CHAPTER 45

CONTROL OF GASEOUS INDOOR AIR CONTAMINANTS

THE ONLY reason to remove a gaseous contaminant from an airstream is that it would otherwise have harmful or annoying effects on the ventilated space or its occupants. These effects are noticeable at different concentration levels for different contaminants. There are four categories of harmful effects: Toxicity, odor, irritation, and material damage. In most cases, contaminants become annoying through irritation or odor before they reach levels toxic to humans, but this is not always true. For example, the potentially deadly contaminant carbon monoxide has no odor.

Traditionally, indoor gaseous contaminants are controlled with ventilation air drawn from outdoors, but available outdoor air may contain undesirable gaseous contaminants at unacceptable concentrations. If so, it requires treatment by gaseous contaminant removal equipment before being used for ventilation. In addition, minimizing outdoor airflow by using a high recirculation rate and filtration is an attractive means of energy conservation. However, recirculated air cannot be made equivalent to fresh outdoor air by removing only particulate contaminants. Noxious, odorous, and toxic gaseous contaminants must also be removed by gaseous contaminant control equipment, which is frequently different from particulate filtration equipment.

This chapter covers design procedures for gaseous contaminant control for occupied spaces only. The procedures discussed in this chapter are appropriate to control odors and gaseous irritants. Control of contaminants for the express purpose of protecting building occupants (whether against deliberate attack or industrial accidents) or to protect artifacts (such as in museums) requires application of the same design principles, but applied more rigorously and with great emphasis on having specific design and performance data, providing redundancy, and added engineering safety factors. Design for protection is not a focus of this chapter, although published design guidance is included and referenced; for more detail, see Chapter 58. Aspects of air-cleaning design for museums, libraries, and archives are included in Chapter 21 of this volume, and control of gaseous contaminants from industrial processes and stack gases is covered in Chapter 25 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

TERMINOLOGY

The terminology used in control of gaseous air contaminants is specific to the field, and the meaning of some terms familiar from particle filtration is slightly different. In particular, gaseous contaminant technology performance is a function of (1) the specific contaminant, (2) its concentration, (3) airflow rate, and (4) environmental conditions. Several methods of measuring the performance of a gaseous control device, some unique to this application, are defined in the following.

Adsorption. Attraction of a sorbate to the surface, both outer surface and inner pore surface, of media by physical forces (Van der Waals forces).

Activity. Mass of sorbate contained in a sorbent at saturation, expressed as a percentage or fraction of the carbon mass (i.e., grams contaminant/grams adsorbent). Activity is an equilibrium property under particular challenge conditions, and is not a function of airflow. (In most cases, commercial sorbent bed filters are changed for efficiency reasons well before the sorbent is saturated.) If a saturated adsorbent bed is then exposed to clean air, some of the adsorbed contaminant will desorb. Activity is generally greater than retentivity.

Breakthrough. While removing gaseous contaminants from an airstream passing through a media bed, the point at which downstream contaminant concentration is measurable and begins to rise rapidly.

Breakthrough curve. Plot of contaminant penetration versus time.

Breakthrough time. Operating time (at constant operating conditions) before a certain penetration is achieved. For instance, the 10% breakthrough time is the time between beginning to challenge an adsorber and the time at which air discharged contains 10% of the contaminant feed concentration. Continued operation leads to 50% and eventually to 100% breakthrough, at which point a physical adsorbent is saturated. For a chemisorber, the media is exhausted. (Some commercial devices are designed to allow some of the challenge gas to bypass the sorbent. These devices break through immediately, and breakthrough time, as defined here, does not apply.)

Catalyst. Any substance of which a small proportion notably affects the rate of a chemical reaction without itself being consumed or undergoing a chemical change. Most catalysts accelerate reactions, but a few retard them (negative catalysts, or inhibitors).

Channeling. Disproportionate or uneven flow of fluid (gas or liquid) through passages of lower resistance, which can occur in fixed beds or columns of granular media because of nonuniform packing, irregular sizes and shapes of media, gas pockets, wall effects, and other causes.

Challenge. Airstream containing contaminant(s) of interest that is fed to the air cleaner.

Chemisorption (chemical adsorption). Binding a sorbate to the surface of a solid by forces with energy levels approximately those of a chemical bond.

Concentration. Quantity of one substance dispersed in a defined amount of another.

Density, apparent (bulk density). Mass under specified conditions of a unit volume of a solid sorbent, including its pore volume and interparticle voids.

Efficiency. (1 – Penetration); usually expressed as a percentage or decimal fraction.

Efficiency curve. Plot of contaminant removal efficiency against time for a particular challenge concentration and airflow.

HEPA. High-efficiency particle air filter.

The preparation of this chapter is assigned to TC 2.3, Gaseous Air Contaminants and Gas Contaminant Removal Equipment.

Mass transfer zone. Depth of adsorption media required to remove essentially all of an incoming contaminant; dependent on media, contaminant nature, contaminant inlet concentration, and environmental conditions.

Mean particle diameter. Weighted average particle size, in millimeters, of a granular adsorbent; computed by multiplying the percent retained in a size fraction by the respective mean sieve openings, summing these values, and dividing by 100.

Media. Granular or pelletized adsorbent (or chemisorbent) used in gaseous contaminant control equipment.

Penetration. Ratio of breakthrough (downstream) concentration to challenge (inlet) concentration, usually expressed as a percentage or decimal fraction. Unlike particulate filters, physical adsorbents and chemisorbents both decline in efficiency as they load. The decline can be very sudden, and is usually not linear with time.

Pressure drop. Difference in pressure between two points in an airflow system, caused by frictional resistance to airflow in a duct, filter, or other system component, or by a media bed or air-cleaning devices.

Removal efficiency. Measure of amount of challenge gas removed at a given time by physical and/or chemical means.

Residence time. Theoretical time period that contaminant molecule is within the boundaries of the media bed. The longer the residence time, the higher the efficiency, and the longer the bed life. For gaseous contaminant control equipment, residence time is computed as

$$\text{Residence time} = \frac{\text{Bed area exposed to airflow} \times \text{Bed depth}}{\text{Airflow rate}} \quad (1)$$

For commercial gaseous contaminant air cleaners, residence time computation neglects the fact that a significant fraction of the volume of the bed is occupied by the media. For example, a unitary adsorber containing trays totaling 40 ft^2 media in a 1 in. deep bed, challenged at 2000 cfm, has a residence time of 0.1 s. Given this definition, a deeper media bed, lower airflow rate, or adsorbers in series increase residence time and thus adsorber performance. Because gaseous contaminant air cleaners all tend to have approximately the same granule size and the same kind of activated carbon, residence time is a generally useful indicator of performance. In some engineering disciplines, the volume of the adsorbent media is subtracted from the nominal volume of packed beds when calculating residence time. This gives a shorter residence time value and is not normally used for HVAC.

Different ways of arranging the media, different media, or different media granule sizes all change the residence time. The geometry and packaging of some adsorbent technologies makes computation of residence time difficult. For example, the flow pattern in pleated fiber-carbon composite media is difficult to specify, making residence time computation uncertain. Therefore, although residence times can be computed for partial-bypass filters, fiber-adsorbent composite filters, or fiber-bonded filters, they cannot be compared directly and may serve more as a rating than as an actual residence time. Manufacturers might publish equivalent residence time values that say, in effect, that this adsorber performs the same as a traditional deep-bed adsorber, but no standard test exists to verify such a rating.

Retentivity. Amount of a particular adsorbate remaining in an adsorbant after a saturated bed reaches equilibrium in clean air, usually stated as a percentage or fraction of the sorbate mass. Retentivity represents the ability of an adsorbent to resist desorption of the adsorbate. Retentivity is generally less than activity.

Saturation. State of a physical adsorbent when it contains all the contaminant it can hold at the challenge concentration, temperature, and humidity.

Vapor-phase contaminant. Substance in gas form that naturally occurs as a solid or liquid at the temperature and pressure of the location where it is present.

VOCs. Volatile organic compounds.

GASEOUS CONTAMINANTS

Ambient air contains nearly constant amounts of nitrogen (78% by volume), oxygen (21%), and argon (0.9%), with varying amounts of carbon dioxide (about 0.03%) and water vapor (up to 3.5%). In addition, trace quantities of inert gases (neon, xenon, krypton, helium, etc.) are always present.

Gases other than these natural constituents of air are usually considered contaminants. Their concentrations are almost always small, but they may have serious effects on building occupants, construction materials, or contents. Removing these gaseous contaminants is often desirable or necessary.

Sources of nonindustrial contaminants are discussed in Chapter 12 in the 2005 *ASHRAE Handbook—Fundamentals*. However, for convenience, data on some of the contaminants in cigarette smoke (Table 1), and some contaminants emitted by building materials (Table 2), indoor combustion appliances (Table 3), and occupants (Table 4) are provided here.

Table 5 gives typical outdoor concentrations for gaseous contaminants at urban sites; however, these values may be exceeded if the building under consideration is located near a fossil fuel power plant, refinery, chemical production facility, sewage treatment plant, municipal refuse dump or incinerator, animal feed lot, or other major source of gaseous contaminants. If such sources have a significant influence on the intake air, a field survey or dispersion model must be run. Many computer programs have been developed to expedite such calculations.

Using Source Data to Predict Indoor Concentrations

Source data such as those in Tables 1 to 5 provide raw information on which control system designs can be based. Outdoor air contaminants enter buildings through the outdoor air intake and through infiltration. The indoor sources enter the occupied space air and are distributed through the ventilation system. If measurements are not available, source data can be used to predict the contaminant challenge to air-cleaning systems using building air quality models. The following relatively simple published model is intended as an introduction to the topic.

Meckler and Janssen (1988) described a model for calculating the effect of outdoor pollution on indoor air quality, which is outlined in this section. A recirculating air-handling schematic is shown schematically in Figure 1. In this case, mixing is not perfect; the horizontal dashed line represents the boundary of the region close to the ceiling through which air passes directly from the inlet diffuser to the return air intake. Ventilation effectiveness E_v is the fraction of total air supplied to the space that mixes with room air and does not

Table 1 Major Contaminants in Typical Cigarette Smoke

Contaminant	Weighted Mean ETS Generation Rate, μg/cigarette	Weighted Standard Error, μg/cigarette	Method
Carbon monoxide	55,101	1,064	Nondispersive IR
Ammonia	4,148	107	Cation exchange cartridge
Acetaldehyde	2,500	54	DNPH cartridge
Formaldehyde	1,330	34	
Summary VOC measurements			
Total HC by FID	27,810	83	FID
Total sorbed and IDed VOC	11,270		Sorbent tube/GC
Total sorbed VOC	1,907.1	525	Sorbent tube/GC
Respirable particles	13,674	411	Gravimetric

DNPH = 2,4-dinitrophenylhydrazine; IR = infrared; VOC = volatile organic compound; ETS = environmental tobacco smoke; FID = flame ionization detector; GC = gas chromatography.
Source: Martin et al. (1997).

bypass the room along the ceiling. Meckler and Janssen suggest a value of 0.8 for E_v. Any people in the space are additional sources and sinks for gaseous contaminants. In the ventilated space, the steady-state contaminant concentration results from the summation of all contaminants added to the space *a* divided by the total ventilation and amounts removed *b*. The steady-state concentration C_{ss} for a single component can be expressed as (Meckler and Janssen 1988)

$$C_{ss} = a/b \tag{2}$$

where

$$a = C_x(Q_i + 0.01PE_vQ_v/f) + 0.5885(G_i + NG_O) \tag{3}$$

$$b = Q_e + Q_h + Q_L + k_dA + NQ_O(1 - 0.01P_O) + (E_vQ - Q_v)(1 - 0.01P)/f \tag{4}$$

and

A = surface area inside ventilated space on which contaminant can be adsorbed, ft^2
C_{ss} = steady-state indoor concentration of contaminant, µg/m^3
C_x = outdoor concentration of contaminant, µg/m^3
E_v = ventilation effectiveness, fraction
f = $1 - 0.01P\,(1 - E_v)$
G_i = generation rate for contaminant by nonoccupant sources, µg/h
G_O = generation rate for contaminant by an occupant, µg/h
k_d = deposition velocity on *a* for contaminant, fpm
N = number of occupants
P = filter penetration for contaminant, %
P_O = penetration of contaminant through human lung, %
Q = total flow, cfm
Q_e = exhaust airflow, cfm
Q_h = hood flow, cfm
Q_i = infiltration flow, cfm
Q_L = leakage (exfiltration) flow, cfm
Q_O = average respiratory flow for a single occupant, cfm
Q_v = ventilation (makeup) airflow, cfm

Flow continuity allows the expression for *b* to be simplified, which may make it easier to determine flows:

$$b = Q_i + Q_v + k_d A + NQ_O(1 - 0.01P_O) \tag{5}$$

The parameters for this model must be determined carefully so that nothing significant is ignored. Leakage flow Q_L, for example, may include flow up chimneys or toilet vents.

