

CONTROL OF GASEOUS INDOOR AIR CONTAMINANTS

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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 those listed 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.

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. Control of gaseous contaminants from industrial processes and stack gases is covered in Chapter 25 of the 2000 *ASHRAE Handbook—HVAC Systems and Equipment*.

GASEOUS CONTAMINANTS

The only reason to remove a gaseous contaminant from an airstream is that it has 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 their odors before they reach levels toxic to humans, but this is not always true. For example, the potentially deadly contaminant carbon monoxide has no odor.

Sources of nonindustrial contaminants are discussed in Chapter 12, Air Contaminants, in the 2001 *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 outdoor concentrations for gaseous contaminants at urban sites. These values are typical; however, they may be exceeded if the building under consideration is located near a fossil fuel power plant, refinery, chemical production facility, sewage

Table 1 Major Contaminants in Typical Cigarette Smoke

Contaminant	Weighted Mean ETS Generation Rate, mg/cigarette	Weighted Standard Error, mg/cigarette	Method
Carbon monoxide	55.101	1.064	nondispersive IR
Ammonia	4.148	0.107	cation exchange cartridge
Acetaldehyde	2.50	0.054	DNPH cartridge
Formaldehyde	1.33	0.034	
Summary VOC measurements			
Total HC by FID	27.810	0.483	FID
Total sorbed and IDed VOC		11.270	Sorbent tube/GC
Total sorbed VOC	19.071	0.525	Sorbent tube/GC
Respirable particles	13.674	0.411	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).

Table 2 Generation of Gaseous Contaminants by Building Materials

Contaminant	Average Generation Rate, $\mu\text{g}/(\text{h}\cdot\text{m}^2)$						
	Caulk	Adhesive	Lino-leum	Carpet	Paint	Varnish	Lacquer
C-10 Alkane	1200						
<i>n</i> -Butanol	7300						760
<i>n</i> -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

Contaminant	Average Generation Rate, $\mu\text{g}/(\text{h}\cdot\text{m}^2)$						
	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).

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

Table 3 Generation of Gaseous Contaminants by Indoor Combustion Equipment

	Generation Rates, $\mu\text{g}/\text{kJ}$					Typical Heating Rate, kW	Typical Use, hour/day	Vented or Unvented	Fuel
	CO_2	CO	NO_2	NO	HCHO				
Convective heater	51 000	83	12	17	1.4	31	4	U	Natural gas
Controlled-combustion wood stove		13	0.04	0.07		13	10	V	Oak, pine
Range oven		20	10	22		32	1.0*	U	Natural gas
Range-top burner		65	10	17	1.0	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. (1985b); and Wade et al. (1975).

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

Contaminant	Typical Emission, $\mu\text{g}/\text{h}$	Contaminant	Typical Emission, $\mu\text{g}/\text{h}$
Acetaldehyde	35	Methane	1710
Acetone	475	Methanol	6
Ammonia	15 600	Methylene chloride	88
Benzene	16	Propane	1.3
2-Butanone (MEK)	9700	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, $\mu\text{g}/\text{m}^3$	Contaminants	Typical Concentration, $\mu\text{g}/\text{m}^3$
Acetaldehyde	20	Methylene chloride	2.4
Acetone	3	Nitric acid	6
Ammonia	1.2	Nitric oxide	10
Benzene	8	Nitrogen dioxide	51
2-Butanone (MEK)	0.3	Ozone	40
Carbon dioxide	612 000*	Phenol	20
Carbon monoxide	3000	Propane	18
Carbon disulfide	310	Sulfur dioxide	240
Carbon tetrachloride	2	Sulfuric acid	6
Chloroform	1	Tetrachloroethylene	2.5
Ethylene dichloride	10	Toluene	20
Formaldehyde	20	1,1,1-Trichloroethane	4
<i>n</i> -Heptane	29	Trichloroethylene	15
Mercury (vapor)	0.005	Vinyl chloride monomer	0.8
Methane	1,100	Xylene	10
Methyl chloride	9		

*Normal concentration of carbon dioxide in air. The concentration in occupied spaces should be maintained at no greater than three times this level (1000 ppm).

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).

treatment plant, municipal refuse dump or incinerator, animal feed lot, or other major source of gaseous contaminants. If such sources will 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.

