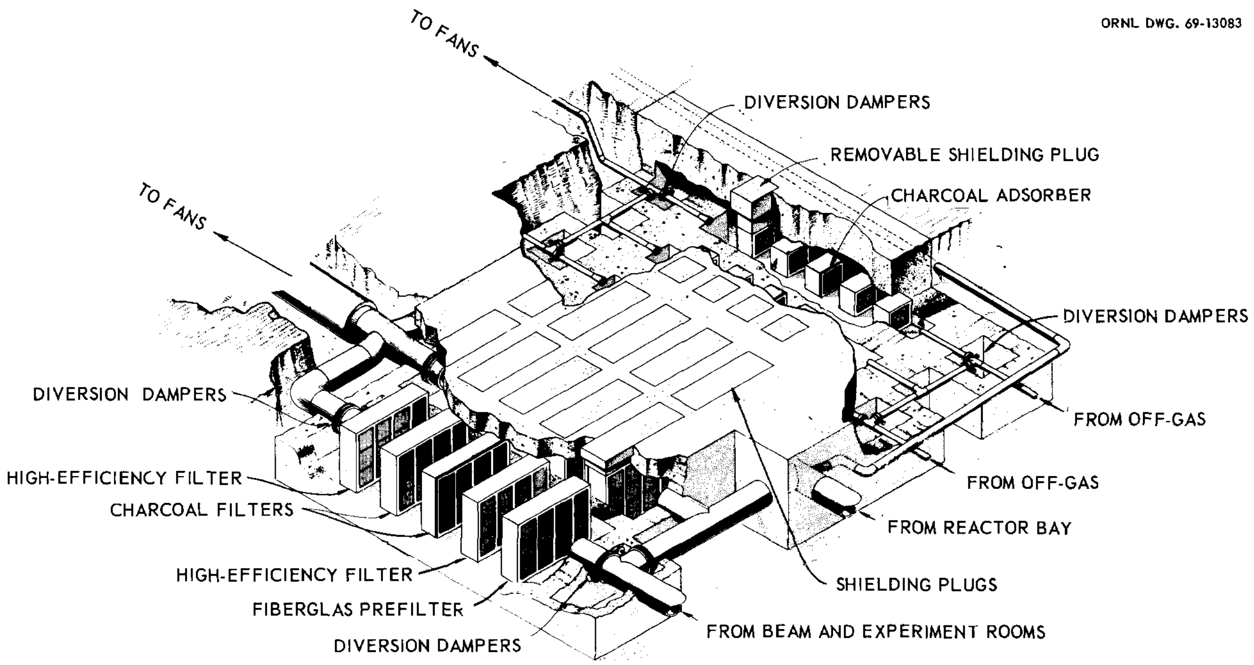


Fig. 8.15. High Flux Isotope Reactor filter system. Courtesy Oak Ridge National Laboratory.

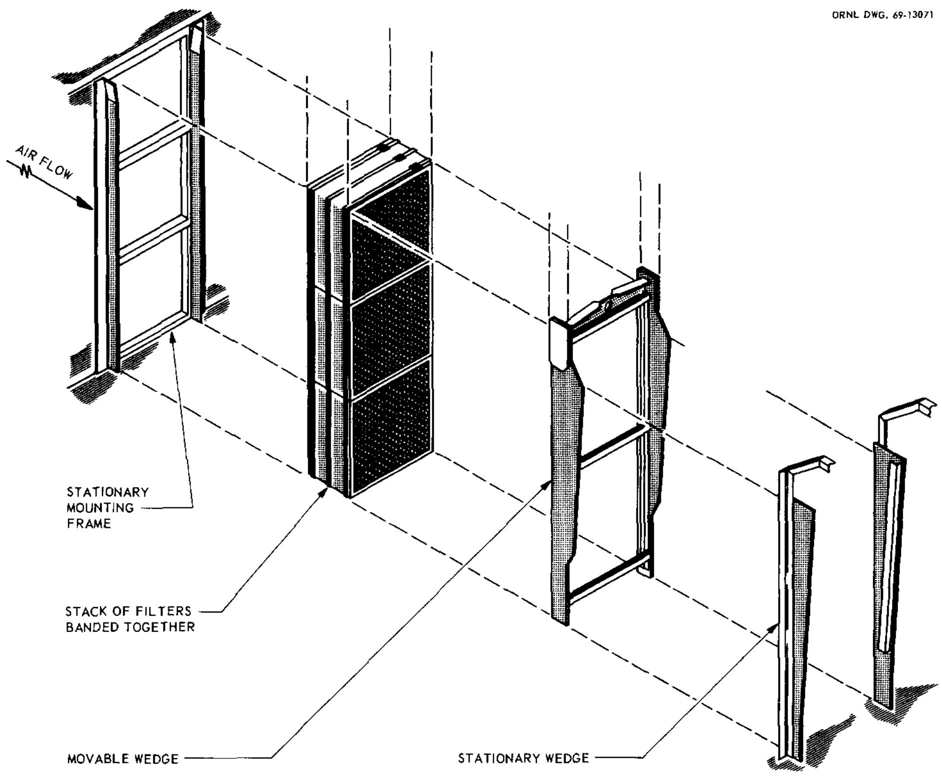


Fig. 8.16. Exploded view of filter clamping method, High Flux Isotope Reactor filter system. Actual distance from face of stationary mounting frame to stationary wedge is approximately 15 in.

8.2.4 Savannah River Reactor Filter System[5]

This system differs from the preceding systems in that the entire filter housing is removed when it is necessary to make a remote filter change. The complete system consists of five housings, four normally on line and one in standby. Each housing contains a bank of 24 knitted-fabric moisture separators (Fig. 3.13), a bank of 40 steel-cased HEPA filters, and a bank of 40 pleated-bed charcoal adsorbers in series, as shown in Fig. 8.17. The housings are mounted on railroad trucks which run on rails on the roof of the reactor building, and are sealed to isolation valves in the wall of the building by means of an inflatable pneumatic seal. To remove a contaminated filter assembly, the isolation valves are closed, the housing is released and run to the edge of the building, then is lifted and lowered to a railroad siding or truck-trailer on the ground by crane. Operation of the isolation valves and of the clamps holding the housing to the building and movement of the housing are controllable either from the reactor control room or from a local control panel on the outside of the building at ground level.

Radiation levels are low enough under normal conditions to permit direct access for filter service. Access doors in the housing permit entry to each bank, and components are clamped to the mounting frames by a nut-and-bolt arrangement.

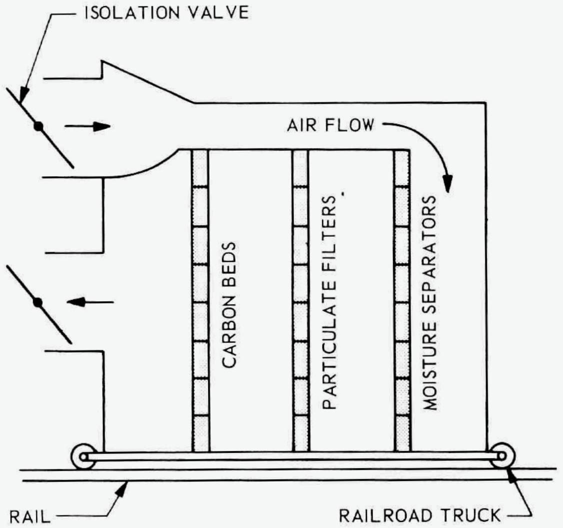
8.2.5 TURF Filter System[6]

This system is installed in a radiochemical plant, the Thorium-Uranium Recycle Facility (TURF), at the Oak

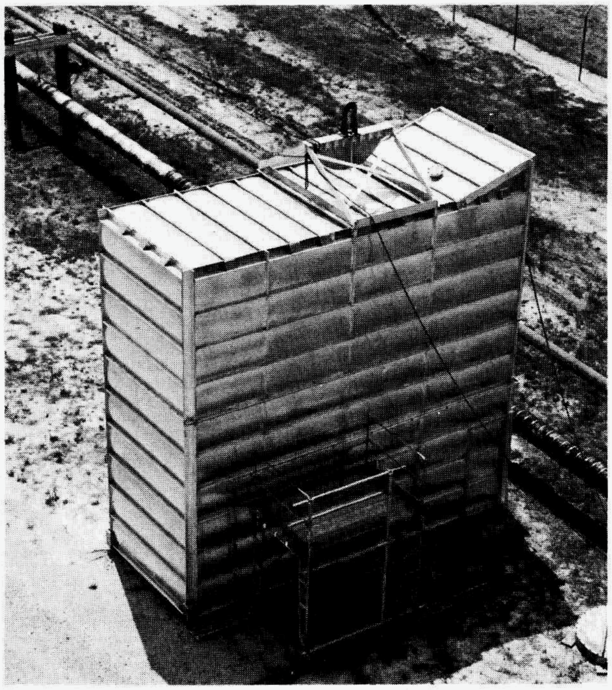
[5]W. S. Durant *et al., Activity Confinement System of the Savannah River Plant Reactors,* USAEC Report DP-1071, Savannah River Laboratory, August 1966.

[6]C. A. Hahs, Developments in Contaminated Filter Removal Equipment, *Proceedings of the Ninth AEC Air Cleaning Conference,* USAEC Report CONF-660904, Harvard Air Cleaning Laboratory, January 1967. (NOTE – this covers the TURF filter system.)

Ridge National Laboratory. The filters are installed in a steel enclosure which is sealed to the building exhaust system by means of the spring-loaded hydraulically actuated stainless steel bellows assemblies shown in Fig. 8.18. Each housing contains a bank of three prefilters in series with a bank of three HEPA filters. Replacement is always by remote procedures. To replace filters, isolation valves in the system are closed, the shielding block is removed, and the water-filled shielded carrier is moved into position (Fig. 8.19). The closure plates are pushed down by an extended-reach tool from outside of the carrier, and bellows assemblies are released by



SECTION THROUGH HOUSING INSTALLED ON ROOF OF BUILDING.



VIEW OF HOUSING BEFORE INSTALLATION. NOTE SIZE COMPARED TO SCAFFOLDING AND FENCE IN BACKGROUND, LIFTING EYE ON TOP.

Fig. 8.17. Filter housing for Savannah River production reactor. Courtesy Savannah River Laboratory.

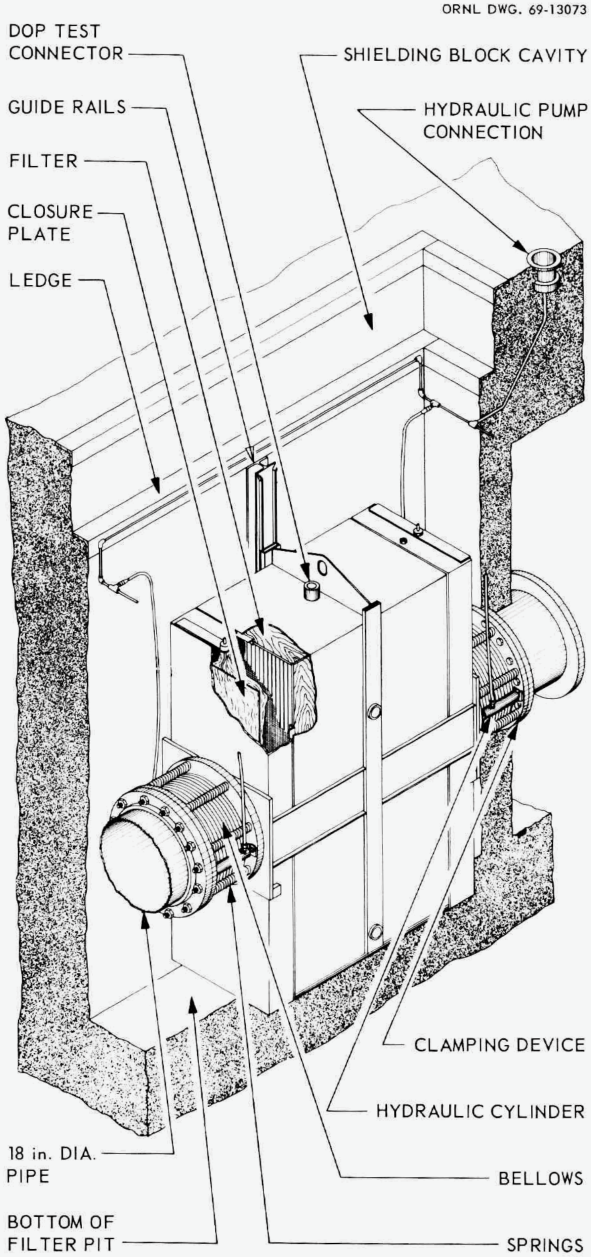


Fig. 8.18. TURF filter installation. Filters installed in replaceable housing, sealed to ducts by means of bellows assemblies. Courtesy Oak Ridge National Laboratory.