The steady-state concentration is of interest for design. It may also help to know how rapidly concentration changes when conditions change suddenly. The dynamic equation for the building in Figure 1 is

$$C_I = C_{ss} + (C_0 - C_{ss})e^{-b\theta/V} \tag{6}$$

where

V = volume of the ventilated space, ft^3
C_0 = concentration in space at time θ = 0
C_I = concentration in space θ minutes after a change of conditions

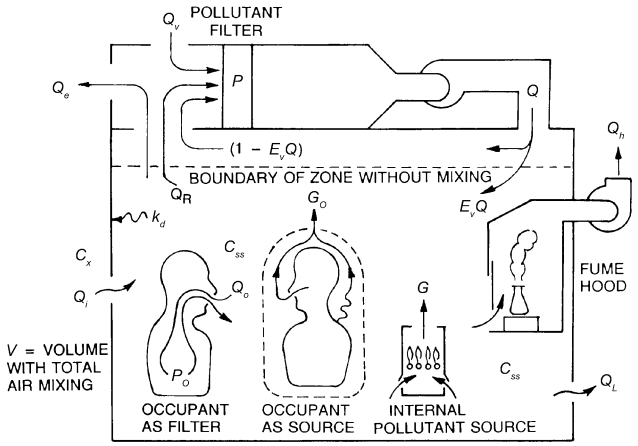

Fig. 1 Recirculatory Air-Handling and Gaseous Contaminant Schematic

Table 2 Example Generation of Gaseous Contaminants by Building Materials

	Average Generation Rate, µg/(h·m^2)						
Contaminant	**Caulk**	**Adhesive**	**Linoleum**	**Carpet**	**Paint**	**Varnish**	**Lacquer**
C-10 Alkane	1200						
n-Butanol	7300						760
n-Decane	6800						
Formaldehyde			44	150			
Limonene		190					
Nonane	250						
Toluene	20	750	110	160	150		310
Ethyl benzene	7300						
Trimethyl benzene		120					
Undecane						280	
Xylene	28						310

	Average Generation Rate, µg/(h·m^2)						
Contaminant	**GF Insulation**	**GF Duct Liner**	**GF Duct Board**	**UF Insulation**	**Particle Board**	**Underlay**	**Printed Plywood**
Acetone					40		
Benzene					6		
Benzaldehyde					14		
2-Butanone					2.5		
Formaldehyde	7	2	4	340	250	600	300
Hexanal					21		
2-Propanol				6			

GF = glass fiber; UF = ureaformaldehyde foam
Sources: Matthews et al. (1983, 1985), Nelms et al. (1986), and White et al. (1988).

Table 3 Example Generation of Gaseous Contaminants by Indoor Combustion Equipment

	Generation Rates, µg/Btu					Typical Heating Rate, 1000 Btu/h	Typical Use, hour/day	Vented or Unvented	Fuel
	CO_2	**CO**	**NO_2**	**NO**	**HCHO**				
Convective heater	53,500	88	13	18	1.45	31	4	U	Natural gas
Controlled-combustion wood stove		14	0.04	0.07		13	10	V	Oak, pine
Range oven		210	11	23		32	1.0*	U	Natural gas
Range-top burner		68	11	18	1.1	9.5/burner	1.7	U	Natural gas

*Sterling and Kobayashi (1981) found that gas ranges are used for supplemental heating by about 25% of users in older apartments. This increases the time of use per day to that of unvented convective heaters.
Sources: Cole (1983); Leaderer et al. (1987); Moschandreas and Relwani (1989); Sterling and Kobayashi (1981); Traynor et al. (1985); and Wade et al. (1975).

Table 4 Example Total-Body Emission of Some Gaseous Contaminants by Humans

Contaminant	Typical Emission, μg/h	Contaminant	Typical Emission, μg/h
Acetaldehyde	35	Methane	1,710
Acetone	475	Methanol	6
Ammonia	15,600	Methylene chloride	88
Benzene	16	Propane	1.3
2-Butanone (MEK)	9,700	Tetrachloroethane	1.4
Carbon dioxide	32×10^6	Tetrachloroethylene	1
Carbon monoxide	10,000	Toluene	23
Chloroform	3	1,1,1-Trichloroethane	42
Dioxane	0.4	Vinyl chloride monomer	0.4
Hydrogen sulfide	15	Xylene	0.003

Sources: Anthony and Thibodeau (1980); Brugnone et al. (1989); Cohen et al. (1971); Conkle et al. (1975); Gorban et al. (1964); Hunt and Williams (1977); and Nefedov et al. (1972).

Table 5 Typical Outdoor Concentration of Selected Gaseous Air Contaminants

Contaminants	Typical Concentration, ppbv	Contaminants	Typical Concentration, ppbv
Acetaldehyde	11	Methylene chloride	0.7
Acetone	1.3	Nitric acid	2.3
Ammonia	1.7	Nitric oxide	8.2
Benzene	2.5	Nitrogen dioxide	27
2-Butanone (MEK)	0.1	Ozone	20
Carbon dioxide	340,000*	Phenol	5.2
Carbon monoxide	2,600	Propane	10
Carbon disulfide	100	Sulfur dioxide	92
Carbon tetrachloride	0.3	Sulfuric acid	1.5
Chloroform	0.2	Tetrachloroethylene	0.4
Ethylene dichloride	2.5	Toluene	5.3
Formaldehyde	16	1,1,1-Trichloroethane	0.7
n-Heptane	7	Trichloroethylene	2.8
Mercury (vapor)	0.0006	Vinyl chloride	0.3
Methane	1,700	Xylene	2.3
Methyl chloride	4.4		

*Normal concentration of carbon dioxide in air. The concentration in occupied spaces should be maintained at no greater than three times this level (1000 ppmv).
Sources: Braman and Shelley (1980); Casserly and O'Hara (1987); Chan et al. (1990); Cohen et al. (1989); Coy (1987); Fung and Wright (1990); Hakov et al. (1987); Hartwell et al. (1985); Hollowell et al. (1982); Lonnemann et al. (1974); McGrath and Stele (1987); Nelson et al. (1987); Sandalls and Penkett (1977); Shah and Singh (1988); Singh et al. (1981); Wallace et al. (1983); and Weschler and Shields (1989).

C_{ss} is given by Equation (2), and b by Equation (5), with the parameters for the new condition inserted.

Reducing air infiltration, leakage, and ventilation air to reduce energy consumption raises concerns about indoor contaminant build-up. A low-leakage structure may be simulated by letting $Q_i = Q_L = Q_h = 0$. Then

$$C_{ss} = \frac{\frac{0.01PE_vQ_vC_x}{f} + 2119(G_i + NG_O)}{Q_e + K_dA + NQ_O(1 - 0.01P_O) + \frac{(E_vQ - Q_v)(1 - 0.01P)}{f}} \quad (7)$$

Even if ventilation airflow $Q_v = 0$, a low-penetration (high-efficiency) gaseous contaminant filter and a high recirculation rate help lower the internal contaminant concentration. In commercial structures, infiltration and exfiltration are never zero. The only inhabited spaces operating on 100% recirculated air are space capsules, undersea structures, and structures with life-support to eliminate carbon dioxide and carbon monoxide and supply oxygen.

Real buildings generally have many rooms, with multiple and varying sources of gaseous contaminants and complex room-to-room air changes. In addition, mechanisms other than adsorption may eliminate gaseous contaminants on building interior surfaces. Nazaroff and Cass (1986) provide estimates for contaminant deposition velocity k_d in Equations (2) to (5) that range from 0.0006 to 0.12 fpm for surface adsorption only. A worst-case analysis, yielding the highest estimate of indoor concentration, is obtained by setting $k_d = 0$. Nazaroff and Cass (1986) and Sparks (1988) describe computer programs to handle these calculations. Details on multizone modeling can be found in Chapter 34 of the 2005 *ASHRAE Handbook—Fundamentals*.

The assumption of bypass and mixing used in the models presented here approximates the multiple-room case, because gaseous contaminants are readily dispersed by airflows. Also, a gaseous contaminant diffuses from a zone of high concentration to one of low concentration, even with low rates of turbulent mixing.

Quantities appropriate for the flows in Equations (2) to (7) are discussed in the sections on Local Source Control and Dilution Through General Ventilation. Infiltration flow can be determined approximately by the techniques described in Chapter 27 of the 2005 *ASHRAE Handbook—Fundamentals* or, for existing buildings, by tracer or blower-door measurements. ASTM *Standard* E741 defines procedures for tracer-decay measurements. Tracer and blower-door techniques are given in ASTM (1980); DeFrees and Amberger (1987) describe a variation on the blower-door technique useful for large structures.

PROBLEM ASSESSMENT

Consensus design criteria (allowable upper limit of C_{ss} for any contaminant) do not exist for most nontoxic chemicals. Chapter 9 of the 2005 *ASHRAE Handbook—Fundamentals* discusses health effects of gaseous contaminants and provides some guidance on acceptable indoor concentrations, and Chapter 12 of that volume discusses the nature and non-health-related effects of gaseous contaminants, as well as providing some guidance on assessment.

Ideally, design for control of gaseous contaminants is based on accurate knowledge of the identity and concentration (as a function of time) of the contaminants to be controlled. This knowledge may come from estimates of source strength and modeling or direct measurement, or from direct measurements of the contaminants. Unfortunately, definitive assessment is seldom possible, so often careful observation, experience, and judgment must supplement data as the basis for design.

Two general cases exist: (1) new ventilation systems in new buildings for which contaminant loads must be estimated or measured, and (2) modification of existing ventilation systems to solve particular problems. For the first case, models such as described previously must be used. Identify contaminant-generating activities, estimate and sum the building sources, and identify outside air contaminants. Gaps in contaminant load data must be filled with estimates or measurements. Once contaminants and loads are identified, design can begin.

For control of a particular problem, measurements may also be required to identify the contaminant. Assessing the problem can become an indoor air quality investigation, including building inspection, occupant questionnaires, and local sampling and analysis. The *Building Air Quality Guide* (EPA 1991) is useful for such investigations. Again, once the contaminants and loads are understood, design can begin.

Contaminant Load Estimates

Valuable guidance on estimating contaminant loads in industrial situations is given by Burton (2003). In the 2005 *ASHRAE*

Handbook—Fundamentals, Chapter 12 discusses sampling and measurement techniques for industrial and nonindustrial environments, and Chapter 13 covers evaluating odor levels.

Results of sampling and analysis identify contaminants and their concentrations at particular places and times or over known times. Several measurements, which may overlap or have gaps in the contaminants analyzed and times of measurement, are usually used to estimate the overall contaminant load. Measurements are used to develop a time-dependent estimate of contamination in the building, either formally through material balance or informally through experience with similar buildings and contamination. The degree of formality applied depends on the severity of potential health or corrosion effects.