Use of Source Data to Predict Indoor Concentrations

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 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).

$$C_{ss} = a/b \quad (1)$$

where

$$a = C_x(Q_i + 0.01P E_v Q_v / f) + 2119(G_i + NG_O) \quad (2)$$

$$b = Q_e + Q_h + Q_L + k_d A + NQ_O (1 - 0.01P_O) + (E_v Q - Q_v)(1 - 0.01P)/f \quad (3)$$

and

A = surface area inside ventilated space on which contaminant can be adsorbed, m^2

C_{ss} = steady-state indoor concentration of contaminant, mg/m^3

C_x = outdoor concentration of contaminant, mg/m^3

E_v = ventilation effectiveness, fraction

$f = 1 - 0.01P (1 - E_v)$

G_i = generation rate for contaminant by nonoccupant sources, mg/s

G_O = generation rate for contaminant by an occupant, mg/s

k_d = deposition velocity on a for contaminant, m/s

N = number of occupants

P = filter penetration for contaminant, %

P_O = penetration of contaminant through human lung, %

Q = total flow, m^3/s

Q_e = exhaust airflow, m^3/s

Q_h = hood flow, m^3/s

Q_i = infiltration flow, m^3/s

Q_L = leakage (exfiltration) flow, m^3/s

Q_O = average respiratory flow for a single occupant, m^3/s

Q_v = ventilation (makeup) airflow, m^3/s

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

$$b = Q_i + Q_v + k_d A + NQ_O (1 - 0.01P_O) \quad (4)$$

The parameters for this model must be determined carefully so that nothing significant is ignored. The 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

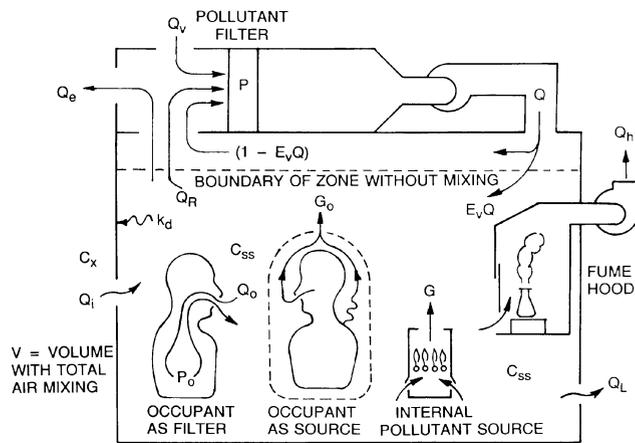


Fig. 1 Recirculatory Air-Handling and Gaseous Contaminant Schematic

conditions change suddenly. The dynamic equation for the building in [Figure 1](#) is

$$C_I = C_{ss} + (C_0 - C_{ss})e^{-b\theta/V} \quad (5)$$

where

V = volume of the ventilated space, m^3

C_0 = concentration in space at time $\theta = 0$

C_I = concentration in space θ minutes after a change of conditions

C_{ss} is given by Equation (1), and b by Equation (4), with the parameters for the new condition inserted.

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

$$C_{ss} = \frac{\frac{0.01PE_vQ_vC_x}{f} + (G_i + NG_o)}{Q_e + K_dA + NQ_o(1 - 0.01P_o) + \frac{(E_vQ - Q_v)(1 - 0.01P)}{f}} \quad (6)$$

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 may have many rooms, with multiple 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 (1) through (6) that range from 3 to 600 $\mu m/s$ 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.

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 a zone of low concentration even with low rates of turbulent mixing.

Quantities appropriate for the flows in Equations (1) through (6) 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 26, Ventilation and Infiltration, of the 2001 *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

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 the design.

Two general cases exist: (1) new ventilation systems in new buildings for which the 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 add up 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 the second case, 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 EPA *Building Air Quality Guide* (EPA 1991) is useful for such investigations. Again, once the contaminants and loads are understood, design can begin.

Valuable guidance on estimating contaminant loads in industrial situations is given by Burton (2000). Sampling and measurement techniques for industrial and nonindustrial environments are discussed in Chapter 12, Air Contaminants, in the 2001 *ASHRAE Handbook—Fundamentals*; evaluating odor levels is covered in Chapter 13, Odors, of that volume.