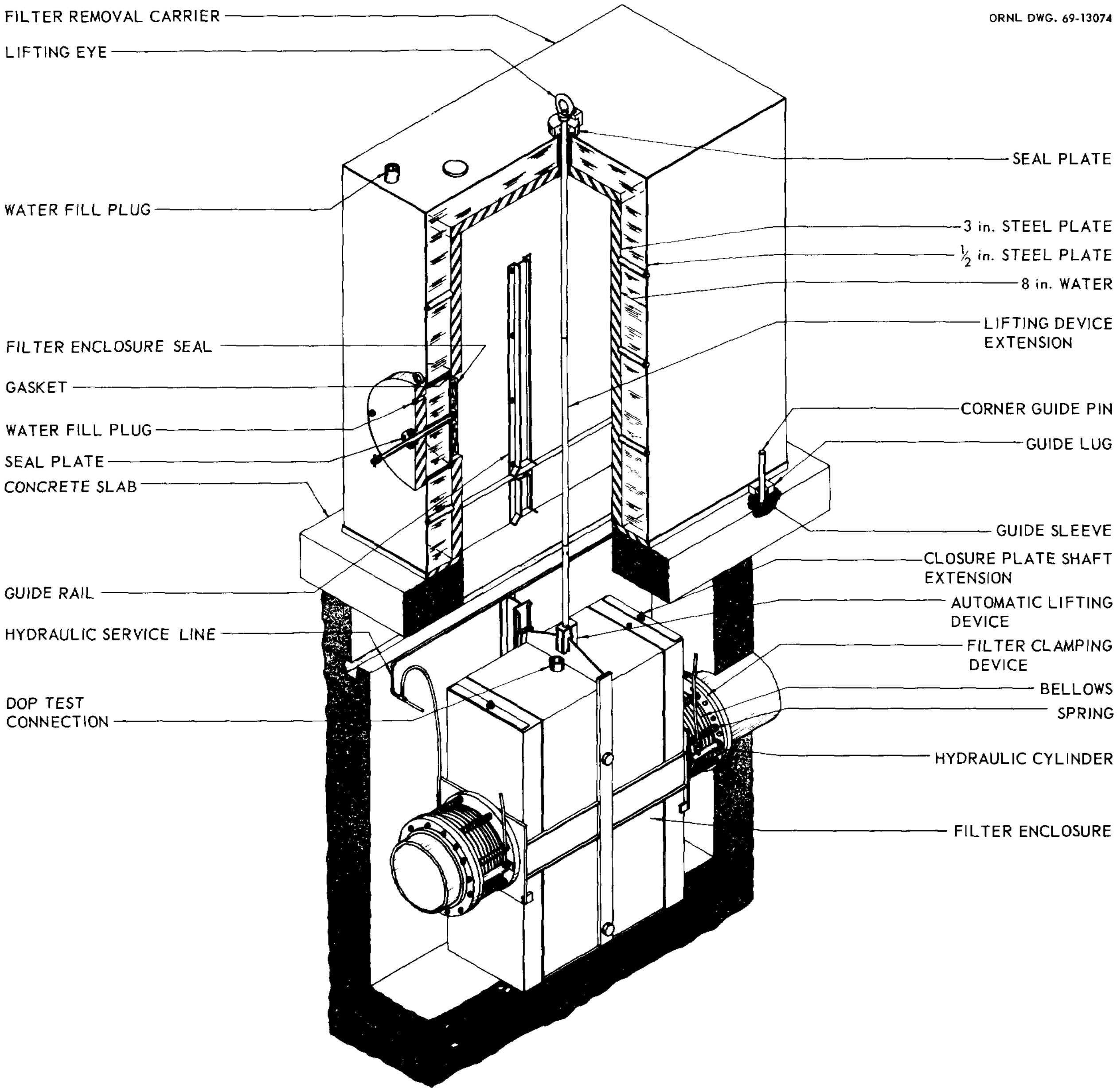


Fig. 8.19. *TURF filter system.* Carrier positioned over pit preparatory to removal of filter housing. Courtesy Oak Ridge National Laboratory.

means of the hydraulic cylinders, a lifting rod is attached to the lifting eye of the housing (Fig. 8.19), and the housing is drawn up into the carrier. A mobile crane then lifts the entire assembly, a bottom plate is installed on the carrier, and the assembly is moved by truck-trailer to a disposal area. The housing is not salvageable. A new housing, with filters already installed, is then lowered into position, and the bellows assemblies are released to seal it into the duct.

This type of installation is very costly because of the close tolerances that must be maintained to ensure proper performance and because the housings are not salvageable.

8.2.6 Hot-Cell Filter Systems

First-stage exhaust filters that are installed inside a hot cell require no special shielding but do require careful planning of filter changing procedures to avoid interference with equipment and operations being carried on within the cell. Figure 8.20 shows a cross section of a hot cell with a typical filter-prefilter installation. The filters are clamped in place with special wing nuts to facilitate manipulation by the electro-

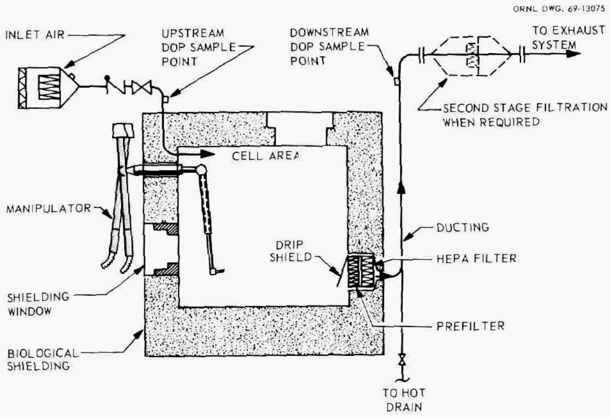


Fig. 8.20. Hot-cell filter installation with filters replaceable from inside the cell.

mechanical manipulator. To remove contaminated filters, the wing nuts are removed, and the filter is picked up by the manipulator, placed in a plastic bag or box, and positioned beneath the access port at the top of the cell preparatory to pickup by a hoist or extended-reach tool. Installation requirements for this type of installation are discussed in Chap. 5.

Second-stage filters are recommended for backup protection during a filter change and to permit first-stage filter changing without shutting down the exhaust fans. The second-stage filters should be installed outside of the cell in a sealed enclosure and should be accessible for direct maintenance.

Figure 8.21 shows a hot-cell filter installed outside of the cell at the Argonne National Laboratory. This is an "incessant" filter installation in which the old filter is pushed out of position as the new filter is moved in, thereby keeping a filter in the duct opening at all times. Because it is a first-stage filter, contamination levels are very high, and the entire installation is heavily shielded with lead. A filter is changed by positioning the lead-shielded carrier (Fig. 8.22) at the end of the

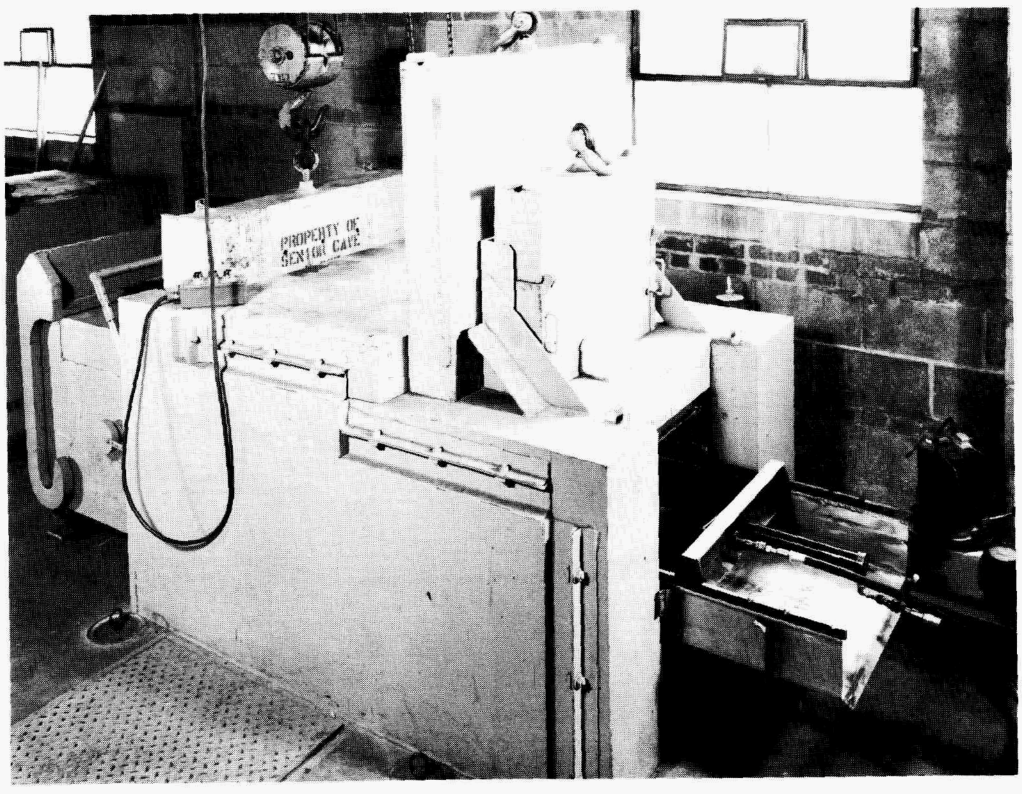


Fig. 8.21. "Incessant" filter housing for first-stage hot-cell filter, Argonne National Laboratory. Courtesy Argonne National Laboratory.

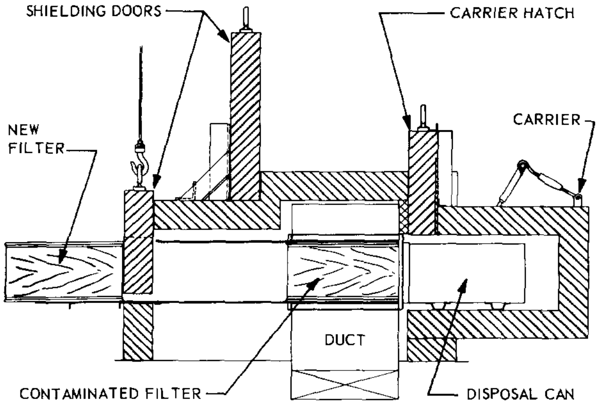


Fig. 8.22. "Incessant" filter changer; carrier and new filter in position for filter change. Courtesy Argonne National Laboratory.

housing, removing the shielding doors, and pushing in a new filter, which pushes the old filter into the carrier. The door of the carrier is then closed, the carrier is removed, and the housing doors are replaced. The filters have gaskets on both sides and seal in place simply by the interference of the gaskets with the mating seal flanges inside the housing.

This type of filter installation is costly and requires considerable manpower (three to five man-days) to change a single 1000-cfm filter. The mechanical features of filter changers of this general design have given considerable difficulty at some sites, and the changers are often operated simply by opening both ends, removing the old filter by hand, and pushing the new filter in by hand. "Incessant" filters are not generally recommended.

8.3 REACTOR POSTACCIDENT AIR-CLEANUP FILTER SYSTEMS

Because of conservative design practices and engineering and safety features, the probability of a major accident involving meltdown of the fuel of a nuclear reactor is remote. However, the possibility does exist and must be planned for. One element in this planning is the provision of an air cleaning system to remove the large quantities of airborne fission products and gases that would be generated by such an accident. There are two types of systems: recirculating and once-through. The type used and the filter components required in the system depend on the reactor type and containment design.

8.3.1 Reactor Containment

With respect to containment, there are three major types: vented containment, pressure containment, and pressure suppression with secondary containment.[7] These are illustrated in Figs. 8.23, 8.24, and 8.25 respectively.

Vented containment is used for the AEC production reactors and for many research reactors. Vented containment structures are usually rectangular buildings of

[7] W. B. Cottrell and A. W. Savolainen (eds.), *U.S. Reactor Containment Technology,* USAEC Report ORNL-NSIC-5, Oak Ridge National Laboratory, 1965.