CONTROL STRATEGIES

Four control strategies may be used to improve the indoor air quality in a building: (1) elimination of sources, (2) local hooding with exhaust or recirculated air cleaning, (3) dilution with increased general ventilation, and (4) general ventilation air cleaning with or without increased ventilation rates. Usually, the first three are favored because of cost considerations. Control by general air cleaning is difficult because it is applied after the contaminants are fully dispersed and at their lowest concentration.

Elimination of Sources

This strategy is the most effective and often the least expensive. For instance, prohibiting smoking in a building or isolating it to limited areas greatly reduces indoor pollution, even when rules are poorly enforced (Elliott and Rowe 1975; Lee et al. 1986). Control of radon gas begins with installing traps in sewage drains and sealing and venting leaky foundations and crawlspaces (EPA 1986, 1987). Using waterborne materials instead of those requiring organic solvents may reduce VOCs, although Girman et al. (1984) show that the reverse is sometimes true. Substituting carbon dioxide for halocarbons in spray-can propellants is an example of using a relatively innocuous contaminant instead of a more troublesome one. Growth of mildew and other organisms that emit odorous contaminants can be restrained by controlling condensation and applying fungicides and bactericides, provided they are registered for the use and carefully chosen to have low off-gassing potential.

Local Source Control

Local source control is more effective than control by general ventilation when discrete sources in a building generate substantial amounts of gaseous contaminants. If these contaminants are toxic, irritating, or strongly odorous, local control and outdoor exhaust is essential. Bathrooms and kitchens are the most common examples. Some office equipment benefits from direct exhaust. Exhaust rates are sometimes set by local codes. The minimum transport velocity required for capturing large particles differs from that required for gaseous contaminants; otherwise, the problems of capture are the same for both gases and particles.

Hoods are normally provided with exhaust fans and stacks that vent to the outdoors. Hoods need large quantities of tempered makeup air, which requires a great deal of fan energy, so hoods waste heating and cooling energy. Makeup for air exhausted by a hood should be supplied so that the general ventilation balance is not upset when a hood exhaust fan is turned on. Back diffusion from an open hood to the general work space can be eliminated by surrounding the work space near the hood with an isolation enclosure, which not only isolates the contaminants, but also keeps unnecessary personnel out of the area. Glass walls for the enclosure decrease the claustrophobic effect of working in a small space.

Increasingly, codes require filtration of hood exhausts to prevent toxic releases to the outdoors. Hoods should be equipped with controls that decrease their flow when maximum protection is not needed. Hoods are sometimes arranged to exhaust air back into the occupied space, saving heating and cooling that air. This practice must be limited to hoods exhausting the most innocuous contaminants because of the risk of filter failure. Design and operation of effective hoods are described in *Industrial Ventilation: A Manual of Recommended Practice* (ACGIH 2004), and in Chapter 30 of this volume.

Dilution Through General Ventilation

In residential and commercial buildings, the chief use of local source control and hooding occurs in kitchens, bathrooms, and occasionally around specific point sources such as diazo printers. Where there is no local control of contaminants, the general ventilation distribution system provides contaminant control through dilution. These systems must meet both thermal load requirements and contaminant control standards. Complete mixing and a relatively uniform air supply per occupant are desirable for both purposes. The air distribution guidelines in Chapters 33 and 35 of the 2005 *ASHRAE Handbook—Fundamentals* are appropriate for contamination control by general ventilation. Airflows set by ASHRAE *Standard* 62.1 must be met.

When local exhaust is combined with general ventilation, a proper supply of makeup air must equal the exhaust flow for any hoods present. Supply fans may be needed to provide enough pressure to maintain flow balance. Clean spaces are designed so that static pressure forces air to flow from cleaner to less clean spaces, and the effects of doors opening and wind pressure, etc., dictate the need for backdraft dampers. Chapter 16 covers clean spaces in detail.

CONTROL BY VENTILATION AIR CLEANING

If eliminating sources, local hooding, or dilution cannot control contaminants, or are only partially effective, the air must be cleaned. Designing such a system requires understanding of the capabilities and limitations of control processes.

Design goals are discussed at greater length in the section on Air Cleaner System Design, but it is appropriate to mention at this point that complete and permanent removal of every contaminant is often not necessary. Intermittent nuisance odors, for instance, can often be controlled satisfactorily and economically using a design that "shaves the peak" to below the odor threshold and then slowly releases the contaminant back into the air, still below the odor threshold. On the other hand, such an approach would be inappropriate for a contaminant that affected occupants' health.

Gas Contaminant Control Processes

Many chemical and physical processes remove gases or vapors from air, but those of commercial interest to the HVAC engineer are physical adsorption and chemisorption. The operational parameters of greatest interest are removal efficiency, pressure drop, operational lifetime, first cost, and operating and maintenance cost. Other processes currently have extremely limited application in HVAC work, and are only briefly discussed.

Physical Adsorption. Adsorption is a surface phenomenon similar in many ways to condensation. Contaminant gas molecules strike a surface and remain bound to it (adsorbed) for an appreciable time. Surfaces of gaseous contamination control adsorption media are expanded in two ways to enhance adsorption. First, the media are provided in granular, pelletized, or fibrous form to increase the gross surface exposed to an airstream. Second, the media's surface is treated to develop microscopic pores, greatly increasing the area available for molecular contact. Typical activated alumina has a surface area of 1 to 1.6×10^6 ft^2 per pound; typical activated carbon has a surface area from 4 to 8×10^6 ft^2/lb. Pores of various microscopic sizes and shapes form minute traps that can fill with condensed contaminant molecules.

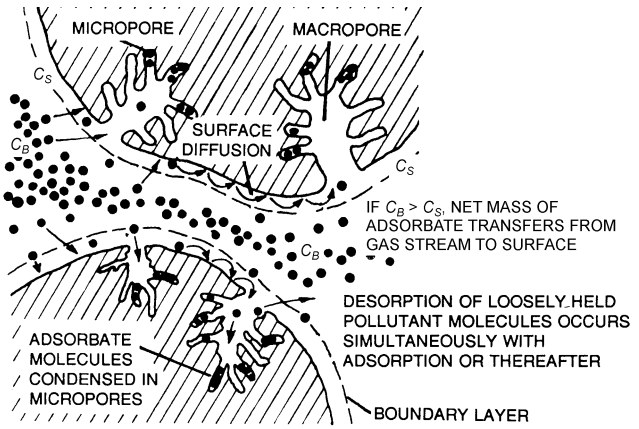

Fig. 2 Steps in Contaminant Adsorption

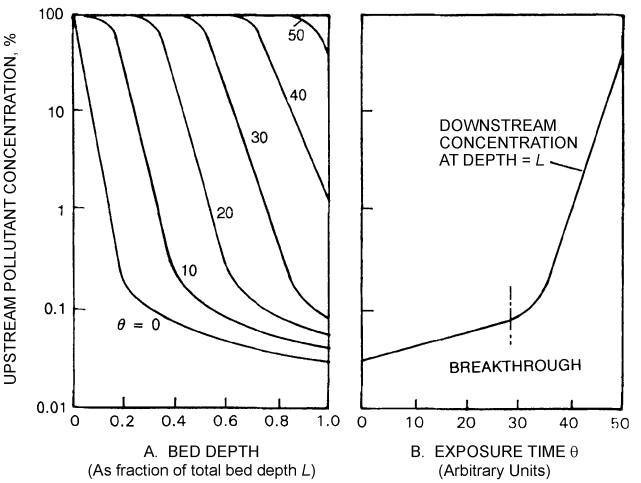

Fig. 3 Dependence of Contaminant Concentration on Bed Depth and Exposure Time

The most common adsorbent granules are millimeter-sized, and the granules are used in the form of packed beds. In general, packed beds composed of larger monodispersed particles have lower pressure drops per unit depth of sorbent than those composed of smaller monodispersed particles. On the other hand, more adsorbent can be packed in a given volume with smaller particles, and that adsorbent is more accessible to the contaminant, but the pressure drop is higher at a fixed bed depth.

Several steps must occur in adsorption of a molecule (Figure 2):

1. The molecule is transported from the carrier gas stream across the boundary layer surrounding the adsorbent granule. This occurs randomly, with molecular movement both to and from the surface; the net flow of molecules is toward the surface when the concentration of contaminant in the gas flow is greater than at the granule surface. For this reason, adsorption decreases as contaminant load on the adsorbent surface increases. Very low concentrations in the gas flow also result in low adsorption rates.
2. The molecules of the contaminant diffuse into the pores to occupy that portion of the surface. Diffusion distances are lower and adsorption rates higher for smaller particles of adsorbent.
3. The contaminant molecules are bound to the surface. (Sorption is exothermic, releasing energy. At the low concentrations and sorption rates generally found in HVAC applications, sorbents operate nearly isothermally.)

Any of these steps may determine the rate at which adsorption occurs. In general, step 3 is very fast for physical adsorption, but reversible: adsorbed molecules can be desorbed later, either when cleaner air passes through the adsorber bed or when another contaminant arrives that either binds more tightly to the adsorber surface or is present at a much higher concentration. Complete desorption usually requires adding thermal energy to the bed.

When a contaminant is fed at constant concentration and constant gas flow rate to an adsorber of sufficient bed depth L, the gas stream concentration within the bed varies with time θ and bed depth, as shown in Figure 3A. When bed loading begins ($\theta = 0$), the contaminant concentration decreases logarithmically with bed depth; deeper into the bed, the slope of the concentration-versus-bed depth curve flattens at a very low value. Later, the entrance of the adsorber bed becomes loaded with contaminant, so contaminant concentrations in the gas stream are higher at each bed depth.

Distribution of contaminant in an adsorber bed is often described in terms of an idealized **mass transfer zone (MTZ)**. Conceptually, all contaminant adsorption takes place in the MTZ. Upstream, the adsorbent is spent and the concentration is equal to the inlet concentration. Downstream, all contaminant has been adsorbed and the concentration is zero. The movement of the MTZ through the media bed is known as the **adsorption wave**. Though in actuality the front and back of the zone are not sharply defined, for many media/contaminant combinations the MTZ provides a very useful picture of media performance.

For the same constant contaminant feed, the pattern of downstream concentration versus time for an adsorber of bed depth L is shown in Figure 3B. Usually, downstream concentration is very low until breakthrough time θ_{BT}, when the concentration rises rapidly until downstream concentration is the same as upstream. The logarithmic scale makes the downstream concentration appear higher than it is. At the breakthrough point, the downstream concentration is at less than 0.1% of the upstream, just as the slope of the curve increases. For purposes of defining the MTZ, choosing this point is reasonable. For protection purposes, any contaminant downstream might be too much; for nuisance odors, staying below the odor threshold might be adequate. The interval between these various breakthrough times could be very short or significant, depending on contaminant and media. However, not all adsorber/contaminant combinations show as sharp a breakthrough as in Figure 3B.

Multiple contaminants produce more complicated penetration patterns: individually, each contaminant might behave as shown in Figure 3B, but each has its own time scale. The better-adsorbing contaminants are captured in the upstream part of the bed, and the poorer are adsorbed further downstream. As the challenge continues, the better-adsorbing compound progressively displaces the other until the displaced component can leave the adsorber bed at a higher concentration than it entered.

Underhill et al. (1988) and Yoon and Nelson (1988) discuss the effect of relative humidity on physical adsorption. Water vapor acts as a second contaminant, altering adsorption parameters by reducing the amount of the first contaminant that can be held by the adsorber and shortening breakthrough times. For solvent-soluble VOCs adsorbed on carbon, relative humidity's effect is modest up to about 50%, and greater at higher percentages. On the other hand, chemicals that dissolve in water may experience increased sorption into the water layer at high relative humidities.