Contaminant Load Estimates

The results of sampling and analysis identify the contaminants and their concentrations at particular places and times or over known times. Several measurements, which may overlap or have gaps concerning the contaminants analyzed and times of measurement, are usually used to estimate the overall contaminant load. The 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 the 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. 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. The design and operation of effective hoods are described in Chapters 13, 14, 29, and 30 and in *Industrial Ventilation: A Manual of Recommended Practice* (ACGIH 1995), and in [Chapter 30. Industrial Local Exhaust Systems](#), 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. Such 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 guidelines for air distribution given in Chapters 32 and 34 of the 2001 *ASHRAE Handbook—Fundamentals* are appropriate for contamination control by general ventilation. The airflows set by *ASHRAE Standard 62* 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 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.

Gaseous Contaminant Air Cleaning Terminology

Several methods of measuring the performance of a gaseous control device, some unique to this application, have been developed. The meaning of some terms familiar from particle filtration are slightly different. In general, gaseous adsorber performance is a function of (1) the specific contaminant, (2) its concentration, (3) the airflow rate, and (4) environmental conditions.

Penetration is the ratio of control device outlet concentration to that at the inlet (challenge concentration) for a constant challenge. **Efficiency** is defined as $(1 - \text{penetration})$. Penetration and efficiency are usually expressed as percentages or decimal fractions. Unlike particulate filters, physical adsorbents and chemisorbents both decline in efficiency as they load. The decline can be very sudden, and not usually linear with time. Because their efficiency declines with use, the time at which the measurement is made must be given with efficiency or penetration readings.

The sudden decline in efficiency leads to the concept of **breakthrough time**, defined as the 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 a portion of the challenge gas to bypass the sorbent. These devices break through immediately, and breakthrough time, as defined above, does not apply.)

At **saturation**, the physical adsorbent contains all the contaminant it can hold at the challenge concentration, temperature, and humidity. This point is its **activity**, expressed as a percentage of the carbon mass or fraction (i.e., g contaminant/g adsorbent). Activity is an equilibrium property, 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. The amount remaining after a saturated bed reaches equilibrium in clean air is the **retentivity** of the adsorbent.

Residence time is the period that the 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

$$\text{Residence time} = \frac{\text{Bed area exposed to airflow} \times \text{Bed depth}}{\text{Airflow rate}} \quad (7)$$

For example, a unitary adsorber containing trays totaling 4 m² media in 25 mm deep bed, challenged at 1 m³/s, has a residence time of 0.1 s. Given this definition, a deeper media bed, lower airflow rate, or adsorbents in series increase the residence time and thus adsorber performance. Because gaseous contaminant air cleaners all have tended 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

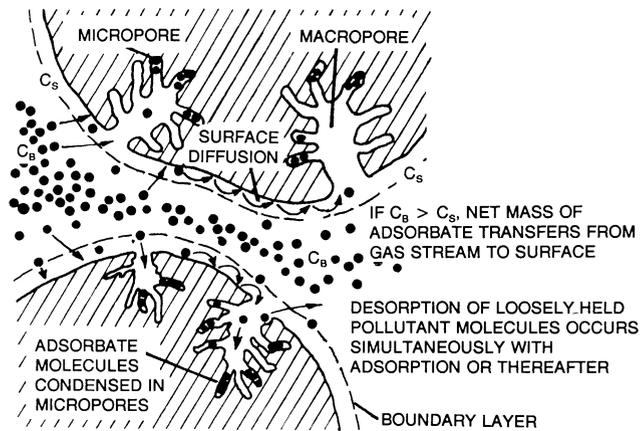


Fig. 2 Steps in Contaminant Adsorption

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.

Control Processes

Many chemical and physical processes remove gases or vapors from air. The gaseous contamination control processes of commercial interest to the HVAC engineer are physical adsorption and chemisorption. 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. Adsorbed contaminant gas molecules are those that strike a surface and remain bound to it 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 surface of the adsorbent media is treated to develop microscopic pores, greatly increasing the area available for molecular contact. Typical activated alumina has a surface area of 200 m² per gram; typical activated carbon has a surface area from 1000 to 1500 m²/g. Pores of various microscopic sizes and shapes form minute traps that can fill with condensed contaminant molecules.

The most common granular adsorbents are millimeter-sized, and the granules are used in the form of packed beds. In general, packed beds composed of larger monodisperse particles have lower pressure drops per unit depth of sorbent than those composed of smaller monodisperse 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 the adsorbing 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.