ORNL DWG. 69-13077

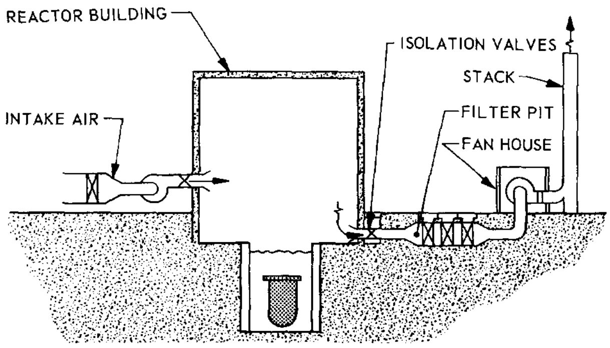


Fig. 8.23. Vented containment with once-through postaccident air-cleanup system.

ORNL DWG. 69-13078

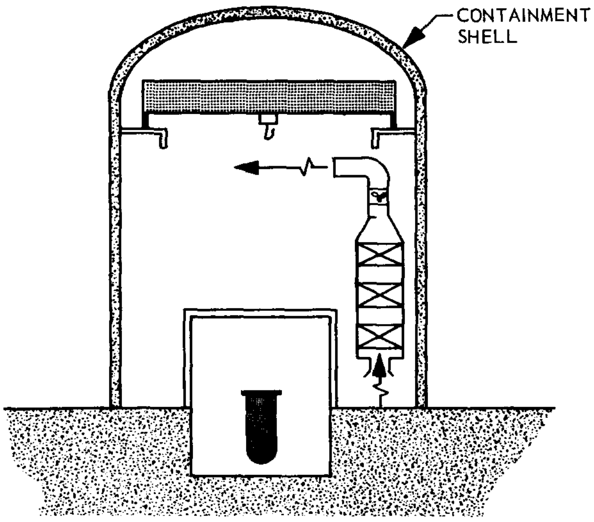


Fig. 8.24. Pressure containment with internal recirculating postaccident cleanup system.

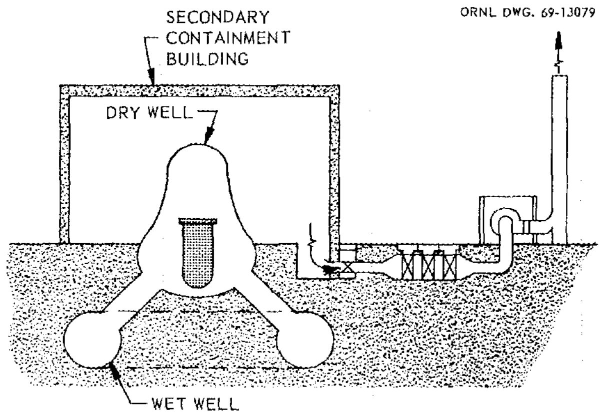


Fig. 8.25. Pressure-suppression containment with once-through postaccident cleanup system venting secondary containment.

relatively conventional design, built to withstand an internal pressure of several pounds per square inch in the event of a major reactor accident. A once-through exhaust air cleaning system, which is continuously on line during both normal and abnormal operation of the reactor, is provided. The air cleaning system has three functions: (1) building ventilation during normal reactor operations, (2) venting the building to prevent overpressurization in the event of a major accident, and (3) purification of the contaminated air resulting from an accident before it is released to the atmosphere. The air cleaning systems for the Brookhaven reactor, the Hanford production reactors, and HFIR, discussed earlier in this chapter, are examples of this type.

In pressure containment (Fig. 8.24), which is used for most pressurized water reactors (PWR) and some boiling water reactors (BWR), the reactor is installed in a large spherical or cylindrical pressure vessel designed to withstand the maximum pressures and temperatures resulting from a major accident. The postaccident cleanup system recirculates entirely within the containment space and serves to remove contaminants from the containment air to reduce the activity level of any air that leaks from the containment following an accident. The postaccident air-cleanup system is usually supplemented with a purge system for cleaning the containment air following periods of normal operation, prior to the entry of personnel.

The third containment type (Fig. 8.25), used in most BWR's, consists of a primary containment surrounded by a secondary-containment building of relatively conventional design. The primary containment consists of the dry well, in which is located the reactor system, and a pressure-suppression pool or wet well which is kept half filled with water. In the case of a major accident, reactor coolant flashed to steam is released under water in the wet well to suppress the buildup of temperature and pressure in the primary containment. Under normal reactor operating conditions, the primary containment is unventilated and the secondary containment is kept at a slight negative pressure, relative to the atmosphere, by means of a ventilating system which exhausts through a bank of HEPA filters. Under accident conditions, the normal ventilating system is shut down and isolated from the secondary containment, and the building is vented through a once-through postaccident air-cleanup system to (1) remove any radioactivity that leaked into the secondary containment before and after the isolation valves of the primary containment closed and (2) prevent overpressurization of the secondary building during the immediate postaccident period. Since the secondary containment "sees" only leakage from the primary containment, the environmental conditions to which the air cleaning components (moisture separator, filter, and absorber) are exposed are relatively innocuous as compared with the environment seen by those components in vented or pressure-containment systems.

8.3.2 Requirements of the Postaccident Air-Cleanup System

In vented and pressure containments, all components of the postaccident air-cleanup system – dampers, moisture separators, filters, adsorbers, turning vanes, ducts, housing, fans, and motors – must be designed, constructed, and maintained for effective and reliable operation during the high-temperature, high-pressure postaccident period and for a period of hours, days, or weeks after temperature and pressure have returned to normal. Design basis accident (DBA) conditions may include shock, elevated pressure, rapid pressure transients, high temperature and humidity, steam, free water, high-density air and gases, high radiation levels, and large quantities of highly radioactive particles and fission product gases. Pressure changes in some reactor systems may be as great as 40 or 45 psi in from 1 to 10 sec; condensing steam temperatures may exceed 275°F; air density may be two to three times normal; and radiation levels may reach 10^8 to 10^9 rads.

Fission product afterheat may result in deterioration and possibly ignition of charcoal adsorbers or dust on filters and in desorption of radioactive iodine unless adequate cooling is maintained. High moisture loading may damage or reduce the effectiveness of filters and adsorbers unless adequate moisture separators and drains are provided. Rapid pressure transients may produce differential pressures large enough to damage or collapse inadequately designed ducts, housing, and dampers. Motors located inside the primary containment, unless adequately cooled, may overheat and burn out in a short period of time under postaccident conditions. Controls and electrical power circuits must withstand the high temperature, pressure, and moisture conditions. Fans must provide the required flow rate under both normal atmospheric conditions and under the high temperatures, pressures, and air densities which will prevail following an accident. Missiles resulting from burst piping or reactor components may destroy ducts, housing, and system components located inside a primary containment unless adequate shielding is provided. Shock waves may damage the housing, filters, and filter mounting frames unless proper attention is paid to structural design and snubbing of the wave. Multiple air cleaning systems, operating in parallel, are required to provide backup protection in the event of system failure, and provision for remote maintenance may be necessary to reactivate failed air cleaning components.

The components required in the postaccident air-cleanup system are a function of the reactor type and the postaccident environment to which the components will be exposed. Typical arrangements are shown in Fig. 8.26. Liquid-metal-cooled reactors may require no more than HEPA filters preceded by graded-density deep-bed prefilters to handle the large quantities of smoke that would be generated from reaction of the coolant with moisture or contaminants. Most water and gas reactors, on the other hand, will require moisture separators, HEPA filters, and adsorbers in addition to cooler, heaters, and sometimes prefilters. When charcoal adsorbers are provided, two HEPA filters are recommended, one upstream and one downstream of the absorber. The functions of the upstream filter are (1) to remove radioactive particulates from the air, (2) to prevent clogging of the charcoal, and (3) to prevent bypassing of the charcoal (since if no filter were provided, iodine adsorbed on particles could penetrate and desorb downstream of the charcoal beds). The downstream filter should be provided for backup protection in the event of failure of the first filter and to prevent the escape of radioactive carbon dust that might leak from the adsorbers. Purge systems generally require only HEPA filters. Secondary-containment exhaust systems may or may not require moisture separators, according to the predicted quantities of free water and steam that might escape from the primary containment before the isolation valves were fully closed.

8.3.3 Recirculating Air-Cleanup Systems

Most recirculating systems are totally enclosed within the containment shell in current reactors and are thus subject to the extremely severe conditions that will prevail in the containment space following a major accident. They are generally an integral part of the containment air cooling system. Usually located high in

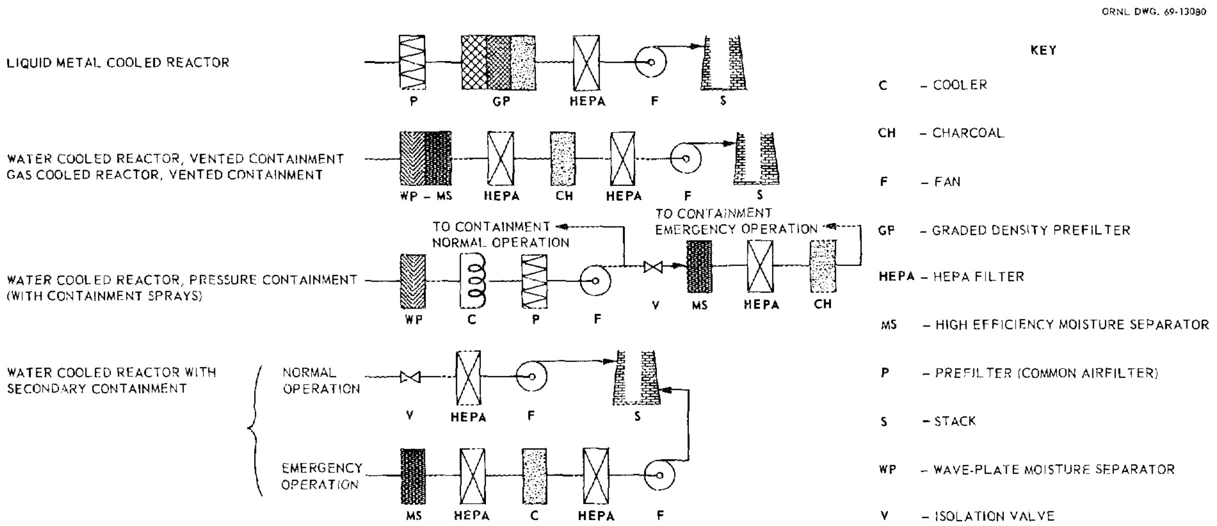


Fig. 8.26. Air cleaning system arrangement for various types of reactors and reactor containments.

the containment space, the components are subject to extreme shaking in the event of an earthquake (the amplification of ground-level earthquake acceleration may be as much as 30 to 150X, according to the distance of the components above ground level).[8] In most systems today, the components are in the direct path of missiles and shock waves generated by an accident. Conventionally designed ducts and filter housings may be subject to external loadings sufficient to cause collapse due to the lag in pressure within the duct or housing as the pressure in the remainder of the containment space rises rapidly following an accident. In addition, because the ducts are open on both ends and the fans are operating continuously during normal operation preceding an accident, there is no way to protect the components from the severe temperature, pressure, and moisture conditions which would prevail immediately after the accident.

If a recirculating postaccident air-cleanup system is to have any chance of survival following a major accident, it must be built at ground level, of very heavy construction, with provision for pressure relief during the initial pressure surge, and be isolated from the immediate postaccident environment, as shown in Fig. 8.27.

The most serious drawback of internal recirculating systems is the inability to replace or repair components following a major accident. Once the containment vessel is closed following an accident, there is no way to gain entrance for maintenance. Even though there is considerable redundancy (most reactors have five or more individual recirculating loops, operating in parallel), there is serious question whether enough of the loops can survive long enough in the postaccident environment to perform their intended function; extended operation following the accident would, in the author's view, lead almost certainly to filter failure. In view of the fragility of the components, the severe postaccident operating conditions, and the inability to repair or replace components, internal recirculating systems may be too unreliable for consideration in future reactors. For this reason, an external recirculating system, as shown in Fig. 8.28, is recommended. In this design, the components are out of the direct path of missiles and shock waves, can be protected from the worst of the immediate postaccident environment by means of isolation valves, are not subject to collapsing forces during the rapid postaccident pressure surge, and can be designed for postaccident maintenance. The major drawback is cost, since ducts, filter housing, and fan housing are extensions of the primary containment and would have to meet the same leak criterion of 0.1% of their volume in 24 hr.[9] Although they would be designed for remote maintenance, provision should be made for direct access for service, filter changing, and testing under normal reactor conditions in order to minimize operating cost.