Chemisorption. The three physical adsorption steps also apply to chemisorption. However, the third step in chemisorption is by chemical reaction with electron exchange between the contaminant molecule and the chemisorber. This action differs in the following ways from physical adsorption:

- Chemisorption is highly specific; only certain contaminant compounds will react with a particular chemisorbent.
- Chemisorption is generally not reversible. Once the adsorbed contaminant has reacted, it is not desorbed. However, one or more

reaction products, different from the original contaminant, may be formed in the process, and these reaction products may enter the air as a new contaminant.
- Water vapor often helps chemisorption or is necessary for it, whereas it usually hinders physical adsorption.
- Chemisorption per se is a monomolecular layer phenomenon; the pore-filling effect that takes place in physical adsorption does not occur, except where adsorbed water condensed in the pores forms a reactive liquid.

Most chemisorptive media are formed by coating or impregnating a highly porous, nonreactive substrate (e.g., activated alumina, zeolite, or carbon) with a chemical reactant. The reactant will eventually become exhausted, but the substrate may have physical adsorption ability that remains active when chemisorption ceases.

Other Processes. Physical adsorption and chemisorption are the most commonly used processes, but the following processes are used in some applications.

Liquid absorption devices (scrubbers) and **combustion devices** are used to clean exhaust stack gases and process gas effluent. They are not commonly applied to indoor air cleanup. Additional information may be found in Chapter 25 of the 2004 *ASHRAE Handbook—HVAC Systems and Equipment*.

Catalysts can clean air by stimulating a chemical reaction on the surface of the media. **Catalytic combustion** or **catalytic oxidation (CatOx)** oxidizes moderate concentrations of unburned hydrocarbons in air. In general, the goal with catalytic oxidation is to achieve an adequate reaction rate (contaminant destruction rate) at ambient temperature. Reaction products are a concern, because oxidation of nonhydrocarbons or other reactions can produce undesirable byproducts. This technology has been used industrially for years, but its potential use for indoor air cleaning is relatively new. Equipped with custom catalysts and operated at elevated pressures and temperatures, CatOx can be extremely effective at the removal of indoor contaminants, but is not currently cost-competitive in commercial indoor air or HVAC applications. Availability of waste heat significantly improves CatOx cost competitiveness. CatOx systems have potential application in security and protection applications.

Photocatalysis uses light [usually ultraviolet (UV)] and a photocatalyst to perform **reduction-oxidation (redox)** chemistry on the catalyst's surface. The device admits reactant gas species, notably air contaminants, in a feed stream and emits product species. The photocatalyst can be granular, bulk, or unsupported, or it can be supported as a thin film on media such as glass, polymer, or metal. The light sources must emit photons of energy greater than that of the intrinsic band-gap energy (E_g) of the photocatalyst. For example, the photocatalyst titanium dioxide (TiO_2) has band-gap energy of 3.1 eV; ultraviolet light has sufficient energy to overcome the E_g of TiO_2. The characteristic chemistry consists of reactant gases adsorbing onto the photocatalyst, followed by reaction chemistry, product formation, and desorption. With appropriate irradiance and flow rate of the reactant species, photocatalysis can almost completely oxidize a wide variety of organic compounds such that the exit gas stream contains carbon dioxide and water.

At its current level of catalyst and lamp development, UV photocatalysis is not cost-competitive for indoor air control, but the technology is developing rapidly. It is attractive because of its promise of reduced maintenance (no filters to maintain and dispose of) and cost compared to conventional technology. ASHRAE Research Project RP-1134 exhaustively reviewed the literature on UV photocatalysis (Tompkins et al. 2005a, 2005b).

Biofiltration is effective for low concentrations of many VOCs found in buildings (Janni et al. 2001). It is suitable for exhaust air cleaning, and is used in a variety of applications, including plastics, paper, and agricultural industries and sewage treatment plants. Operating costs are low, and installation is cost-competitive. However, concerns over using uncharacterized mixtures of bacteria in the filter, possible downstream emissions of microbials or chemicals, and the risk of unexpected or undetected failure make it unsuitable for cleaning air circulated to people.

Ozone is often touted as a panacea for removing gas-phase contaminants from indoor air. However, considerable controversy surrounds its use in indoor air. Ozone is a criteria pollutant and its maximum allowable concentration [8 h time-weighted average (TWA)] is regulated in both indoor (OSHA 1994) and outdoor air (EPA 1997). Some ozone generators can quickly produce hazardous levels of ozone (Shaughnessy and Oatman 1991). Furthermore, the efficacy of ozone at low concentrations for removing gaseous pollutants has not been documented in the literature (Boeniger 1995). Human sensory results obtained in conjunction with a study by Nelson et al. (1993) showed that an ozone/negative ion generator used in a tobacco-smoke environment (1) produced unacceptable ozone levels at the manufacturer's recommended settings, and (2) when adjusted to produce acceptable ozone levels, produced more odor and eye irritation over time than environmental tobacco smoke (ETS). Other work by Nelson (unpublished) has shown the rapid oxidation of NO to NO_2 by ozone and only a minor decrease in nicotine concentrations when ozone is used to "clean" the air. In light of the potential for generating hazardous ozone levels indoors and the lack of scientific data supporting its efficacy, using only ozone to combat ETS in indoor air is not recommended.

Odor counteractants and **odor masking** are not truly control methods; they may apply only to specific odors and have limited effectiveness. They also add potential contaminants to the air.

EQUIPMENT

General Considerations. With a few exceptions, adsorption and chemisorption media are supplied as granules or pellets, which are held in a retaining structure that allows air being treated to pass through the media with an acceptable pressure drop at the operating airflow. Granular media have traditionally been a few millimetres in all dimensions, typically on the order of 4×6 or 4×8 U.S. mesh pellets or flakes, because these sizes have an acceptable pressure drop at the required operating conditions.

Numerous other sizes are available. Typical configurations of units in which millimetre-sized granular or pelletized media are held between perforated retaining sheets or screens are shown in Figures 4A, 4B, and 4E. The perforated retainers or screens must have holes smaller than the smallest particle of the active media. A margin without perforations must be left around the edges of the retaining sheets or screens to minimize the amount of air that can bypass the active media. Media must be tightly packed in the structure so that open passages through the beds do not develop. Aluminum; stainless, painted, plated, or coated steel; plastics; and kraftboard are all used for retainers.

Adsorptive media may also be retained in fibrous filter media or other porous support structures that can be pleated into large filters, as shown in Figures 4C and 4F. The adsorptive media must be bound to the supporting fibers in such a way that media micropores are preserved (i.e., not sealed by binders) and adequate overall adsorptive capacity is maintained. Media supported in this way are generally much smaller (down to approximately 80 mesh). Small-particle adsorbents have higher efficiency than the same adsorbent in larger particles. The smaller particles must be uniformly distributed and supported so the pressure drop of the composite is acceptable. Because the adsorbent is intimately bound to, and its performance affected by, the support structure, these adsorbers must be evaluated by tests on the complete composite structure, not the granular adsorbent alone.

Granular media adsorbers are available in two working classes: **total-** or **full-detention** and **partial-detention** units. Full-detention units initially contain the mass transfer zone totally within the bed, as depicted by the $\theta = 0$ curve of Figure 3A. Other popular commer-

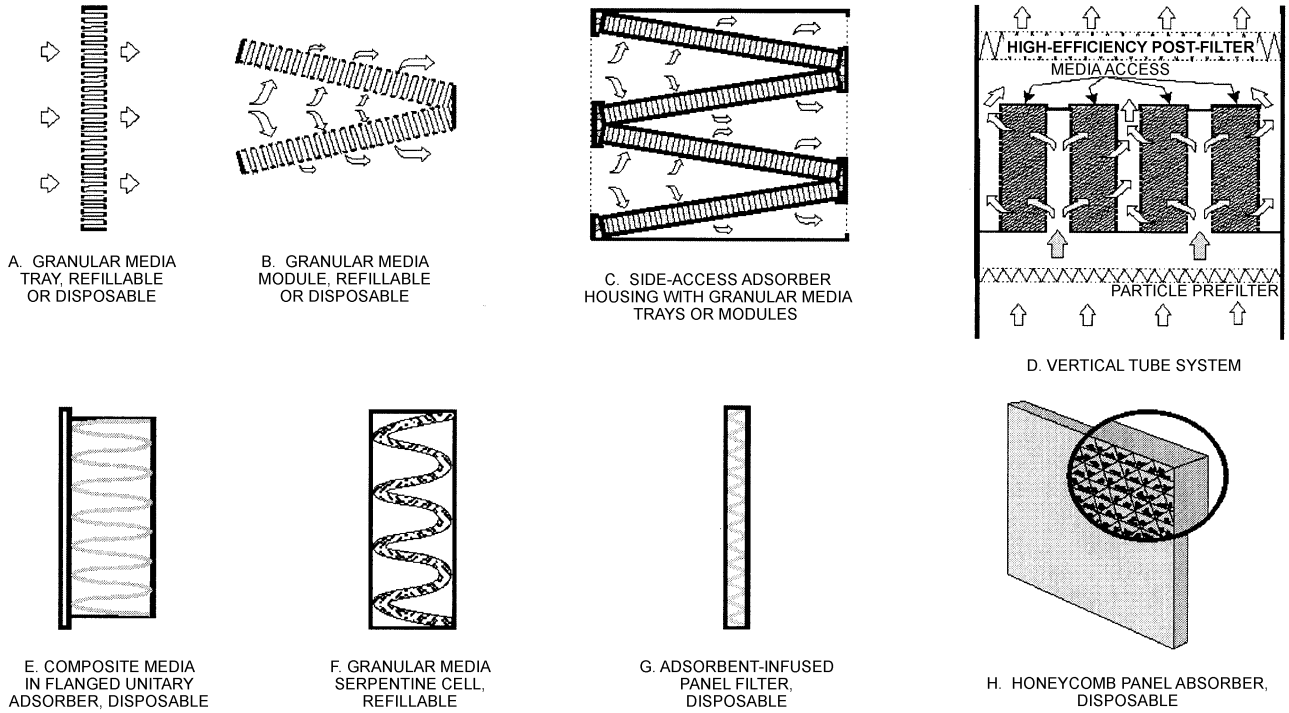

Fig. 4 Sectional and Schematic Views of Typical Adsorber and Chemisorber Configurations

cial designs may allow the challenge gas to bypass the unit or have short residence times. Partial-detention units are called partial-bypass if large open areas are designed into the bed or device. Partial-detention units are useful when 100% control is not needed to achieve design objectives or when high recirculation rates allow them to effectively remove contaminants from a space.

Generally, in total-detention units, all the air passes through a media bed that is usually at least 0.5 in. thick, with a residence time of 0.02 s or more, although they can be much thicker and have longer residence times. At their rated flow, they have an initial efficiency of nearly 100% (full detention) for modest challenge concentrations of the contaminants they control well. Partial-detention units operated at capacity have initial efficiencies of 80% or below. They typically have lower pressure drops than full-detention units. They may allow 50% or more of the air approaching them to bypass the media bed and remain untreated, as do 50% fill honeycomb panels and some partial-bypass unit adsorbers. Similarly, some adsorbent-bonded carbon panels operating at face velocities of approximately 300 fpm or more have very low residence times and are best classed as partial-detention units even though all the air passes through the adsorber.

Equipment Configurations. Unitary adsorbers in built-up banks or **side-access housings** holding individual media-filled trays, modules, or cells, are both available. Built-up banks require space upstream of the filter bank to install the adsorbers and for maintenance. Larger equipment benefits from the maintenance simplicity of built-up front-access banks. Side-access housings are an integral part of a duct run, and are usually selected if the system is small (about 3000 cfm or less) or if in-line space is limited.

A **unitary adsorber** has either a permanent holding frame filled with multiple trays, modules, or panels, or a single, disposable box-type unit or adsorbent-bonded media cell. Unitary adsorbers incorporate channels to retain trays, modules, or panels either vertically or horizontally. Their size depends on what they are intended to hold.

Media trays (Figure 4A) vary in thickness from 0.625 to 6 in. and may be constructed of painted or stainless steel or plastic. Their height and breadth are sufficient to span the housing in which they are placed. **Modules** (Figure 4B) are usually designed to hold media in a V-panel configuration. They may be refillable or disposable.

Panel adsorbers (Figure 4H) usually use a base of fibrous honeycomb material to hold the granular media. The efficiency and pressure drop of these panels can be controlled by the amount of media placed in each honeycomb opening; 50, 75, and 100% fills are common.

Disposable, box-type units may use multiple media-filled panels arranged in a V configuration and sealed into frames with or without headers. Fiber-adsorbent composite media may be pleated and assembled into disposable box-type unitary filters, which may be of heavy or lightweight construction depending on the filter's capacity.

Adsorbent-bonded media is often pleated into a cardboard or metal frame and provide both gaseous and particulate contamination control. These filters usually are only used for extremely light-duty peak-shaving applications because the available adsorbent is relatively limited.

A partially filled granular media holder can have a preferred orientation because the media may be able to move. For example, a vertical, 50% filled honeycomb panel adsorber has about 50% open area and 50% carbon granules in the direction of flow through the panel. The same panel adsorber, oriented horizontally in downflow, becomes a packed bed with a media thickness of about half the panel depth because the granules pack against the bottom retaining screen. In upflow, the adsorbent is lifted by the airflow and forms a packed or percolating bed against the retaining screen at the top, causing sorbent abrasion. The pressure drop and adsorption performance of each of these orientations is different. Most manufacturers rate their products in only one orientation and do not investigate other applications.

Side-access adsorber housings hold the same types of trays, modules, and panels used with unitary adsorbers. The housings have doors on one or both sides and often include channels for particulate prefilters or afterfilters. The adsorber units slide into place on rails or channels that require tight seals to prevent bypass leakage. The housings are often mounted adjacent to the air handler.

Numerous specialty and proprietary housing designs have been developed to meet stringent performance or space requirements.

Annular thick-bed designs include the U.S. M98 military protective filter (a bed of specialty carbon packaged in a cylindrical housing) and a vertical tube system, shown in Figure 4D, which is manually filled with media through a top access hatch.

Filter Housing and Adsorber Module Integrity. Performance of any air cleaner installation is limited by the integrity of the total installation. A 100% efficient filter mounted in a housing that allows 10% bypass is a 90% efficient installation. Bypass is of little consequence for low-efficiency installations because efficiency is not important and such installations generally have low pressure drop across the filter. It becomes more important for high-efficiency installations.

Generally, gas contaminant air cleaners and housings of any nominal size, if made by different manufacturers, differ slightly in dimensions and tolerances. Manufacturers are generally willing to state the overall effectiveness of a filter and housing only if they make both. Designers should consider the desired overall efficiency and ensure that the housing and filter together meet performance goals. If future efficiency upgrades are contemplated, it may be cost-effective to use a better housing than required by the initial design goals.

Filter-sealing systems must be specified to be consistent with the intended use. A partial-detention filter may appropriately be designed without any seal beyond that of the cardboard frame to filter housing. On the other hand, a thick-bed design intended for a protection application may require a knife-edge-into-gel seal developed for cleanroom applications to achieve its intended level of performance.

Many filters intended for HVAC application use foam gasketing, which may be installed on the filter or housing. If foam gasketing is used, it must be compatible with the gas stream so it does not fail over the design life. Design details that affect performance include joints (butt-joint gasket corners leak more often than dove-tail joints), cell structure (open-cell foam is more likely to be penetrated than closed), and frame or housing integrity (distortion from poor installation or shipping damage can preclude good sealing).

Further, filter seals and gasketing have finite lifetimes and require maintenance. Failure to correctly install equipment or maintain gaskets leads to increased penetration in many applications. Inspection is required at installation and periodically thereafter.

Preventing bypass is critical for protection applications (whether of people or artifacts). These applications typically use thick beds, which have the highest pressure drops and for which even low penetration is deleterious. One method of detecting significant bypass is to measure whether the filter achieves its rated pressure drop at full flow. Designers of protective air cleaning systems should consult Chapter 21 and specialty design guidance.

AIR CLEANER SYSTEM DESIGN

Air cleaner system design consists of determining and sizing the air cleaning technology to be applied, and then choosing equipment with characteristics (size and pressure drop) that can be incorporated into the mechanical design.

The gaseous contaminant control designer ideally should have the following information:

- Exact chemical identity of the contaminants present in significant concentrations
- Rates at which contaminants are generated in the space
- Rates at which contaminants are brought into the space with outdoor air
- Time-dependent performance of the proposed air cleaner for the contaminant mixture at concentration and environmental conditions to be encountered
- A clear goal concerning what level of air cleaning is needed

This information is usually difficult to obtain. The first three items can be obtained by sampling and analysis, but funding is usually not sufficient to obtain samples except in very simple contamination cases. Designers must often make do with a chemical family (e.g., aldehydes). Investigation may allow a rough estimate of contaminant generation rate based on quantity of product used daily or weekly. Experience with the particular control application or published guidance [e.g., Rock (2006) for environmental tobacco smoke] can be very helpful.

Experimental measurements of air cleaner performance are usually not available, but can be estimated using the equations in the section on Using Source Data to Predict Indoor Concentrations when the exact chemical identity of a contaminant is known. The chemical and physical properties influencing a contaminant's collection by control devices can usually be obtained from handbooks and technical publications. Contaminant properties of special importance are relative molecular mass, normal boiling point (i.e., at standard pressure), heat of vaporization, polarity, chemical reactivity, and diffusivity.

Air cleaner performance with mixtures of chemically dissimilar compounds is very difficult to predict. Some gaseous contaminants, including ozone, radon, and sulfur trioxide, have unique properties that require design judgment and experience.

Finally, design goals must be considered. For a museum or archive, the ideal design goal is total removal of the target contaminants and no subsequent desorption. For any chemical that may affect health, the design goal is to reduce the concentration to below the level of health effects. Again, desorption back into the space must be minimized. For odor control, however, 100% removal may be unnecessary and desorption back into the space at a later time with a lower concentration may be economical and acceptable.

The first step in design is selecting an appropriate adsorption medium. Next, the air cleaner's location in the HVAC system must be decided. Then the air cleaner must be sized so that sufficient media is used to achieve design efficiency and capacity goals and to estimate media replacement requirements. Finally, commercial equipment that most economically meets the needs of the application can be selected. These steps are not completely independent.

Air Cleaner Location and Other HVAC Concerns

Outside Air Intakes. Proper location of the outside air intake is especially important for applications requiring gaseous contaminant filters because outside contaminants can load the filters and reduce their operating lifetime. Outside air should not be drawn from areas where point sources of gaseous contaminants are likely: building exhaust discharge points, roads, loading docks, parking decks and spaces, etc. See Chapter 44 for more information on air inlets.

To further help reduce the amount of contaminants from outside air, at least on days of high ambient pollution levels, the quantity of outside air should be minimized.

Air Cleaner Locations. The three principal uses for gaseous contaminant control equipment in an HVAC system are

- *Outside Air Treatment.* Air-cleaning equipment can be located at the outside air intake to treat outside air only. This treatment is used principally when indoor gaseous contaminants are adequately controlled by outdoor air ventilation, but the outdoor air needs to be cleaned to achieve satisfactory air quality.
- *Bypass or Partial Supply Air Treatment.* Bypass can be achieved with a bypass duct and control damper or by installing an air cleaner that allows substantial bypass. Partial supply air treatment may be appropriate where a specific threshold contamination level is targeted, when outside and inside contamination rates are known, and the required level of reduction is small to moderate.
- *Full Supply Air Treatment.* Full treatment achieves the best contaminant control, but with the highest cost and largest equipment volume. This approach is most often used in ventilation

strategies that reduce outdoor air while maintaining good indoor air quality.

When outdoor air quality is adequate, treatment of recirculated ventilation air alone may be adequate to control indoor contaminants such as bioeffluents. Full or bypass treatment of the supply air may be appropriate, depending on the source strength.

Media Selection

Media selection is clear for many general applications, but for others is a matter of judgment. In general, gaseous contaminants that have the same or higher boiling point as water can be removed by physical adsorption using standard activated carbon. Those with a lower boiling point usually require chemisorption for removal. Figure 5 shows the media and equipment selection process.

In practice, different examples of the same application may be served well by somewhat different media selections. Any guidance must be tempered by consideration of the specifics of a particular location, and guidance given by different manufacturers may differ somewhat. Table 6 consolidates general guidance for numerous commercial applications from multiple manufacturers. Within each media group, the applications are listed alphabetically; similar applications appear in more than one list, because some applications may be well served with either a single medium or by a blend, with the best choice determined by the specific contaminants present (both chemical identity and concentration.) Acceptability may hinge on a specific, hard-to-control chemical that is present at one site but not at another. Adsorption capacity for a particular chemical or application may vary from these guidelines with changes in

- **Competitive adsorption.** Multiple contaminants confound performance estimates.
- **Temperature.** Activity decreases with a temperature increase.
- **Humidity.** Effect of humidity (generally for rh > 50%) depends on the contaminant. Carbon capacity for water-miscible solvents increases; capacity for immiscible or partially miscible solvents decreases.
- **Concentration.** Increased contaminant concentration improves activity.

Table 7 provides a general guide to selection of media to control particular chemicals or types of chemicals. As was true of Table 6, some difference in opinion exists as to which media is best, as indicated for the chemicals followed by an exclamation point.

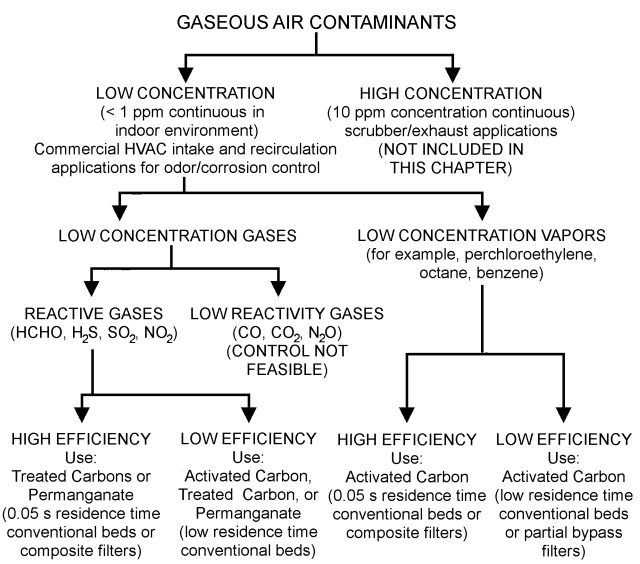

Fig. 5 Media and Equipment Selection Schematic
(Adapted with permission. ©1992 Extraction Systems, Inc.)

Sizing Gaseous Contaminant Control Equipment

There are currently two common sizing approaches: using manufacturers' guidance, and using the absorbent performance equations in the section on Using Source Data to Predict Indoor Concentrations. Adsorbent performance and contaminant concentration data required to use the equations are not generally available; however, test methods are being developed that may allow broader use of performance equations.

Manufacturers' Design Guidance. Most manufacturers of control system components offer selection guidance. Some of the methods for traditional granular beds are summarized here. Note that inclusion of this information or exclusion of other methods does not imply acceptance or endorsement by ASHRAE, but is meant to be an abbreviated overview of present-day practice. The general expectation is of an HVAC application service life of 9 to 18 months for a 3120 h air-conditioning year. These values are simply a summary of conventional wisdom directed at meeting that goal, and they can be substantially in error. The manufacturer's recommendations have been annotated to put the entire discussion in the same terminology.