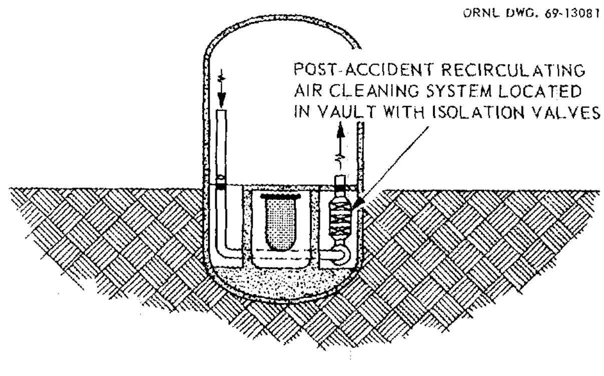


Fig. 8.27. Pressure containment with internal recirculating post-accident cleanup system located in a vault for protection from immediate post-accident environment.

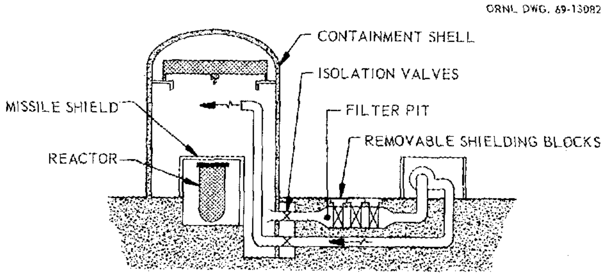


Fig. 8.28. Pressure containment with external recirculating post-accident cleanup system to permit maintenance or replacement of components by remote methods following a major accident.

8.3.4 Once-Through Postaccident Air-Cleanup Systems

Because they are located outside of the primary containment, once-through air-cleanup systems can be designed for remote maintenance following a major

[8] C. G. Bell, Jr., Oak Ridge National Laboratory, personal communication to C. A. Burchsted.

[9] 10-CFR-100, Reactor Site Criteria, *Code of Federal Regulations,* Title 10, Part 100, U.S. Government Printing Office, 1966.

accident. At least for vented containments, postaccident maintenance is considered a necessity and is the rule in the major USAEC reactors described earlier in this chapter; however, we believe that no commercial reactor facility has given consideration to this problem to date. Ducts for vented containment systems must be of heavy construction to withstand shock loadings and should preferably be designed with several right-angle bends to snub shock waves before they get to filter system components. Because air cleaning systems venting secondary containments are not subject to the severe postaccident conditions, postaccident maintenance is not so important; even in these it is recommended that consideration be given to ways and means of replacing components should they fail following an accident. Redundant systems (i.e., two or more filter trains in parallel, with multiple fans) are necessary both for reliable operation and to minimize interference with reactor operation during normal component maintenance. Ducts and filter housing of both vented and secondary containment systems must meet the same leak criteria as the building to which they are attached.

Once-through systems have been used or proposed on at least three reactors with pressure containment at the date of this handbook. In all cases the once-through system supplements a recirculating air-cooling and -cleanup system and is designed to go into operation after the postaccident pressure has decayed. These systems have the advantage of providing a preferential leak path to minimize leakage from other parts of the containment shell and thus control the inadvertent escape of airborne radioactivity. The systems are quite small (2000 or 3000 cfm) as compared with once-through systems for vented containments. The ducts and housings of such systems must meet the same leak criterion as the primary containment shell (0.1% of their volume in 24 hr). Isolation valves are necessary to protect the components from the initial postaccident conditions and to throttle air flow during operation.[10]

8.3.5 Noble Gas

None of the foregoing discussion has considered the problem of noble gases (xenon, krypton, etc.). Because of their chemical inertness and the inability to physically attract them to available adsorbents under postaccident conditions of temperature and humidity, the only method we presently have for counteracting the effects of radioactive noble gases is dilution with large quantities of air and discharge to the atmosphere, a practice which is more and more being questioned.[11] Holdup for decay, although used frequently for normal off-gas, is impractical for the extremely large volumes that would have to be contained in the event of a major accident unless means can be found to separate those gases from the containment air. Means of separating noble gases are under investigation.[12,13]

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[10] G. W. Keilholtz *et al.*, "Air cleaning as an engineered safety feature in light-water-cooled power reactors," USAEC Report ORNL-NSIC-25, Oak Ridge National Laboratory, 1968, paragraph 3.41.

[11] J. D. Abbatt, "World Health Considerations in Airborne Pollution and Special Reference to Radioactive Wastes," *Treatment of Airborne Radioactive Wastes*, International Atomic Energy Agency, Vienna, 1968.

[12] R. H. Rainey *et al.*, "Separation of Radioactive Xenon and Krypton from Other Gases by Use of Permselective Membranes," *Treatment of Airborne Radioactive Wastes*, International Atomic Energy Agency, Vienna, 1968.

[13] J. R. Merriman and J. H. Pashley, Engineering Development of an Absorption Process for the Concentration and Collection of Krypton and Xenon, *Third Summary Progress Report, January Through June, 1968*, USAEC Report K-1770, Oak Ridge Gaseous Diffusion Plant, March 27, 1969.

Appendix A. Sample Specifications

The following specifications are typical of those used in USAEC facilities. They are intended as samples only, and the user is cautioned to review his own requirements and the requirements of the specifications very carefully before using them in part or in their entirety. For example, the prefilter specification covers only a single type of element. These specifications illustrate the type of requirements that should be included, the care needed in the description of components, and the minimum requirements of importance. The adsorber specification is in two parts, one for charcoal, which is applicable to any type of unit, and one for a 1000-cfm pleated-bed cartridge.

PROCUREMENT SPECIFICATION A-1

HEPA FILTER, FIRE RESISTANT, MOISTURE RESISTANT, OPEN FACE, 1000 CFM

1. **SCOPE**

1.1 This specification covers an open-face rectangular fire-resistant high-efficiency particulate air (HEPA) filter for radioactive service. This filter meets the requirements of USAEC Health & Safety Bulletin 212.

2. **REFERENCES**

2.1 USAEC Health & Safety Bulletin 212, *Minimal Specification for the Fire-Resistant High-Efficiency Filter Unit.*

2.2 Edgewood Arsenal, U.S. Army, Instruction Manual 136-300-175, *Instruction Manual,* Q-107 Penetrometer (latest edition).

2.3 Military Specification MIL-F-51079, as amended, *Filter Medium, Fire Resistant, High Efficiency* (latest edition).

2.4 Military Specification MIL-R-6130, as amended, *Rubber, Cellular, Chemically Blown* (latest edition).

2.5 Military Qualified Products List QPL-6130, current edition, *Rubber, Cellular, Chemically Blown.*

2.6 USAEC Health & Safety Bulletin for *Filter Unit Inspection and Testing Service* for current year.

2.7 ASTM Standard D1056, *Sponge and Cellular Rubber Products* (latest edition).

2.8 ASTM Standard A165, *Electrodeposited Coatings of Cadmium on Steel* (latest edition).

2.9 Underwriter's Laboratories Standard UL-586, *High Efficiency Air Filter Units* (latest edition).

2.10 USA Standard Z25.1, *Rules for Rounding Off Numerical Values* (latest edition).

2.11 ASTM Standard A366, *Cold-Rolled Carbon Steel Sheets, Commercial Quality* (latest edition).

2.12 U.S. Department of Commerce Commercial Standard CS-132, *Hardware Cloth* (latest edition).

3. **PERFORMANCE**

3.1 Filtration Efficiency: 0.03% penetration, maximum, through complete filter (medium, frame, and gasket) when operated at rated capacity and at 20% of rated capacity and tested with thermally generated DOP of uniform 0.3-μ droplet size in accordance with Edgewood Arsenal Manual. The increase in penetration when tested at 20% of rated capacity shall not exceed 0.01%.

3.2 Air Flow Capacity: 1000 cfm minimum.

3.3 Air Flow Resistance: 1.0 in. H_2O, gage, maximum, at manufacturer's rated air flow capacity.

3.4 Air Flow Velocity Through Filter Medium: 5 fpm ± 20% when operating at manufacturer's rated capacity.

4. **QUALIFICATION**

4.1 Fire Resistance: In accordance with UL-586.

4.2 Moisture and Overpressure Resistance: Filter shall withstand an overpressure of at least 10 in. H_2O for at least 15 min without visible damage or decrease in filtration efficiency at either the manufacturer's rated air flow or 20% of flow, as determined by testing four units of the same construction that is to be furnished on the order, selected at random from the manufacturer's production line. Filters shall be preconditioned for 24 hr in static 95°F, 95% relative humidity air and then tested in 95°F, 95% relative humidity air containing water spray in an amount of at least 1¼ lb per minute per 1000 cfm at a flow rate to produce a pressure drop of 10 in. H_2O across the filter pack.

4.3 Shock and Vibration: Filters shall withstand a rough handling test without visible damage or decrease in filtration efficiency at either the manufacturer's rated air flow or 20% of flow, as determined by testing two units of the same construction that is to be furnished on the order, selected at random from the manufacturer's production line. The rough handling test shall consist of rigidly fixing the filter to a shaking table and shaking it for 15 min at ¾ in. amplitude and a frequency of 200 cpm.

5. **MATERIALS OF CONSTRUCTION**

5.1 Medium: 0.015-in.-thick (minimum) fiber glass or fiber glass and asbestos having a basis weight of 48 lb per 3000 sq ft (minimum), containing no more than 5% combustible or organic material, in accordance with MIL-F-51079 except: (1) Para. 3.2.10 shall be deleted; (2) Para. 3.2.6.2 shall be changed to read, "The minimum tensile strength after folding shall be no less than 50% of the original tensile strength. . . ."

5.2 Frame: 16-gage cold-rolled carbon steel in accordance with ASTM A366.

5.3 Separators: 0.0015-in.-thick (minimum) aluminum alloy 5052-H39 or 3003-H19.

5.4 Sealant: Elastomeric, polyurethane, or epoxy, which shall produce a filter that meets the requirements of UL-586 and which, after curing, shall not check, crack, or lose more than 5% of its weight when heated for 48 hr at 300°F.

5.5 Face Guard: 4 X 4 mesh galvanized hardware cloth, in accordance with CS-132.

5.6 Gasket: ¼ X ¾ in. neoprene, grade SCE-43, in accordance with ASTM D1056, with cut surfaces all around. Material shall be listed in QPL-R-6130, type II, grade A.

6. **CONSTRUCTION**

6.1 Filter Pack shall be made by pleating a continuous web of medium back and forth over corrugated separators and shall be sealed into the frame with a material meeting the requirements of this specification. Edges of separators shall extend at least ⅛ in. beyond pleats but no closer than ⅛ in. to the face plane of the frame. Pleats and separators shall not be kinked more than ¼ in. from a straight line drawn from end to end of the pleat and shall be perpendicular with the frame within ±¼ in. of a perpendicular to the frame from the opposite end of the pleat.

The filter pack shall be tight as determined by the following test: a back-and-forth force of approximately $\frac{1}{2}$ lb, imposed by a hand or a neoprene-faced block (3 × 5 in. face) pressed against the center of the filter pack with a force of approximately 3 lb perpendicular to the face of the filter, shall cause no motion or shifting of the separators or filter pack more than $\frac{1}{8}$ in. from the rest position in either direction.

6.2 Repairs: Filter medium shall not be spot-patched to repair holes or tears. The medium may be cut and spliced; in splicing, both pieces shall be coated with an adhesive meeting the requirements of Para. 5.4 for 1 to 2 in. back from the cut edge.

6.3 Frame panels shall be made of 14-gage chromized titanium-stabilized carbon steel having a chromium diffusion coating at least 0.0015 in. thick on each surface and having a minimum chromium content at the surface of 20%. Frame shall be assembled with corrosion-resistant or nickel-plated rivets, bolts, or drivescrews. Frame shall have $\frac{3}{4}$-in.-wide double-turned flange on each face. Joint areas of frame panels shall be coated with sealant before assembly to ensure a leak-tight joint.

a. Dimensions: 24 × 24 × 11$\frac{1}{2}$ in.

b. Tolerances: Face dimensions: +0, −$\frac{1}{8}$ in.
Depth: +$\frac{1}{16}$ in., −0.
Diagonals: Face diagonals and diagonals of any side shall be equal within $\frac{1}{8}$ in. total allowance.
Gasket seating area: square with sides of frame within $\frac{3}{64}$ in. maximum offset. Flat and parallel to opposite flange face within $\frac{1}{16}$ in. total allowance at all points. Width, ±$\frac{1}{16}$ in. Surface finish, 63 μ in. AA, or better. Gap between adjacent frame panels, $\frac{1}{32}$ in. maximum. Offset between adjacent frame panels, $\frac{1}{64}$ in. maximum.

c. Face guards shall be provided on both sides and shall be fastened in such a manner that they will not become loose under rough handling (Para. 4.3). Ends of wires shall not project so that they will touch the filter medium or be a safety hazard to personnel handling the filter unit.