One manufacturer divides HVAC and IAQ applications into three categories and recommends equipment selection based on efficiency and activated carbon weight, as follows:

1. Heavy-duty outdoor air or mixed air IAQ applications with a relatively constant VOC generation rate and relatively constant moderate to severe outdoor air pollution:
   - For cleaned-air-equivalent air quality (i.e., air cleaned well enough to substitute for outdoor air), use equipment with >90% efficiency and 75 to 100 lb of high-grade carbon per 2000 cfm For a 1 in. bed in common commercial unitary adsorbers, this corresponds to a 0.1 s residence time.
   - With severe outdoor air pollution from nearby sources, it may be necessary to size equipment at 90 lb of carbon per 1000 to 1400 cfm, which corresponds to 0.14 to 0.2 s residence time.
2. For medium-duty return or mixed air IAQ applications with constant low to moderate VOC generation and cleaned-air-equivalent air quality, use equipment efficiencies of 20 to 90% and 8 to 75 lb of carbon per 2000 cfm. This corresponds to partial bypass equipment at the low-efficiency end and ranges up to about 0.08 s residence time at the high-efficiency end.
3. For light-duty mixed air IAQ applications with intermittent low to high VOC generation and an intermittent low to high outdoor air pollution load, use equipment efficiencies of >75% for odor control, which corresponds to a partial bypass design.

Another manufacturer offers a variety of adsorbers with both plain and chemically impregnated activated carbon. After determining the application's residence time range,

1. Choose the hardware configuration: replacement cells or disposable units.
2. Specify face size and depth, and verify that the air quantity is within stated limits for residence time.
3. Select the proper chemistry (impregnation) for the application and the adsorber's location in the airstream.

A third manufacturer holds that, in most IAQ investigative work and applications, neither the total load nor specific contaminant is known. A broad-based control design approach is then usually recommended, consisting of two adsorber banks: activated carbon, followed by potassium permanganate-impregnated alumina. Sometimes these two media are combined into one bank because of space or pressure drop limitations.

Table 6 Media Selection by Commercial Application

Commercial Application	Contaminants/Species
Activated Carbon or Carbon/Permanganate-Impregnated Alumina Blend	
Airport terminals (air side and non-air side), art studios, athletic clubs, auditoriums, banks (customer area), banquet rooms, beauty salons, bus terminals, clinics, darkrooms, decal application, dentists'/doctors' offices, dry cleaners (dust area), factories (office area), florists, grocery stores, kitchen exhausts, locker rooms, office buildings, painted rooms, pharmacies, photo stores, photographic studios, physiotherapy, recreation halls, rendering plants, stores	Multiple volatile organic gases/solvent vapors and inorganic gases; possibly some gases poorly adsorbed by carbon Multiple organics and inorganics, fumes, food odors, body odors, floral scents, odorous fumes, moldy odors, paint fumes, furniture, ETS, NO_x, SO_x, O_3, mercaptans, valeric acid, formaldehyde
Activated Carbon/Permanganate-Impregnated Alumina Blend	
Bars, bingo halls, brasseries, cafeterias, casinos, cocktail lounges, conference rooms, correctional facilities, funeral homes, geriatrics, hospitals, hotels (smoking, renovation), ICUs, libraries, lounges, lunch rooms, motels, museums, night clubs, nurseries, paint shops (office), penal institutions, projection booths, psychiatric institutions and wards, public toilets, restaurants, segregated smoking rooms, storage rooms, theaters, waiting rooms	Mixed gases/ETS; good possibility of volatile organic gases and/or solvent vapors ETS, body odors, urine, excreta, perfume, multiple odors, food odors, kitchen fumes, food, furniture/furnishings offgassing, multiple organics and inorganics, paint
Activated Carbon or Permanganate-Impregnated Alumina	
Barber shops, dining rooms	Mixed gases, ETS, food odors
Carbon/Permanganate Blend or Permanganate-Impregnated Alumina	
Embalming rooms, fruit/vegetable storage, greenhouses	Multiple organics; organic gases poorly sorbed by activated carbon Multiple organics, formaldehyde, ethylene
Activated Carbon or Permanganate-Impregnated Alumina/Acid-Impregnated Carbon Blend	
Garbage disposal areas	Mixture of volatile organics and inorganics with ammonia
Permanganate-Impregnated Alumina	
Autopsy rooms, banks (vault area), fish markets, hospitals (autopsy), morgues	Volatile organic gases poorly adsorbed by activated carbon Formaldehyde, trimethyl amine
Permanganate-Impregnated Alumina/Acid-Impregnated Carbon Blend	
Pet shops, animal holding rooms, veterinary hospitals	Mixed organic gases with significant ammonia urine, excreta, animal odors
Activated Carbon/Acid-Impregnated Carbon Blend	
Printing plants	Mixed hydrocarbons and ammonia
Acid-Impregnated Carbon	
Fertilizer plants (office)	Largely ammonia

Notes: Permanganate impregnant is potassium permanganate. Acid impregnants vary. ETS = environmental tobacco smoke

- For light-duty applications, this manufacturer recommends particulate filter media infused with either carbon or permanganate media and pleated into a traditional filter design.
- For medium-duty applications, granular media are used in 1 to 3 in. deep refillable or disposable bulk-fill modules for increased efficiency and service life.
- When specific contaminants and concentrations are known, granular media are specially impregnated and bulk-fill modules or deep beds (up to 48 in.) are used. The latter are recommended for critical applications such as corrosion prevention in computerized control rooms.

A fourth manufacturer evaluates and specifies all of its molecular filters by measuring the initial removal efficiency of the whole filter installed in its frame, and measures the amount of contaminant removed as adsorbent capacity is consumed during the test. Curves of efficiency versus capacity are used to guide the customer through the selection process.

Another form of manufacturer's guidance is given in Table 8, which gives suggested packed-bed residence time ranges, developed for the 4×6 or 4×8 mesh coconut shell carbon typically used in packed beds, for various applications. Residence times in Table 8 are appropriate for moderate to thick beds of large-particle carbons, but do not apply universally to commercial adsorbers. Different ways of arranging the carbon, different adsorbents, or different carbon granule sizes change the residence time required to get a particular result. This is especially true of very finely dispersed activated carbon, which has very fast adsorption kinetics. In addition, the geometry and packaging of some adsorbent technologies make computation of residence time difficult. For instance, cylindrical beds with radial flow have air velocities that decrease from the center to the periphery, so special computational techniques are needed to put residence time on the same basis as for a flat bed. Similarly, the flow pattern in pleated fiber/carbon composite media is difficult to specify, making residence time computation uncertain. Therefore, although residence times can be computed for partial-bypass filters, fiber-adsorbent composite filters, or fiber-bonded filters, they cannot be compared directly with those in Table 8, and serve more as a rating than as an actual residence time. By applying residence time as a rating, manufacturers may publish equivalent residence time values that say, in effect, that this adsorber performs the same as a traditional deep bed adsorber. No standard test exists to verify such a rating.

Tables 6 and 7 provide guidance in selecting sorbent media. Both manufacturers' guidance and absorbent performance Equations (2) to (7) are used to size equipment. A manufacturer's guidance is often followed because adsorbent performance and contaminant concentration data required to use the equations are not generally available.

When calculating adsorber size, use the following approach:

1. Choose an adsorbent suited to the contaminant.
2. Pick an appropriate efficiency for the adsorber (complete removal or partial bypass), depending on the contaminant.
3. Choose a desired operating adsorber end point of 10%, 50%, or other breakthrough, depending on the application and allowable steady-state concentration. A building ventilation performance model, with the adsorber appropriately positioned, allows

Table 7 Media Selection by Contaminant

Gaseous Contaminant	PPIA	AC	AIC	BIC
Acetaldehyde	*	0		
Acetic acid (!)	*	0		0,*
Acetic anhydride (!)	*,0	*		0
Acetone (!)	*	0		
Acetylene	*			
Acrolein	*	0		
Acrylic acid (!)	*	*		0
Allyl sulfide	*	0		
Ammonia (NH_3)			*	
Aniline	0	*		
Arsine	*			
Benzene		*		
Borane (!)	*	0,0		
Bromine		*		
1,3 Butadiene	*	0		
Butane		*		
2-Butanone	*	0		
2-Butoxyethanol	0	*		
Butyl acetate (!)	*,0	0,*		
Butyl alcohol	0	*		
Butyl mercaptan	0	*		
Butylene	0	*		
Butyne	0	*		
Butyraldehyde	0	*		
Butyric acid		*		0
Cadaverine	0	*		
Camphor		*		
Carbon dioxide (CO_2)	Carbon w/catalyst			
Carbon disulfide	0	*		
Carbon monoxide (CO)	Carbon w/catalyst			
Carbon tetrachloride		*		
Chlorine (Cl_2)				*
Chloroform		*		
Creosote (!)	*,0	0,*		
Cyclohexane		*		
Cyclohexanol	0	*		
Cyclohexanone	0	*		
Cyclohexene		*		
Decane		*		
Diborane	*			
Dichlorobenzene		*		

Gaseous Contaminant	PPIA	AC	AIC	BIC
Dichlorofloromethane		*		
R-114 (see note)		*		
Diethylamine	0	*		
Dimethylamine		*	0	
Dioctyl phthalate		*		
Dioxane	*	0		
Ethanol	*	0		
Ethyl acetate	0	*		
Ethyl chloride (!)	*,0	0,*		
Ethylene (C_2H_4)	*			
Ethylene oxide	*	0		
Ethyl ether	0	*		
Ethyl mercaptan (!)	*,*	0		0
Formaldehyde	*			
Gasoline	*			
General halocarbons		*		
General hydrocarbons	0	*		
General VOC	0	*		
Heptane		*		
Hydrogen bromide		0		*
Hydrogen chloride		0		*
Hydrogen cyanide	*			
Hydrogen fluoride	*			*
Hydrogen iodide	0			
Hydrogen selenide				
Hydrogen sulfide	*			*
Iodine		*		
Iodoform	0	*		
Isopropanol	0	*		
Kerosene		*		
Lactic acid		*		
Menthol	0	*		
Mercury vapor	Impreg. AC			
Methanol	0	*		
Methyl acrylate	0	*		
Methyl bromide (!)	0,*	*		
Methyl butyl ketone (!)	*,0	0,*		
Methyl cellosolve acetate	0	*		
Methylchloroform		*		
Methylcyclohexane		*		
Methylene chloride		*		

Gaseous Contaminant	PPIA	AC	AIC	BIC
Methyl formate	0	*		
Methyl isobutyl ketone	0	*		
Methyl sulfide	*			
Methyl vinyl ketone	0	*		
Naphtha		*		
Naphthalene		*		
Nicotine	*	0		
Nitric acid				*
Nitric oxide (NO)	*			0
Nitrobenzene		*		
Nitrogen dioxide	*			0
Nitromethane	*			
Nitrous oxide				*
Octane (!)	0	*,*		
Ozone (O_3) (!)	0	*,*		
Perchloroethylene	0	*		
Peroxy acetyl nitrate (PAN)		*		
Phenol	0	*		
Phosgene	0	*		
Phosphine	*			
Putrescine	*	0		
Pyridine (!)	*	*		
Skatole	0	*		
Silane	*			
Stoddard solvent	*			
Stibine	*			
Styrene (!)	0	*,*		
Sulfur dioxide	*			*
Sulfur trioxide	*			*
Sulfuric acid		0		*
Toluene		*		
Triethylamine		0	*	
Trichlorethylene		*		
1,1,1, trichloroethane (!)	*	0,*		
R-11 (see below)		*		
Turpentine	0	*		
Urea (!)	0	*,*		
Uric acid (!)	*	*		0,0
Vinyl chloride		*		
Xylene		*		

* = primary media selection for contaminant; 0 = secondary media selection.
PPIA = potassium-permanganate-impregnated alumina; AC = activated carbon; AIC = acid-impregnated carbon; BIC = base-impregnated carbon
R-114 is dichlorotetrafluoroethane; R-11 is trichlorofluoromethane.

Comments: Some contaminant molecules have isomers that, because they have different physical properties (boiling point, vapor pressures), require different treatment methods. For some contaminants, preferred treatment is ion exchange or another (nonlisted) impregnated carbon. For some contaminants, manufacturer recommendations differ. "!" is used in these cases.

calculation of the expected indoor concentration at various breakthroughs and efficiencies.

4. Obtain a measurement or estimate of breakthrough time at adsorber use conditions as developed in step (3).
5. Determine the changeout rate for the adsorbent as set by the breakthrough time.
6. Match the computed design requirements to available air cleaning equipment and specify.

Special Cases

Ozone reaches an equilibrium concentration in a ventilated space without a filtration device. It does so partly because ozone molecules react to form oxygen, but also because it reacts with people, plants, and materials in the space. This oxidation is harmful to all three, and therefore natural ozone decay is not a satisfactory way to control ozone except at low concentrations (<0.1 ppmv). Fortunately, activated carbon adsorbs ozone readily, both reacting with it and catalyzing its conversion to oxygen.

Radon is a radioactive gas that decays by alpha-particle emission, eventually yielding individual atoms of polonium, bismuth, and lead. These atoms form ions, called radon daughters or radon progeny, which are also radioactive; they are especially toxic, lodging deep in the lung, where they emit cancer-producing alpha and beta particles. Radon progeny, both attached to larger aerosol particles and unattached, can be captured by particulate air filters. Radon gas itself may be removed with activated carbon, but in HVAC systems this method costs too much for the benefit derived. Control of radon emission at the source and ventilation are the preferred methods of radon control.

Museums, libraries, archives, and similar applications are special cases of air cleaner design for protection, and may require very efficient air cleaning; see Chapter 21 for specifics.

Table 8 Suggested 4 × 6 or 4 × 8 Mesh Coconut Shell Carbon Residence Time Ranges

Application	Residence Time,[a] s
HVAC odor control applications for indoor air quality	
Light to medium duty	0.03 to 0.07
Heavy duty	0.06 to 0.14
Cleanroom corrosion control	
Recirculation	0.03 to 0.07
Intakes	0.03 to 0.14
Industrial corrosion control (refineries, wastewater, pulp, etc.)	0.12 to 0.28+
Corrosive/reactive low-level exhaust applications	0.12 to 0.28+
Toxic gas control[b]	0.28+
Museums	
Standard applications	0.06 to 0.12
Recirculation applications	0.03 to 0.07
Critical air intake	0.28+
Critical recirculation application	0.12 to 0.28
Nuclear applications	0.12 to 0.28+

Notes: [a]All residence times given are rules of thumb using 4 × 6 or 4 × 8 mesh carbon in granular beds for the application indicated. Other carbon packages, such as pleated filters containing finely divided carbon, may be dramatically different. Particularly at low (ppb) contaminant concentrations, well-designed pleated carbon filters can be very efficient and have adequate capacity.
[b]Design for toxic gas control must include appropriate overdesign and fail-safe provisions for all equipment used.
Source: Adapted and used with permission. ©1992 Extraction Systems, Inc.

Table 9 Items Included in Economic Comparisons Between Competing Gaseous Contaminant Control Systems

Capital Costs	Operating Costs
Added filtration equipment	Replacement or reactivation of gaseous contaminant filter media
Fan	
Motor	Disposal of spent gaseous contaminant filter media
Controls	
Plenum	Added electric power
Spare media holding units	Maintenance labor
Floor space	

Gas-phase air cleaners for **building protection** applications, whether to protect occupants against industrial accidents or deliberate acts, cannot reasonably stand alone. It makes little sense to design a complex system that can be easily overcome by physical acts. Air cleaner design alone is not enough. Air cleaning must be part of a complete and in-depth security program. The designer must have a scenario or series of scenarios against which to design protective systems.

Because a given air-cleaning technology may not protect against all challenges, protection against deliberate acts requires a robust design. The air-cleaning technology can be chosen to protect against the most challenging contaminant. Once the challenge contaminants are identified, a more rigorous application of the design method described previously is applied. Military specification hardware is generally suitable, although high-end commercial designs can provide significant protection. Testing of the installed filters is generally required, maintenance costs are significant, and the cost in space allocated to the installation, energy, and capital is high.

U.S. government guidance for the designer is available online (FEMA 2003a, 2003b; NIOSH 2002, 2003). The FEMA Web site also includes a number of other applicable documents. For additional guidance, see Chapter 58.

Energy Concerns

Pressure drop across the contaminant filter directly affects energy use. Data on the resistance of the filter as a function of airflow and on the resistance of the heating/cooling coils must be provided by the manufacturer. Currently, no standard test of pressure drop across a full-scale gaseous air cleaner is specified, but users can require that the initial pressure drop measurement from the particulate test (ASHRAE *Standard* 52.2) be conducted and reported. In addition to the gaseous contaminant filter itself, pressure drop through the housing, any added duct elements, and any particulate filters required up- and/or downstream of the gaseous contaminant filter must be included in the energy analysis.

Choosing between using outside air only and outside air plus filtered recirculated air is complex, but can be based on technical or maintenance factors, convenience, economics, or a combination of these. An energy-consumption calculation is useful. Replacing outdoor air with filtered indoor air reduces the amount of air that must be conditioned at an added expense in recirculation pressure drop. Outdoor air or filtered recirculated air may be used in any ratio, provided the air quality level is maintained. Janssen (1989) discusses the logic of these requirements.

Where building habitability can be maintained with ventilation alone, an economizer cycle is feasible under appropriate outdoor conditions. However, economizer mode may not be feasible at high humidities, because high humidity degrades the performance of carbon adsorbers.

Economic Considerations

Capital and operating costs for each competing system should be identified. Chapter 36 provides general information on performing an economic analysis. Table 9 is a checklist of filtration items to be considered in an analysis. It is important that the fan maintain adequate flow with an in-line air cleaner in place. If a larger blower is required, space must be available. Modifying unitary equipment that was not designed to handle the additional pressure drop through air-cleaning equipment can be expensive. With built-up designs, the added initial cost of providing air cleaners and their pressure drop can be much less because the increases may be only a small fraction of the total.

The life of the adsorbent media is very important. The economic benefits of regenerating spent carbon should be evaluated in light of the cost and generally reduced activity levels of regenerated material. Regeneration of impregnated carbon or any carbon containing hazardous contaminants is never permitted. Spent alumina- or zeolite-based adsorbents also cannot be regenerated.

SAFETY

Gaseous contaminant removal equipment generally has a low hazard potential. Contaminant concentrations are low, temperature is moderate, and the equipment is normally not closed in. Alumina- or zeolite-based media do not support combustion, but carbon filter banks have been known to catch fire, usually from an external source such as a welder's torch. Check local codes and fire authorities for their regulations on carbon. One authority requires automatic sprinklers in the duct upstream and downstream of carbon filter banks. As a minimum, a smoke detector should be installed downstream of the filter bank to shut down the fan and sound an alarm in case of fire.

Access for safe maintenance and change-out of adsorbent beds must be provided. Adsorbers are much heavier than particulate filters. Suitable lifting equipment must be available during installation and removal to prevent injury.

If adsorbent trays are to be refilled on site, safety equipment must be provided to deal with the dust this generates. Hooding, dust masks, and gloves are all required to refill adsorber trays from bulk containers.

INSTALLATION, START-UP, AND COMMISSIONING

This section provides general guidance installing gaseous contaminant removal equipment. Most manufacturers can also provide complete details and drawings for design.

Particulate Filters. A minimum 25 to 30% efficiency particulate filter (per ASHRAE *Standard* 52.1) should be installed ahead of the adsorber bank. Higher efficiency is desirable. Adsorbers and chemisorbers cannot function properly if their surfaces are covered and their pores clogged with dirt. If the air is extremely dirty (e.g., from diesel exhaust), the filter should have a much higher efficiency. One manufacturer requires a 90 to 95% efficiency filter for such applications. Weschler et al. (1994) report that carbon service life for ozone control was lengthened by using improved prefiltration.

Afterfilters are often used in critical applications where dust from media at start-up is likely, or where vibration of the adsorber bank may cause granular media to shed particles. These filters are frequently 25 to 30% efficiency, but higher efficiencies may be needed in some applications.

Equipment Weight. Adsorption equipment is much heavier than particulate filtration equipment, so supporting structures and frames must be designed accordingly. A typical 24 by 24 in. adsorber consisting of a permanent holding frame and sorbent-loaded trays has an installed weight of approximately 200 lb.

Minimize or Eliminate Bypass. Adsorbers and ducts in the outside air supply and in exhaust from hoods must be tightly sealed to prevent bypass of contaminants. Bypass leakage is not critical in most recirculating indoor air systems, but it is good practice to caulk all seams between individual holding frames. Granular media settles and compacts, and media retainers, such as trays or modules, must be loaded with media following manufacturers' recommendations to eliminate bypass through the media bed.

When to Install Media. When to install adsorbers in their holding frames depends on building circumstances. If they are installed at the same time as their holding frames and if the HVAC is turned on during the latter phases of construction, the adsorbers will adsorb paint and solvent vapors and other contaminants before the building is ready for beneficial occupancy. In some situations, adsorbing vapors and gases in the ventilation system before official start-up may be desired or needed. However, adsorber life will be reduced correspondingly. If adsorber frames are not loaded until the building is ready for occupancy, the unadsorbed contaminants may seriously reduce the initial indoor air quality of the building. Thus, shortened life is an acceptable trade-off for the quality of air at the time of occupancy (NAFA 1997). If the media are not in place during fan testing, the test and balance contractor must be instructed to place blank-offs or restrictions in the frames to simulate adsorber pressure drop. The HVAC designer's job specifications must clearly state when media are to be installed.

Pressure Gages. If prefiltration is adequate, adsorber pressure drop will not increase during normal operation. A pressure-drop-measuring device (gage or manometer) is thus not required as it is for a particulate filter bank. However, a gage may be useful to detect fouling or unintentional bypass. If the prefilters or afterfilters are installed immediately adjacent to the adsorbers, it may be more feasible to install the gage across the entire assembly.

Provision for Testing. At any time after installation of new media, determining the remaining adsorbent capacity or operating life may be required. (See the section on When to Change Media under Operation and Maintenance.) The installation should provide access ports to the fully mixed air stream both up- and downstream of the air cleaner. If media samples will be removed to determine remaining life, access must be provided to obtain those samples. No standard method for field evaluation of media life currently exists.

Start-Up and Commissioning

Special procedures are not required during start-up of an air handler with adsorbers. The testing and balancing contractor normally is required to measure and record resistance of all installed filter banks, including adsorbers, for comparison with design conditions.

The commissioning authority may require an activity test on a random sample of media to determine if the new media suffered prior exposure that reduced its life or if it meets specifications. An in situ air sampling test may also be required on the adsorber filter bank; however, no standard method for this test exists. See Chapter 42 for more on commissioning.

OPERATION AND MAINTENANCE

Bypass units and filters with adsorbent-infused media require frequent changing to maintain even low efficiency, but frequent maintenance is not required for complete removal units. Complete removal media adsorbers usually have a replaceable cell that cannot be regenerated or reactivated. This section covers maintenance of complete removal equipment with refillable trays or modules only.

When to Change Media

The changeout point of an adsorbent is difficult to determine. Sometimes media are changed when breakthrough occurs and occupants complain; but if the application is sensitive, tests for estimated residual activity may be made periodically. A sample of the media in use is pulled from the adsorber bank or from a pilot cell placed in front of the bank. The sample is sent to the manufacturer or an independent test laboratory for analysis, and the changeout time is estimated knowing the time in service and the life remaining in the sample.

In corrosion control installations, specially prepared metal "coupons" are placed in the space being protected by the adsorbent. After some time, usually a month, the coupons are sent to an analytical lab for measurement of corrosion thickness, which indicates the effectiveness of the gaseous contaminant control and provides an indication of system life. A standardized methodology for these tests is described in ISA *Standard* 71.04.

Replacement and Reactivation

Replacing media in permanent adsorber trays or modules is not the same as reactivation (regeneration), which is restoring spent activated carbon media to its original efficiency (or close to it). In some unit operations in some industrial applications (e.g., pressure swing adsorption), spent carbon is regenerated in special high-temperature vessels in the absence of oxygen to drive off contaminants. Chemisorber modules can be replaced (media changed), but chemisorber media, including impregnated carbon, cannot be regenerated.