6.4 Gasket: Filter shall have a gasket on one face. Gasket shall be cemented evenly to the frame with an elastomeric adhesive and shall not peel at any point when subjected to a peeling force of 3 lb per $\frac{3}{4}$ in. of line of contact. Gasket shall have notched or rabbeted corners; joint contact surfaces shall be coated with adhesive before assembly to ensure a leak-tight joint; joints shall be made only at the corners of the filter unit.

6.5 Filter frame shall be marked on the top panel (with pleats and separators vertical, reading from the downstream face as determined by testing, Para. 7.1) with indelible ink with the following information:

Manufacturer's name or symbol	Filter serial number
Percent penetration, actual, at manufacturer's rated capacity	Air flow capacity
Penetration at 20% flow	Air flow resistance, actual
Inspector's name or symbol	Date of test

Marking shall be clearly legible from a distance of at least 5 ft under an illumination level of 25 ft-c.

7. TEST AND ACCEPTANCE

7.1 The manufacturer shall test each filter unit for compliance with Para. 3.1, 3.2, and 3.3 and shall report the results of the test in accordance with Para. 6.5.

7.2 Each filter shall be labeled in accordance with UL-586.

7.3 A filter design which has been previously qualified in accordance with Para. 4.2 and 4.3 need not be requalified for the current Purchase Order unless there has been a change in construction or materials of construction. Listing in a current Military or Federal Qualified Products List which includes similar requirements will be accepted as evidence of prior qualification.

7.4 Filter will be tested by the appropriate USAEC Quality Assurance Station (QAS) in accordance with the current USAEC Health & Safety Bulletin for *Filter Unit Inspection and Testing Service.* Filters shall be shipped to the appropriate QAS specified in the Health & Safety Bulletin.

7.5 The QAS will inspect each filter element for physical damage and compliance with this specification. The QAS will test each filter element at 1000 and at 200 cfm, with the filter encapsulated to disclose frame leaks.

7.6 Final acceptance shall be at the QAS. Filters which do not meet the requirements of this specification shall be subject to rejection.

8. PREPARATION FOR DELIVERY

8.1 Packaging: Each filter shall be individually packaged in a corrugated paperboard carton meeting the requirements of the Interstate Commerce Commission. The carton shall have corner braces, inserts, or other nondusting means of shock absorption to protect the filter against damage during handling, shipping, and storage. The carton shall be sealed in such a manner that it can be reused by the QAS for shipping from the QAS to the installation site.

8.2 Each carton shall be clearly marked with the manufacturer's name, the Company's name, a description of the item enclosed, the Company's Purchase Order number, the legend FRAGILE -- HANDLE WITH CARE, and a legend or symbol to indicate THIS SIDE UP. Lettering shall be black or red heavy block type, clearly legible from a distance of at least 20 ft under an illumination of 25 ft-c. The filter shall be placed in the carton so that the pleats and separators are vertical.

8.3 Cartons shall be skidded, strapped to pallets, or otherwise packed in the carrier's truck or railway car so that cartons are properly oriented. Cartons shall not be stacked more than three high unless rigid bracing is provided for the upper tiers. Other items shall not be placed on top of cartons during shipment. A packing list shall be stapled or glued to one carton of each skid or pallet load, which shall clearly state if the shipment is partial or complete.

PROCUREMENT SPECIFICATION A-2

ACTIVATED CHARCOAL, IMPREGNATED

1. SCOPE

1.1 This specification covers impregnated activated charcoal for trapping elemental iodine and radioiodine in the form of organic compounds.

2. REFERENCES

2.1 Military Specification MIL-C-17605, *Charcoal, Activated, Technical, Unimpregnated,* latest edition including latest amendment.

2.2 Proposed ASTM Specification (number unassigned), *Tentative Method of Test for Apparent Density of Granulated Activated Carbon.*

2.3 ASTM Specification E11, *Sieves for Testing Purposes*, latest edition.

2.4 USA Standard Z25.1, *Rules for Rounding Off Numerical Values*, latest edition.

2.5 Proposed ASTM Standard (number unassigned), *Measurement of the Ignition Temperature of Activated Carbon.*

3. PERFORMANCE

3.1 Attenuation of Radioactive Iodine as Elemental Iodine: 99.95% minimum per 2 in. of bed depth at 90% relative humidity.

3.2 Attenuation of Radioactive Iodine as Methyl Iodide: 85.0% minimum per 2 in. of bed depth at 90% relative humidity.

3.3 Ignition Temperature: 340°C (644°F), minimum.

4. REQUIREMENTS

4.1 Charcoal shall be new, commercially pure activated carbon impregnated for trapping of radioactive iodine as methyl iodide.

4.2 Numerical values shall be rounded off in accordance with USA Z25.1.

4.3 Mesh Size: In accordance with ASTM E11.

Nominal Mesh Distribution	Pass Screen No.	Percent	Retained by Screen No.
8 X 16		0.1 max.	8
	16	1.0 max.	

4.4 Bulk Density: 25 to 30 lb per cubic foot of bone-dry carbon.

4.5 Hardness: 94% min.

4.6 Activity for carbon tetrachloride: 50% by weight, min.

4.7 Retentivity for carbon tetrachloride: 30% by weight, min.

4.8 Loss in weight on heating: 2% by weight, max.

5. TESTING PROCEDURES

5.1 Attenuation of Radioactive Iodine as Elemental Iodine: Sample size, 1 in. in diameter by 2 in. deep. Precondition sample by exposing to flowing air at 40 fpm face velocity, 25°C, 90% relative humidity for 16 hr. At same air conditions, with 3-in.-deep collector bed downstream, continuously inject radioactive elemental iodine at a concentration of 1 mg per cubic meter of air for 2 hr, then stop iodine injection but continue air flow for 4 hr at same conditions. Upon completion of final 4-hr period, measure activity in sample and in downstream collector by means of a gamma counter. Attenuation is ratio of activity in sample to total activity in sample and collector bed.

5.2 Attenuation of Radioactive Iodine as Methyl Iodide: Same as Para. 5.1 except iodine injection shall be 17.5 mg of methyl iodide (tagged with radioactive iodine) per cubic meter of air.

5.3 Ignition Temperature: In accordance with proposed ASTM Standard *Measurement of the Ignition Temperature of Activated Carbon.*

5.4 Mesh Size Determination: In accordance with MIL-C-17605.

5.5 Bulk Density: In accordance with proposed ASTM Standard *Apparent Density of Granulated Activated Carbon.*

5.6 Hardness: In accordance with MIL-C-17605.

5.7 Activity for Carbon Tetrachloride: In accordance with MIL-C-17605.

5.8 Retentivity for Carbon Tetrachloride: In accordance with MIL-C-17605.

5.9 Loss in Weight on Heating: In accordance with MIL-C-17605.

6. TEST AND ACCEPTANCE

6.1 Seller shall furnish data and samples in accordance with Tables A.1 and A.2.

6.2 Bid sample shall be representative and shall have same base carbon and treatment and same chemical and physical properties as charcoal to be furnished under order. Lot samples are required for charcoal furnished in cartridges, gas filters, or other devices and shall be representative of each manufacturing lot of charcoal included in such devices.

6.3 Failure to meet the requirements of this specification shall be cause for rejection of charcoal furnished under the Company's Purchase Order.

Table A.1. Data Furnished by Seller

	Descriptive Data, Three Copies with Bid	Test Data from Each Manufacturing Lot, Three Copies with Order
Certified attenuation of radioactive iodine as elemental iodine	X	X
Certified attenuation of radioactive iodine as methyl iodide	X	X
Ignition temperature	X	X
Mesh size	X	X
Bulk density	X	X
Hardness	X	X
Activity for carbon tetrachloride	X	X
Retentivity for carbon tetrachloride	X	X
Loss in weight on heating (moisture content)	X	X

Table A.2. Samples Furnished by Seller

	With Bid	With Order
200-g sample representative of charcoal to be furnished	X	
200-g sample representative of each manufacturing lot furnished in special devices (not required for bulk shipments)		X

7. PREPARATION FOR SHIPMENT

7.1 Packaging – Bulk Charcoal shall be packaged in sealed impermeable plastic bags, sealed drums with impermeable plastic liner, or other moisture-resistant packaging approved by the Company. The charcoal shall be packaged in such a manner that crushing and fracture of individual granules are minimized during handling, shipping, and storage.

7.2 Marking: Seller shall tag each package of bulk charcoal and permanently mark each cartridge, gas filter, or other device giving the following information: Manufacturer's name, grade designation, and lot number; manufacturer's name, grade designation, and lot number for base carbon; Company's specification number; and Company's Purchase Order number.

PROCUREMENT SPECIFICATION A-3

CHARCOAL ADSORPTION UNIT, PLEATED BED

1. SCOPE

1.1 This specification covers a pleated-bed activated-charcoal adsorption unit for trapping elemental iodine and radioiodine in the form of organic compounds.

2. REFERENCES

2.1 Procurement Specification A-2, *Activated Charcoal, Impregnated.*

2.2 ASTM A240, *Stainless Steel Plate, Sheet, and Strip* (latest edition).

2.3 ASTM D1056, *Sponge and Cellular Rubber Products* (latest edition).

2.4 Military Qualified Products List QPL-R-6130, *Rubber, Cellular, Chemically Blown* (latest edition).

2.5 USAEC Report DP-870, *Nondestructive Test of Carbon Beds for Reactor Containment Applications* (Savannah River Laboratory).

3. PERFORMANCE REQUIREMENTS

3.1 Iodine Trapping Efficiency – In accordance with Procurement Specification A-2 for activated charcoal.

3.2 Leak Efficiency – 99.9% minimum when tested in accordance with Para. 5.2.

3.3 Air Flow Capacity – 1000 standard cubic feet per minute when used for trapping elemental iodine only; 800 standard cubic feet per minute (two beds in series) when used for trapping methyl iodide.

3.4 Air Flow Resistance – 1.0 in. H_2O, maximum, at rated air flow capacity.

4. TECHNICAL REQUIREMENTS

4.1 Materials

a. Activated Charcoal: In accordance with Procurement Specification A-2.

b. Stainless Steel: Type 304L sheet, annealed and pickled, 2B finish or better, in accordance with ASTM A240.

c. Frame: Stainless steel, 14-gage minimum, with 11-gage reinforcing ribs welded to removable sides.

d. Charcoal-Bed Screens and Dividers: Stainless steel, 24-gage minimum; perforations shall be 0.048 in. diam max. Screens shall have at least 220 holes per square inch with 1-in.-wide unperforated margins on sides that contact removable sides of frame.

e. Charcoal-Bed Caps and Spacers: Stainless steel, 20-gage minimum.

f. Gaskets: Closed cell neoprene, grade SCE-43, in accordance with ASTM D1056. Also shall be listed in QPL-6130, type II, grade A.

g. Adhesive: Natural or synthetic rubber base, moisture-, heat-, and ozone-resistant, self-extinguishing when exposed to open flame. Adhesive shall not crack, check, or delaminate from neoprene or metal surfaces when exposed to 250°F air for 8 hr, after curing.

4.2 Construction

a. Seller shall submit detail drawings showing construction, weld-joint details, and dimensions of the proposed filter with the bid.

b. Charcoal Bed: Bed shall be 1 in. thick (plus 1/8 in., minus 0 in.) at all points. Pleats may have either rounded or square noses on both upstream and downstream faces and shall have dividers which extend the full width of the pleat at each nose to prevent settling of the charcoal and to space the screens. The nose of each pleat shall be covered with a nonperforated cap which extends the full width of the pleat and which extends inward from the outer extremity of the nose for at least 1 in. on each side of the nose to prevent direct impingement of air on the nose area and to prevent channeling of the charcoal. Edges of the screen shall be continuously seal-welded to the nonremovable frame sides. Outer pleats shall make an angle of at least 7° with the frame sides so that air will flow through those pleats. Nonperforated edges of the screens shall seal into 3/8-in.-thick gaskets; compression of the sealing gaskets shall be at least 50% in the contact areas.

c. Frame: Frame shall have two removable sides bolted with stainless steel machine screws and hardenable stainless steel nuts. Frame shall have $^3/_4$-in.-wide double-turned flanges on both faces. Outside dimensions of frame face shall be 24 X 24 inches (plus 0, minus $^1/_8$ in.). Depth of frame shall be $11^1/_2$ in. (plus $^1/_{16}$ in., minus 0). Faces of frame shall be flat and parallel with $^1/_{16}$ in. total allowance. Flange faces shall be square with the frame sides within ±2°. Face diagonals shall be equal within $^1/_8$ in. total allowance. Maximum offset between adjacent flange-face members after the frame is bolted together shall be $^1/_{64}$ in. Maximum gap between adjacent flange-face members after frame is bolted together shall be $^1/_{32}$ in. All welds shall be inspected for leaks and cracks using liquid penetrant; weld defects shall be ground out and repaired, and the area reinspected using liquid penetrant. All welds shall be ground smooth to the touch.

d. Charging: Charcoal shall be packed to a packing density of 29 lb/cu ft minimum, bone dry carbon, based on the apparent density method. Charcoal shall be vibrated during charging to eliminate settling of charcoal during handling, shipping, and operation. Charcoal bed shall be filled to overflowing and vibrated for 2 min at a frequency of 200 cps and amplitude of $^3/_4$ in. with no settling before the final frame side is bolted in place. After charging, fines shall be blown out with clean oil-free compressed air at a minimum nozzle velocity of 5000 fpm, blowing only in the direction of air flow through the bed, that is, from nongasketed face to gasketed face.

e. A $^3/_4$-in.-wide by $^1/_4$-in.-thick gasket shall be glued to the downstream flange of the filter upon completion of assembly. Gasket shall have cut surfaces on both $^3/_4$-in.-wide faces. Gasket shall be a continuous strip or shall have notched or rabbeted corners, the mating surfaces of which shall be coated with adhesive before assembly.

4.3 Marking: Each filter element shall be legibly and permanently marked on the top frame panel (with pleats horizontal) with the following information.

Manufacturer's name, designation, and serial number of filter unit.
Manufacturer's name, grade designation, and lot number for activated charcoal.
Manufacturer's name, grade designation, and lot number for base carbon.
Arrow or other indication of direction of air flow during test.
Air flow capacity and resistance, as determined by test.
Leak efficiency.

5. ACCEPTANCE AND TEST

5.1 Seller shall submit the following for Company approval: (1) shop drawings of filter element as specified in 4.2*a* of this specification with bid and (2) data and samples for activated charcoal as specified in 6.0 of Specification A-2 with bid and with order.

5.2 Seller shall test each filter for resistance at rated capacity and for leaks. Leak test shall be made at an air flow rate of 250 cfm standard air thoroughly mixed with 500 ppm refrigerant 112. Readings of the refrigerant 112 concentration upstream and downstream of the filter shall be made using a gas chromatograph having a sensitivity of at least 0.03 ppm halides in air containing the ordinary amount of hydrocarbons. Efficiency = 100 times (one minus ratio of downstream concentration to upstream concentration). A detailed description of the leak test (except using refrigerant 12) is given in USAEC Report DP-870.

5.3 Seller shall notify the Company at least ten working days before the start of tests. Company may elect to witness Seller's tests. Final acceptance shall be at the installation site following inspection and in-place leak tests. Filters that do not meet the requirements of this specification shall be subject to rejection.

5.4 If settling of charcoal occurs during shipping, handling, or operation, Seller shall recharge the bed at the installation site, using his own personnel and at no expense to the Company.

6. PREPARATION FOR DELIVERY

6.1 Packaging: Filters shall be individually wrapped in heat-sealed plastic bags which are impermeable to moisture and shall be individually packaged in wood or corrugated paperboard cartons having corner braces, inserts, or other means of shock prevention to protect the filter during handling, shipping, and storage.

6.2 Filters shall be placed in cartons with pleats horizontal. Each carton shall be clearly marked: FRAGILE – HANDLE WITH CARE – THIS SIDE UP. Lettering shall be heavy block type at least ¾ in. high.

PROCUREMENT SPECIFICATION A-4

AIR FILTER, EXTENDED MEDIUM, 80% EFFICIENCY

1. **SCOPE**

1.1 This specification covers common air filters for use in ventilating and radioactive exhaust service. Filters are extended-medium dry type, with pleated medium and full-depth rigid frame.

2. **REFERENCES**

2.1 National Bureau of Standards (NBS) bulletin (mimeographed) *A Test Method for Air Filters,* by A. S. Dill, January 26, 1966.

2.2 Underwriters' Laboratories (UL) Standard UL-900, *Air Filter Units* (current edition).

2.3 Underwriter's Laboratories *Building Materials List* (current edition or supplement).

2.4 ASTM Standard D1056, *Sponge and Cellular Rubber Products* (current edition).

3. **PERFORMANCE**

3.1 Filtration Efficiency: 80 to 90% NBS Atmospheric Stain (dust spot), average, in accordance with NBS bulletin.

3.2 Air Flow Capacity: 1000 to 2000 cfm.

3.3 Dust Holding Capacity: 4 lb NBS standard test dust (with linters), minimum. Air flow resistance of loaded filter, operating at rated air flow capacity, shall not exceed 1.0 in. H_2O.

4. **OTHER REQUIREMENTS**

4.1 Fire Resistance: Class 1 in accordance with UL-900. Filters shall be labeled in accordance with UL-900 and shall be listed in the current UL *Building Materials List.*

4.2 Overpressure Resistance: Filters shall withstand an air flow which will produce a pressure drop across the filter of at least 5 in. H_2O for at least 15 min without visible damage or loss in filtration efficiency.

5. **MATERIALS OF CONSTRUCTION**

5.1 Medium: Waterproofed fiber glass or fiber glass and asbestos paper.

5.2 Separators: 0.0015-in.-thick (minimum) aluminum alloy, H19 temper.

5.3 Frame: Steel, mineral board, fire-resistant exterior-grade plywood, or wood particle board.

5.4 Gasket: ¼-in.-thick neoprene, grade SCE43, in accordance with ASTM D1056.

6. **CONSTRUCTION**

6.1 Filter pack shall be formed by pleating a continuous web of medium back and forth over corrugated separators and shall be sealed into a rigid frame extending the full depth of the filter pack. Faces of frame shall extend at least ⅛ in. beyond the separators. Pleats shall not be kinked more than ¼ in. from a straight line drawn from end to end of the pleat and shall be perpendicular to the frame within ±¼ in. of a perpendicular drawn to the frame from the opposite end of the pleat. The filter pack shall be tight as determined by the following test:

A back-and-forth force of approximately ½ lb, imposed by a hand or by a 3 × 5 in. neoprene-sponge-faced block pressed against the center of the filter pack with a force of approximately 1 lb perpendicular to the face of the filter pack, shall cause no motion or shifting of any pleat or separator more than 3/16 in. from its original position.

6.2 Frame shall have $\frac{1}{2}$- to $\frac{3}{4}$-in.-wide flange on both faces.
Dimensions: 24 X 24 X 11$\frac{1}{2}$ in.
Tolerances: Face dimensions: +0, $-\frac{1}{8}$ in.
Depth: $+\frac{1}{16}$ in., -0.
Diagonals: equal within $\frac{1}{8}$ in. total allowance.

6.3 Gasket: Filter shall have a gasket on one face. Gasket shall have cut surfaces on both faces (no natural skin) and shall be cemented evenly to the flange of the frame. The gasket shall not peel off at any point when subjected to a peeling force of 3 lb per inch of width.

6.4 Marking: Each filter shall be marked or labeled on the top frame panel (i.e., with pleats vertical) with the following information.

Manufacturer's name or symbol	Model or catalog number
Air flow capacity	Air flow resistance
Certified average efficiency	UL certification

7. **TEST AND ACCEPTANCE**

7.1 Seller shall certify that the filter meets the requirements of Para. 3 and 4.

7.2 Seller shall furnish typical test data to support the certification if requested by the Company.

7.3 Seller shall package the filters to prevent damage during shipment. Final acceptance shall be at the installation site. Filters which are damaged or which do not meet the requirements of this specification shall be subject to rejection.

PROCUREMENT SPECIFICATION A-5

MOISTURE SEPARATOR, 1600 CFM AIR FLOW

1. **SCOPE**

1.1 This specification covers a 1600-cfm knitted-fabric moisture separator for removal of large quantities of mist and water spray from air at high throughput and low pressure drop in a radioactive filtration system.

2. **REFERENCES**

2.1 Procurement Specification A-1, *HEPA Filter, Fire Resistant, Moisture Resistant, Open Face, 1000 cfm.*

2.2 ASTM A240, *Stainless Steel Plate, Sheet, and Strip* (latest edition).

2.3 ASTM D1056, *Sponge and Cellular Rubber Products* (latest edition).

2.4 USAEC Report DP-1071, *Activity Confinement System of the Savannah River Plant Reactors,* E. I. du Pont de Nemours & Company, Savannah River Laboratory, August 1966.

3. **PERFORMANCE**

3.1 Filtration Efficiency: 99.9% for all water droplets 1 to 3 μ in diameter and larger for air containing 0.005 lb per cubic foot and at an air velocity of 430 to 450 fpm. See Para. 6.3 for test procedure.

3.2 Air Flow Capacity: 1600 cfm for air containing up to 0.005 lb per cubic foot of free moisture as water spray or condensed steam.

3.3 Air Flow Resistance: 0.95 in. H_2O ±0.05 in. H_2O at a flow rate of 1600 cfm standard air per minute.

3.4 Water Capacity: 8 lb free water (as condensed steam or water spray) per minute (1 gpm) without plugging or carryover.

4. REQUIREMENTS

4.1 Performance shall be determined on a representative moisture separator selected at random from the manufacturer's production line.

4.2 Overpressure Resistance: Moisture separator shall withstand an overpressure of at least 15 in. H_2O for a period of at least 15 min without visible damage, as determined by testing the unit selected for performance testing under Para. 4.1. Overpressure tests shall be made after completion of performance tests or in conjunction with performance tests.

4.3 Shock and Vibration: Filters shall withstand a rough handling test without visible damage, as determined by testing the unit previously tested for overpressure resistance. Rough handling test shall consist of rigidly fixing the filter to a shaking table and shaking it for 15 min at $^3/_4$ in. amplitude and a frequency of 200 cpm.

5. CONSTRUCTION

5.1 Separator shall consist of a number of mats knitted from 20-μ max diameter monofilament TFE plastic yarn and stainless steel wire. The pack shall be constrained by 4 × 4 in. screens made from 16-gage (minimum) stainless steel wire. Edge compression of the pack, when installed in the frame, shall be $^3/_8$ in. minimum, $^1/_2$ in. maximum.

5.2 Frame shall be made from 16-gage (minimum) type 304L stainless steel formed into a channel cross section 2 in. wide with 1-in. sides. Corners shall be welded, and welds shall be ground smooth and flush with the surrounding base metal.

5.3 Gasket: A $^1/_4$ × 1 in. neoprene gasket, grade SCE-43 in accordance with ASTM D1056, shall be cemented evenly to one face of the frame with an elastomeric adhesive. Gasket shall not peel at any point when subjected to a peeling force of 4 lb per 1 in. of line of contact. Gasket may be notched or rabbeted only at corners, and all contact surfaces at such joints shall be coated with adhesive before assembly to ensure a leak-tight joint.

5.4 Marking: Frame shall be metal-stamped or etched with the following information:

Manufacturer's name or symbol	Manufacturer's model number
Serial number	Air flow capacity
Specification number	Air flow resistance

6. TEST AND ACCEPTANCE

6.1 Seller shall submit a description of the proposed moisture separator with his bid, including performance characteristics, number of mats per element, yarn and wire diameter, packing density, and typical test reports, including conditions of tests.

6.2 A moisture separator design which has been previously qualified in accordance with Para. 3.0, 4.2, and 4.3 need not be requalified for the current Purchase Order unless there has been a change in construction or materials of construction.