Building operating personnel may choose to dump and refill trays and modules at the site after replacing those removed with a spare set already loaded with fresh media. They may also choose to dump the trays locally and send the empty trays to a filter service company for refilling, or they may simply exchange their spent trays for fresh ones. Disposing of spent sorbent by dumping must be limited to building air quality applications where no identifiable hazardous chemicals have been collected.

ENVIRONMENTAL INFLUENCES ON AIR CLEANERS

Environmental conditions, particularly temperature and humidity, affect the performance of most gaseous contaminant control equipment. Physical sorbents such as activated carbon are particularly susceptible. The user should confirm performance for any control device at the expected normal environmental conditions as well as at extremes that might be encountered during equipment outages. The following information is an overview.

High relative humidity in the treated airstream lowers efficiency of physical adsorbers, such as carbon, because of competition for sorption sites from the much more numerous water molecules. Often, performance is relatively stable up to 40 to 50% rh, but some compounds can degrade at higher humidities. The chemical nature of the contaminant(s) and the concentration both affect performance degradation as a function of relative humidity. On the other hand, very low relative humidities may make some chemisorption impossible. Therefore, media performance must be evaluated over the expected range of operation, and the relative humidity and temperature of the gaseous contaminant control should be held within design limits.

The effect of relative humidity swings can be better understood by considering a hypothetical adsorber with a saturation capacity for a contaminant and inlet concentration of 10% at 50% rh and 5% at 70% rh. Over an extended period at its normal operating condition of 50% rh, the sorbent might reach a loading of 2%. At this point a humidity swing to 70% rh would not cause a problem, and the sorbent could load up to 5% capacity. Should the humidity then swing back to 50%, the sorbent could continue to adsorb up to 10% by weight of the contaminant. However, if the sorbent were loaded to 8% by weight at 50% rh and the humidity rose to 70% rh, the carbon would be above its equilibrium capacity and desorption would occur until equilibrium was reached.

Similarly, swings in temperature and contaminant concentration can affect physical sorbent performance. Increasing temperature reduces capacity, and increasing concentration increases capacity. Additionally, changes in the identity of the contaminant in the airstream can affect overall performance as strongly sorbed contaminants displace weakly held contaminants.

All adsorption media have a modest ability to capture dust particles and lint, which eventually plug the openings in and between media granules and cause a rapid rise in the pressure drop across the media or a decrease in airflow. All granular gaseous adsorption beds need to be protected against particle buildup by installing particulate filters upstream. A prefilter with a minimum ASHRAE *Standard* 52.1 dust-spot efficiency of 25 to 30% is recommended.

Vibration breaks up the granules to some degree, depending on the granule hardness. ASTM *Standard* D3802 describes a test for measuring the resistance of activated carbon to abrasion. Critical systems using activated carbon require hardness above 92%, as described by *Standard* D3802.

Adsorption and chemisorption media sometimes accelerate corrosion of metals they touch. Consequently, media holding cells, trays, and modules should not be constructed of uncoated aluminum or steel. Painted steel or ABS plastic are common and exhibit good material service lives in many applications. Coated or stainless steel components may be required in more aggressive environments.

TESTING MEDIA, EQUIPMENT, AND SYSTEMS

Testing may be conducted in the laboratory with small-scale media beds or small pieces of treated fabric or composite material; on full-scale air cleaners in a laboratory test rig capable of generating the test atmosphere; or in the field. Laboratory tests with specific challenge gases are generally intended to evaluate media for developmental, acceptance, or comparative purposes. Full-scale tests using specific challenge contaminants are required to evaluate a complete adsorber as constructed and sold, and ultimately are needed to validate performance claims. Field tests under actual job conditions are used to ensure that the air cleaners were properly installed and to evaluate remaining media life.

Laboratory Tests of Media and Complete Air Cleaners

Small granular media samples have been tested in a laboratory for many years, and most manufacturers have developed their own methods. ASTM *Standard* D5228 describes a test method, but it is not entirely applicable to HVAC work because indoor air tends to have a wide range of contaminants at concentrations several orders of magnitude lower than used in testing.

Fundamental Media Properties Evaluation. The test used to evaluate fundamental properties of sorption media is static: measurement of the adsorption isotherm. In this test, a small sample of the adsorbent media is exposed to the pollutant vapor at successively increasing pressures, and the mass of pollutant adsorbed at each pressure is measured. The low-pressure section of an isotherm can be used to predict kinetic behavior, although the calculation is not simple. For many years, the test outlined in ASTM *Standard* D3467, which measured a single point on the isotherm of an activated carbon using carbon tetrachloride (CCl_4) vapor, was widely used for specifying performance of activated carbons. The test has been replaced by one described in ASTM *Standard* D5228, which uses butane as a test contaminant, because of carbon tetrachloride's toxicity. A correlation has been developed between the results of the two procedures so that users accustomed to $CC1_4$ numbers can recognize the performance levels given by ASTM D5228. It is a qualitative measure of performance at other conditions, and a useful quality control procedure. Another qualitative measure of performance is the Brunauer-Emmett-Teller (BET) method (ASTM *Standard* D4567), in which the surface area is determined by measuring the mass of an adsorbed monolayer of nitrogen. The results of this test are reported in square metres per gram of sorbent or catalyst. This number is often used as an index of media quality, with high numbers indicating high quality.

Small-Scale Dynamic Media Testing. ASHRAE is developing *Standard* 145.1, a flow-through test of media at small scale (about 2 in. diameter) and relatively high concentration (100 ppm). The test is intended to provide data for meaningful comparisons of media. *Standard* 145.1 is being developed based on several publications describing similar test procedures. Steady concentrations of a single contaminant are fed to a media bed, and the downstream concentration is determined as a function of the total contaminant captured by the filter (ASTM 1989; Mahajan 1987, 1989; Nelson and Correia 1976).

Because adsorber performance is a function of concentration, testing at high concentrations does not directly predict performance at low concentrations. The corrections described in the section on Physical Adsorption must be applied. If attempts are made to speed the test by high-concentration loading, pollutant desorption from the filter may confuse the results (Ostojic 1985). An adsorber cannot be tested for every pollutant, and there is no general agreement on which contaminants should be considered typical. Nevertheless, tests run according to the previously mentioned references do give useful measures of filter performance on single contaminants, and they do give a basis for estimates of filter penetrations and filter lives. Filter penetration data thus obtained can be used as P in Equations (3), (4), and (7) to estimate steady-state indoor concentrations.

VanOsdell et al. (2006) presented data from ASHRAE Research Project RP-792 showing that, for particular VOCs, tests at high concentration may be extrapolated to indoor levels. In addition, tests of a carbon with one chemical, toluene, are used to predict breakthough times for four other chemicals with modest success. The breakthrough times correlated well on a log-log plot of breakthrough time versus challenge concentration, and the predictions, based only on chemical properties and toluene and carbon performance data, were within approximately 100% of measured.

Because physical adsorbers, chemisorbers, and catalysts are affected by the temperature and relative humidity of the carrier gas and the moisture content of the filter bed, they should be tested over the range of conditions expected in the application. Contaminant capture and reaction product generation need to be evaluated by sweeping the test filter with unpolluted air and measuring downstream concentrations. Reaction products may be as toxic, odorous, or corrosive as captured pollutants.

Flow-Through Laboratory Tests of Complete Air Cleaners. Flow-through tests of complete air cleaners are the full-scale system test analog of the media tests described previously. In critical applications, such as chemical warfare protective devices and nuclear safety applications, sorption media are evaluated in a small canister, using the same carrier gas velocity as in the full-scale unit. The full-scale unit is then checked for leakage through gaskets, structural member joints, and thin spots or gross open passages in the sorption media by feeding a readily adsorbed contaminant to the filter and probing for its presence downstream (ASME *Standard* AG-1). Some HVAC filter manufacturers perform full-scale laboratory testing routinely for development and testing.

Chamber Decay Laboratory Tests of Complete Air Cleaners. Gaseous contaminant control devices can be tested in sealed chambers by recirculating contaminated air through them and measuring the decay of an initial contaminant concentration over time. Chamber decay tests are generally used for devices that physically cannot be tested in a duct, or that have single-pass efficiencies so low that they cannot be reliably measured using up- and downstream measurements. The procedures used are gaseous contaminant analogs to the Association of Home Appliance Manufacturers (AHAM) particulate air cleaner test method, but no consensus test standard exists and test methods vary between laboratories. Decay tests can provide valuable data, but the results are affected by factors extraneous to the air cleaner itself, such as errors introduced by adsorption on the chamber surfaces, leaks in the chamber, and the drawing of test samples. Robust test quality assurance and quality control are required to obtain meaningful data. Daisey and Hodgson (1989) compared the pollutant decay rate with and without the control device to overcome these uncertainties.

Field Tests of Installed Air Cleaners

Gaseous contaminant air cleaners are expensive enough to place a premium on using their full capacity. For odor control applications, the most reliable measure of the continued usefulness of gaseous contaminant air cleaners may be a lack of complaints, and complaints often serve as early indicators of exhausted beds. This approach is not acceptable for toxic contaminants, for which more formal procedures must be used. Unfortunately, and despite significant effort, there is not a simple, accepted standard for field-testing gaseous air-cleaning equipment. Two approaches have been used: (1) laboratory testing of samples of media removed from the field and (2) in situ upstream/downstream gas measurements using the ambient contaminant(s) as the challenge.

The classic and still widely used technique of evaluating the status of a granular air cleaner in the field is to remove a small sample and ship it to a laboratory. Media manufacturers offer this service. The sample needs to be representative of the air cleaner, so should be obtained from near the center of the air cleaner. Consolidated multiple small samples are more representative of the air cleaner than one larger sample. The sample needs to be handled and shipped so that it remains representative when it reaches the laboratory; laboratories can suggest procedures. Given a representative sample and good handling, sampled media test results give a good indication of the state of a media bed.

Unfortunately, media sampling as a field-testing procedure has disadvantages. First, it applies only to granular media that can be sampled; cutting a hole in a bonded or pleated media product to obtain a sample destroys the filter. In addition, opening a granular media air cleaner to obtain samples is sufficiently disagreeable to prevent its frequent application.

These disadvantages have led to attempts to find more convenient ways to evaluate filters in the field. The most widely used alternative approach is to sample the air up- and downstream of the filter and use the ratio to estimate the remaining filter capacity.

Field tests of gaseous contaminant air cleaners are conducted using the same general techniques discussed under contaminant measurement and analysis. Depending on the contaminant, type of air cleaner, and application, field testing can be accomplished with active or passive sampling techniques. Liu (1998) discussed the relative merits of the various techniques. Either may be superior in any given case. For indoor air applications with relatively constant contaminant sources, passive samplers have advantages by capturing an integrated sample and being more economical. (Real-time samplers are used infrequently in this role.)

Up- and downstream measurements are evaluated by converting them to efficiency or fractional penetration and comparing them to measurements made at the time of installation. Because gaseous challenge contaminants cannot be injected into the HVAC system in occupied buildings, the up- and downstream samplers are exposed only to the ambient contaminants, which usually vary in nature and concentration. This complicates interpretation of the data, because air cleaner efficiency varies with concentration and nature of the contaminant. Efficiency from field samples is most directly interpreted if there is a single contaminant (or relatively consistent group of contaminants evaluated as TVOC) with a relatively constant challenge concentration. For multiple contaminants at multiple concentrations, judgment and experience are needed to interpret downstream measurements. Bayer et al. (2005) attempted to use single-component analyses to evaluate air cleaners in the field. That is, the up- and downstream samples were analyzed not for TVOC, but for particular chemicals (heptane, toluene, ethyl benzene, and formaldehyde). Bayer et al. found that the time variations in the challenge made the efficiency determinations so variable that the procedure could not be used reliably.

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