6.3 Filtration efficiency shall be determined by exposing a representative separator to flowing air at a rate of at least 1600 cfm while injecting water spray at a rate of 1 gpm at the separator face. Spray nozzle shall produce a spray consisting of drops of 250 to 300 μ mass-median diameter, maximum. Provision shall be made for accurately (within ±5%) measuring the weight of water introduced to the duct, the weight of water condensing in the duct, and the weight of water collected by the separator. Efficiency = 100 times (weight of water collected in separator) divided by (weight of water introduced minus weight of water condensing in the duct). The separator shall also be exposed to saturated steam at a flow rate of at least 1000 cfm for 1 hr; there shall be no visible water droplets downstream of the separator during the test. For a further discussion of these tests, see USAEC Report DP-1071.

6.4 Where previous qualification has not been accepted in lieu of tests, Seller shall notify the Company at least ten days before the start of tests so that the Company's representative can witness the tests. Seller shall submit a detailed description of the test, including equipment, procedures, and measurement techniques, with the bid.

6.5 Acceptance shall be at the installation site following inspection for damage and compliance with this specification.

Appendix B. Estimating Forms

The attached forms summarize the information needed to make proper comparisons between candidate filter systems. Labor costs for the first form are found from the second form. The second form includes the major items involved in replacing filters in a contaminated exhaust system – additional factors may have to be added for a particular system. A separate cost analysis (first form) must be made for each bank of components for each combination to be prepared. The total system cost is the sum of the costs of the individual banks.

AIR FILTER SYSTEM COST ANALYSIS

Location: ______________ Capacity: ______ cfm. Resistance: Clean ______ in. H_2O. Average: ______ in. H_2O.

Filter unit, manufacturer and model: ______________ Filter Unit Dimensions: ______ X ______ X ______

Estd filter life: ____ mo. System life: ______ years. Hours of operation per year: ______ Escalation: Labor ____ %/year. Materials: ____ %/year. Power: ____ %/year.

Capital costs	Dollars
Mounting frame	______
Additional support structure, service galleries, etc.	______
Filter auxiliaries (loading, cleaning equipment, etc.)	______
Filter units (initial set)	______
Housing	______
Blower, motor, and mounting	______
Controls and instrumentation	______
Remote handling equipment (if required)	______
Wiring and utilities	______
Labor — Hours Rate Burden	
Mechanical	______
Electrical	______
Space ____ sq ft at $ ______ /sq ft	______
Total capital cost	______

Annual operating costs

Amortization at ______ % interest

Power cost, (___ hp) X (778) X (___ kwhr) X (___ hr) = ______

(see Note)

Maintenance

	Dollars per 1000 cfm	Changes per Year	Total Cost (dollars/year)	Escalation Rate	Adjustment Cost**
Replacement filters	______	______	______	______	______
Medium coating mtls*	______	______	______	______	______
Encapsulation mtls*	______	______	______	______	______
Cleaning costs*	______	______	______	______	______
Disposal and burial*	______	______	______	______	______
New material storage	______	______	______	______	______
Labor at ___ hr/unit	______	______	______	______	______

Total average annual maintenance costs ______

*If required.

**Adjustment for estimated future cost increases.

Total average annual cost: $ ______

Total cost for ____ years: $ ______

Note: hp = (cfm X Δp)/(6356 X eff)
where eff = (motor efficiency) X (fan efficiency)

LABOR COST ESTIMATING FORM FOR FILTERS INSTALLED IN RADIOACTIVE EXHAUST SYSTEM

Operation	Personnel		Time	
	Type	Number of Men	X Hours	= Man-Hours
Make ready	Supervisory			
Planning				
Move filters to installation site				
Inspect	Technician			
Prepare area: place barriers, floor coverings, etc.				
Dress mechanics: coveralls ☐ shoe covers ☐ respirators ☐ tape clothing ☐	Mechanic			
Other				
Replace filters	Supervisory			
Prefilters: Quantity				
Final filters: Quantity	Technician			
Bag prefilters				
Bag and/or box final filters	Mechanic			
Other				
Cleanup	Supervisory			
Remove old filters to temporary storage area				
Bag and remove tools, etc.; take to decontamination area				
Bag and remove trash				
Clean up area	Technician			
Health Physics survey				
Undress mechanics				
Leak test bank with DOP				
Burial	Mechanic			
Decontaminate				
Rebalance system				
Other				

Appendix C. Care and Handling of HEPA Filters[1]

The high-efficiency filter unit can be handled without damage if precautions are taken in handling, storage, and installation. Inspection upon delivery and upon withdrawal from stock is important, as is inspection before and after installation. A filter unit should be inspected each time it is handled to guard against installation of a damaged item.

The precautions and recommendations in this publication are based upon actual experience and current development.

I. PACKAGING AND SHIPPING

Packaging practice varies among the filter unit manufacturers. Normally, units are packaged in cardboard cartons with various approaches existing for internal strengthening and impact resistance of the container. Usually a carton will contain one of the larger units, such as the 1000 cfm (cubic feet per minute), 24 × 24 × 11½ in. in size; or it may have two 500 cfm, 24 × 24 × 5⅞ in. The smaller sizes, 50 cfm, 8 × 8 × 5⅞ in., and the 25 cfm, 8 × 8 × 3¹⁄₁₆ in., frequently are packaged in multiple.

When a filter unit is placed in the carton, it is inserted so that the pleated folds are vertical to prevent damage in shipment. To prevent sagging of the pleats, it is important that vertical positioning of the pleats be maintained in handling and storage. Moreover, the vertical position is the position in which the filter unit should be installed for operation.

The shipping carton normally is marked with a conspicuous vertical arrow and "This Side Up" to indicate positioning of the carton in the transporting vehicle. Other markings, "Handle With Care," "Use No Hooks," etc., may be found on these containers.

When a filter unit is shipped with pleats in the horizontal position, the vibration to which it is subjected in transportation and the jarring which usually accompanies handling occasionally cause the filter medium to break at the adhesive line. This can be identified as a hairline crack. Separators infrequently break at this line, depending on the material of which they are made.

Occasionally a filter unit is positioned improperly in the container by the manufacturer. Cartons frequently are not placed in railroad cars or trucks according to the vertical arrow, and they are not handled consistently with the care designated. Consequently, inspection upon delivery at destination is necessary.

II. INSPECTION AND TEST

Inspection starts when a delivery of filter units reaches the purchaser, even while the load still is aboard the carrier. As the shipment is being unloaded, every carton should be inspected for external damage and improper positioning in the cargo space (carton placed with arrow directed horizontally). Damaged cartons, including those with corners dented and those improperly positioned, should be set aside for particularly careful inspection of the filter unit contained. Damage will be more prevalent when filter units are loaded with mixed cargoes or are shipped in a partially loaded carrier.

The filter unit must be removed carefully from its carton. The acceptable method for removal is to open the top flaps of the container after removing the sealing tape. With flaps folded back, the carton should be inverted or upended gently to place the exposed end of the filter unit, or, in one manufacturer's package, the face of the filter unit, on a flat surface, preferably the floor. The surface must be clear of nuts, bolts, and similar protrusions which would damage the face of the unit. Then withdraw the carton from the filter unit. Any attempt to remove the filter unit from the carton by grasping below the exposed filter frame can result in

[1] Based on USAEC Report TID-7023, *High Efficiency Particulate Air Filter Units,* by H. Gilbert and J. H. Palmer.

irreparable damage if fingers puncture the delicate, soft filter medium attached immediately below the frame.

Visual inspection of the filter unit to detect physical damage is necessary. Inspection, however, is not a substitute for DOP testing with a penetrometer.

When visual inspection is made, a strong lamp should be used to examine the exposed areas of both faces to assure that no breaks, cracks, or pinholes are evident. In addition, a less intense light, such as a flashlight, can be employed in a darkened room. The inspector should look for visible defects with the light projected along the full length of each channel created by the separators.

Translucent spots likely will prove to be variations in thickness which occur during manufacture of the filter medium. Breaks or cracks in the medium usually show up on the surface edges of the filter pleats but often are not detected readily. Minor cracks can be of major importance. If the filter unit is installed with this surface-edge damage, the cracks can be extended by air movement through the unit. After examining each channel, the inspector should examine critically the adhesive seal around the filter unit face to be sure that the seal is complete and unbroken. When one face of the filter unit has been inspected, the other face should be examined in the same manner and with the same care.

After the inspector has completed a thorough scrutiny of both faces, he should check the corner joints of the frame for adhesive sealing and tightness. Gasketing about the edge of the frame should be inspected for tight mating of gasket strips and its physical condition. Gasket strips should be examined also for full adhesion to the frame.

Cartons showing damage or dented corners and those cartons found loaded in improper position upon delivery and which were set aside when unloaded from the carrier should be inspected very carefully. Examine the filter unit at all corners and particularly at the point of carton impact for damage to separators and medium. Exterior damage to several protruding separator edges in a small area will not influence filter unit efficiency if the medium is not mashed, punctured, or broken. Even though the medium may not be broken on one face, it is possible to find it damaged at the opposing point on the other face. Large areas of mashed separator edges, even though the medium is not damaged, will obstruct the passage of air through the filter unit and reduce its life. Inspect the improperly stowed filter units for cracks alongside the adhesive seal, for extreme sags in pleats and separators, and for slits or breaks in the medium. These are points of particular examination. The details outlined above for inspection, including examination with lamp and flashlight, also should be employed with these units suspected to be damaged.

Repair of a damaged filter unit, particularly the medium, should not be attempted by the user. Any unit so repaired must be retested by DOP penetrometer to assure that hidden damage does not exist which will reduce filtering efficiency. Repair and retest thus become uneconomical for most users.

Materials used in construction of the filter unit must comply with the purchase order specification, if any. This, so far as practicable, should be determined at the time of inspection. Filter units which have been inspected and found damaged, defective, or not in conformity with the purchase order should be separated from acceptable units, identified, and, accompanied by necessary records, referred to the purchasing, receiving, or other appropriate department for proper handling.

Prior to delivery to the purchaser and his visual inspection, efficiency testing of the filter unit by a penetrometer is advisable. The penetrometer thermally generates, from dioctyl phthalate (DOP), aerosol particles approximately the size of particles which make up tobacco smoke. These particles are diluted in an air stream which flows to the filter unit at its rated capacity in cubic feet per minute (cfm). The penetrometer then photoelectrically detects and indicates the percentage of particles that pass through faults in the filter unit. This is the "penetration." The penetrometer will determine a defective filter unit readily, even when the faults in the unit cannot be found by visual inspection. High penetration due to faults results in an excessive release of particles to the atmosphere. The penetrometer also measures the pressure drop, or "resistance," of the filter unit to the rated air stream. Excessive resistance will shorten the period that the filter unit can be used. Resistance, like penetration, must not exceed a level discussed below.

Standard practice for manufacture of the high-efficiency filter unit requires that the manufacturer's test air flow and test findings of penetration and resistance be marked on the frame of the filter unit. These will be found in a stamp which bears the manufacturer's name, or vendor's name, together with the model number and serial number of the filter unit. Penetration and resistance should be not greater than specified by the purchase order. If not specified, penetration should not exceed 0.03%, and resistance should be not more than 1.0 in. (water gage) at rated air flow.

III. STORAGE

Following inspection, the filter unit should be repacked carefully in the carton in which it was shipped and received. All packing material for internal strengthening of the carton and for protection of the filter unit should be replaced properly. Pleats of the filter unit should conform to the vertical arrow on the carton. This should be done whether the filter unit will be installed at an early date or whether it will be stored. This step should be taken routinely.

Cartons of filter units should be positioned in storage to conform to the vertical arrow. Manufacturer's recommendations for storage heights should be followed. When these are not available, filter units 24 X 24 X 11½ in. and 24 X 24 X 5⅞ in. should be stacked not more than three filter units high.

Mixing other items and materials with filter units in storage should be avoided to prevent damage to the filter units. Recommended aisle widths consistent with good warehousing practice should be provided to reduce damage of filter units from materials-handling equipment and other traffic. Filter units should not be stored in locations where they will be exposed to dampness, excessive heat or cold, or rapidly changing temperatures.

Filter units should be inverted (180°) after every storage period of six months. This will equalize the strain between opposing adhesive seals which bond the filter pack to the frame.

IV. HANDLING

Mechanical warehousing equipment is recommended for handling large quantities of filter units. Skids and pallets should be used to provide a flat bed for movement of the units. Chains, slings, and hooks obviously must not be used. Filter units must be loaded on pallets when fork lift trucks and similar equipment are employed. The cartons should be placed on the pallet so that the arrow on the carton points vertically.

In handling a packaged filter unit physically, a person must make certain that the carton is picked up at opposite corners and deposited carefully on the floor or other surface. The carton should not be dropped or jarred. Any filter unit dropped, whether or not in the carton, should be reexamined for damage as prescribed under "Inspection and Testing."

When a filter unit is lifted, it must be grasped only along the outer surface of the frame. Even slight contact of fingers at almost any point within the frame can puncture the filter medium.

A handle or grip is attached permanently to the wood filter frame at some locations for ease of installation and removal of the filter unit. In such instances, care must be taken in attaching the handle. Screws should not be pounded for starting, and nails should never be used. The recommended method is to drill starting screw holes, making certain that the drill and the length of screws do not penetrate through the frame and pierce the filter medium attached. (Screws must not be longer than ¾ in.) Pounding may crack the filter medium and possibly will loosen the adhesive seal which bonds the filter pack within the frame. Attachment of a handle to a metal-frame filter unit is not recommended.

Filter units should be kept in shipping cartons when moved from one location to another. When transferred for installing, the units should be unloaded at a point which, so far as practicable, will reduce physical handling. Filter units should remain in cartons until ready for installation and then should be unpacked as prescribed under "Inspection and Testing."

If for any reason an unpackaged filter unit must be placed with its face on the floor or other surface, the surface must be cleared of every object or irregularity which might damage the filter pack.

V. INSTALLATION

Craftsmen responsible for installation of the filter unit must be informed of the high-efficiency performance required of it. Moreover, they should know that the filter pack within the frame is delicate and must not be damaged during installation. Equally important, the filter unit must be installed so that unfiltered air will not leak past the unit.

1. Carefully remove filter unit from shipping carton, following the procedure described under "Inspection and Testing."
2. Carefully inspect both faces of the filter unit for cracks in the filter medium, for damage of separators, and for separation of the filter pack at the frame.
3. See that the gasket is cemented firmly to the frame and that the gasket pieces are butted or mated at the joints.
4. The gasket must be compressed firmly. Compression should be applied evenly and equally at all points in increments of 5 ft-lb or less, with the filter frame completely covering the opening.

5. Always install the filter unit with pleats and separators in the vertical position. This will eliminate sagging of pleats from accumulated weight of materials stopped by the filter unit.

Appendix D. Glossary

absolute filter. A filter having a removal efficiency of at least 99.97% for 0.3-μ particles. (See HEPA filter).

activation analysis. A method for identifying and quantitatively measuring chemical elements in a sample. Atoms in the sample are first made radioactive by bombardment with neutrons, charged particles, or other nuclear radiation; and they then give off characteristic nuclear radiation by which they can be identified and their relative abundance can be determined.

activity, radioactive. The number of atoms of a radioactive material decaying or disintegrating per unit of time. The unit of activity is the curie, which is equivalent to 3.7×10^{10} disintegrations per second. In practice, activity is usually expressed in terms of its observable effects; that is, in terms of the types of radiation emitted.

adsorber. A device for removing gases or vapors from air by means of preferential physical condensation and retention of molecules on a solid surface. Adsorbers used in nuclear applications are often impregnated with chemicals to increase their "activity" for organic radioactive iodine compounds.

AEC filter. An HEPA filter with fiber glass medium.

aerosol. A dispersion of very small particles and/or droplets in air.

air-generated DOP. See DOP.

bag in, bag out. A method of introducing and removing items from a contaminated enclosure that prevents the spread of contamination or opening of the contaminated space to the atmosphere through the use of plastic bagging material.

charcoal adsorber. An adsorber with activated charcoal as the adsorption agent.

clean-air device. A clean bench, clean work station, downflow module, or other equipment designed to control air cleanness (particle count) in a localized working area and incorporating, as a minimum, an HEPA filter and a fan.

clean-air system. An air cleaning system designed to maintain a defined level of air cleanness, usually in terms of a permissible number of particles in a given size range, within an enclosed working area.

clean room. An occupied room designed to maintain a defined level of air cleanness under operating conditions. Inlet air is cleaned by means of HEPA filters.

coating. Paint or other protective surface treatment applied by brushing, spraying, or dipping (does not include metallic plates).

containment shell (containment vessel). A gastight enclosure around a nuclear reactor or other nuclear facility designed to prevent fission products from escaping to the atmosphere.

contaminated-exhaust system. An air cleaning system that is designed to remove harmful or potentially harmful particulates, mists, or gases from the air exhausted from an operating area.

contamination. Radioactive material that is harmful to man and/or his environment and that can also spoil experiments or make products or equipment unsuitable or unsafe for some specific use.

criticality. The state of sustaining a chain reaction, as in a nuclear reactor. When fissionable materials are handled or processed, they must be kept in a subcritical geometry, configuration, or mass to avoid accidental criticality.

CWS filter. Chemical Warfare Service filter – a term used for an HEPA filter with cellulose-asbestos medium, kraft paper separators, and untreated plywood casing.

decay heat. The heat produced by radioactive materials as nuclides spontaneously transform into other nuclides or into different energy states. Each decay process has a definite half-life.

decontamination. The removal of unwanted radioactive substances from personnel, rooms, building surfaces, equipment, etc., to render the affected area safe.

Demister. Trademark of Otto H. York Company for a moisture separator.

design-basis accident. The most serious accident that can be hypothesized from an adverse combination of equipment malfunction, operating errors, and other foreseen causes. Formerly called a maximum credible accident or MCA.

DOP smoke. A dispersion of dioctyl phthalate (DOP) droplets in air. Monodisperse DOP is generated by controlled vaporization and condensation of liquid dioctyl phthalate to give a cloud of droplets with diameters of approximately 0.3 μ. Polydisperse DOP is generated by blowing compressed air through liquid dioctyl phthalate and exhausting through special nozzles under controlled conditions to produce a cloud of droplets with a light-scattering mean diameter of approximately 0.7 μ.

dose. The amount of ionizing radiation energy absorbed per unit mass of irradiated material at a specific location, such as a part of the human body, measured in rems, or an inanimate body, measured in rads.

double containment. An arrangement of double barriers in which the second barrier provides backup protection against leakage through or failure of the first.

double filtration. An arrangement of two filters in series with the second providing backup protection against leakage or failure of the first. Also a series arrangement intended to increase the total filtration efficiency.

dry-type filter. A filter having a medium which is not coated with an oil or "adhesive" to improve its collection efficiency and retention.

enclosed filter. A filter that is completely enclosed on all sides and both faces except for reduced end connections or nipples for direct connection into a duct system. Enclosed filters are installed individually in that there is a separate run of duct to each filter unit.

extended-medium filter. A filter having a pleated medium or a medium in the form of bags, socks, or other shape to increase the surface area relative to the frontal area of the filter.

face guard. A screen, usually made from 4-mesh galvanized hardware cloth, permanently affixed to the face of a filter unit to protect it against damage caused by mishandling.

face shield. A screen or protective grille placed over a filter unit after it is installed to protect it from damage that might be caused from operations carried on in the vicinity of the filter.

filter. A device for removing aerosols from the air by means of diffusion, impaction, inertial effects, screening, or a combination of these mechanisms.

filter bank. A parallel arrangement of filters on a common mounting frame enclosed within a single housing.

final filter. The last filter unit in a set of filters arranged in series.

gas chromatograph. An analytical instrument used for quantitative analysis of extremely small quantities of organic compounds whose operation is based upon the absorption and partitioning of a gaseous phase within a column of granular material. The instrument consists of (1) an inlet assembly to produce the vapor, where the organic compound is in the liquid or solid state; (2) an inert carrier gas; (3) a partitioning column; (4) a detector; and (5) a readout device.

gloved box. A sealed enclosure in which all handling of items inside the box is carried out through long rubber or neoprene gloves sealed to ports in the walls of the enclosure. The operator places his hands and forearms in the gloves from the room side of the box so that he is physically separated from the gloved box environment but is able to manipulate items inside the box with relative freedom while viewing the operation through a window.

HEPA filter. High efficiency particulate air filter – also known as AEC, CWS, superinterception, absolute, and superhigh-efficiency filter. A throwaway extended-medium dry-type filter with (1) a rigid casing enclosing the full depth of the medium, (2) a minimum particle removal efficiency of 99.97% for thermally generated monodisperse DOP smoke particles with a diameter of 0.3 μ, and (3) a maximum gage pressure drop of 1.0 in. H_2O when clean and operated at its rated air flow capacity.

hot. Highly radioactive.

hot cell. A heavily shielded enclosure in which radioactive materials can be handled remotely with manipulators and viewed through shielding windows to limit danger to operating personnel.

in-box. Refers to an item within a gloved box that can be handled or manipulated only by means of the box gloves or tools within the box.

in-cell. Refers to an item located within a cell or enclosure that can be handled or manipulated only by means of manipulators and/or a crane and other tools within the cell.

in-duct. Refers to a single-filter arrangement in which the filter unit is clamped between two sections of duct or taped into a space between two sections of duct.

in-place tests. Penetration tests of filter units or charcoal adsorbers made after they are installed.

inches of water. A unit of pressure differential (1 in. H_2O = 0.036 psi).

ionizing radiation. Any radiation (alpha, beta, and gamma) that directly or indirectly displaces electrons from the outer domains of atoms.

isotope. One of several forms or nuclides of the same chemical element that have the same number of protons in the nucleus, and therefore have the same chemical properties, but have differing numbers of neutrons and differing nuclear properties.

maximum permissible dose. That dose of ionizing radiation which competent authorities have established as the maximum that can be absorbed without undue risk to human health.

mc. Millicuries.

medium (plural "media"). The filtering material in a filter.

micron. A unit of length equal to one thousandth of a millimeter or about 0.000039 in.

MIG. Gas metal-arc welding process (see *AWS Welding Handbook*, Sect. 2).

mounting frame. The structure to which a filter unit is clamped and sealed.

nuclear reactor. An apparatus in which a chain reaction of fissionable material is initiated and controlled.

off-gas. The gaseous effluent from a process or operation.

open-face filter. A filter with no restrictions over the ends or faces of the unit, as opposed to the enclosed filter with reduced-size end connections.

overpressure. Pressure in excess of the design or operating pressure.

particle (noun), particulate (adjective). A minute piece of solid matter having measurable dimensions. Also a radioactive particle (alpha, beta) which can liberate ionizing radiation or (neutron) which can initiate a nuclear transformation.

penetration. The measure of the number of particles that pass through a filter (percent penetration = 100 minus efficiency). If there are no leaks in the filter, penetration is a measure of the effectiveness of the filter for particles of a given size or in a given size range.

poison. Any material that tends to decrease the effectiveness of activated charcoal by occupying adsorption sites in the charcoal or by reacting with the impregnants in the charcoal.

prefilter. A filter unit installed ahead of another filter unit to protect the second unit from high dust concentrations or other environmental conditions. The prefilter usually has a lower efficiency than the filter it protects (see **roughing filter**).

rad. Radiation absorbed dose, the basic unit of ionizing radiation. One rad is equal to the absorption of 100 ergs of radiation energy per gram of matter.

radiation. The propagation of energy through matter or space in the form of electromagnetic waves or fast-moving particles (alpha and beta particles, neutrons, etc.). Gamma rays are electromagnetic radiation in which the energy is propagated in "packets" called photons.

radioactivity. The spontaneous decay or disintegration of an unstable atomic nucleus accompanied by the emission of radiation.

rem. Roentgen equivalent man. The unit of absorbed radiation dose in rads multiplied by the relative biological effectiveness of the radiation.

roughing filter. A prefilter with low efficiency for small particles, usually of the panel type.

scrubber. A device in which the gas stream is brought into contact with a liquid so that undesirable components in the gas stream are removed by reacting with or dissolving in the liquid.

separators. Corrugated paper foil (usually aluminum alloy or plastic) used to space the folds of a pleated filter medium and to provide air channels between them.

shielding. A mass of absorbing material placed around a radioactive source to reduce ionizing radiation to levels not hazardous to personnel.

shock overpressure. The pressure intensity over and above atmospheric or operating pressure produced by a shock wave.

specific activity. The radioactivity per unit weight of a material.

spill. The accidental release of radioactive or other contaminating materials.

split system. A filter system consisting of two or more trains operating in parallel, and one or more of the trains may be on standby.

TIG. Gas Tungsten-arc welding process (see *AWS Welding Handbook,* Sect. 2).

train. A set of components arranged in series. In a filter system this may be as simple as a damper, HEPA filter, fan, and damper or as complex as a damper, condenser, moisture separator, heater, prefilter, HEPA filter, charcoal adsorber, another charcoal adsorber, HEPA filter, fan, and damper.

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