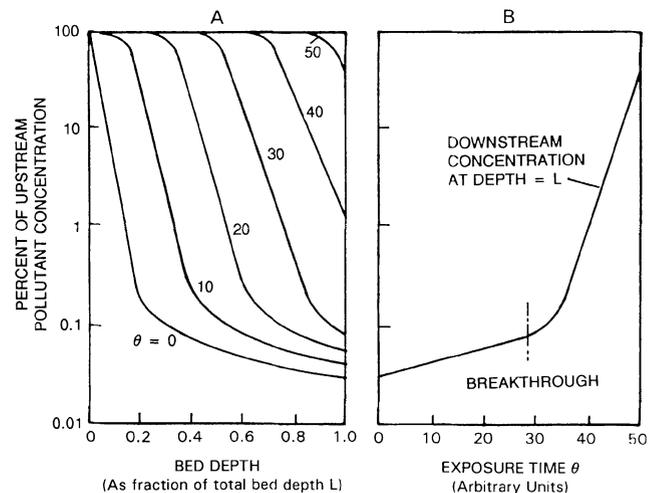


Fig. 3 Dependence of Contaminant Concentration on Bed Depth and Exposure Time

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 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. At later times, the entrance of the adsorber bed becomes loaded with contaminant, so contaminant concentrations in the gas stream are higher at each bed depth.

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 the downstream concentration is very low until breakthrough time θ_{BT} , when the concentration rises rapidly until the downstream concentration is the same as the upstream. 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. Essentially, water vapor acts as a second contaminant, altering the adsorption parameters by reducing the amount of the first contaminant that can be held by the adsorber and shortening breakthrough times. For VOCs

adsorbed on carbon, the effect of relative humidity is modest up to about 50%, and greater at higher 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 chemisorber.
- 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 2000 *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** 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 reactions other than oxidation can produce undesirable by-products.

Photocatalysis uses light and a photocatalyst to perform reduction-oxidation (redox) chemistry on the surface of the catalyst. 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 completely oxidize a wide variety of organic compounds. Information on this process can be found in the report on ASHRAE *Research Project* RP-1132 (Idem 2002).

Biofiltration is effective for low concentrations of many VOCs found in buildings (Janni et al. 2001). Operating costs are low, and installation is cost-competitive. However, concerns over using uncharacterized mixtures of bacteria in the filter, possible downstream emissions of microbes or chemicals, and the risk of unexpected or undetected failure make it unsuitable for cleaning air circulated to people. 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.

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 in granular or pelletized form, which are held in a retaining structure that allows the air being treated to pass through the media with an acceptable pressure drop at the operating airflow. Granular media has traditionally been a few millimetres in all dimensions. Pellets or flakes that pass through a screen with an aperture of 4.8×2.4 mm or 3.4×3.4 mm are typical 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 [4D](#). 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 [4E](#). 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 is generally much smaller in size (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 such that the pressure drop of the composite is acceptable. Because the adsorbent is intimately bound to, and its performance affected by the support structure, these adsorbents must be evaluated by tests on the complete composite structure, not the granular adsorbent alone.

Granular media adsorbents 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-

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 12 mm 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 1.5 m/s 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 1.4 m³/s or less) or if inline 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 16 to 50 mm 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 4G) 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 capacity of the filter.

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 and 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.

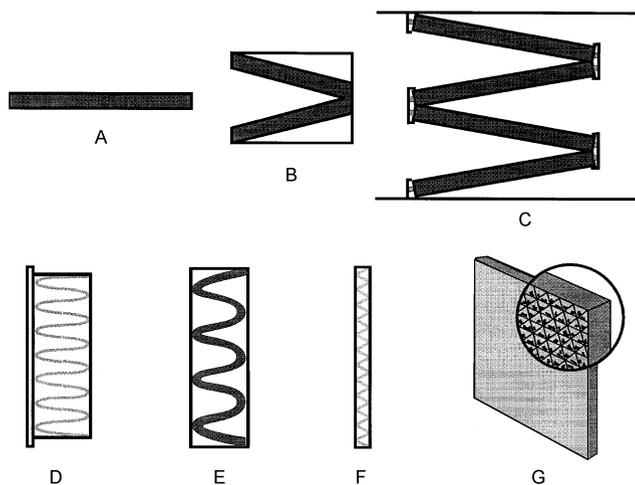
AIR CLEANING DESIGN

Ideally, the gaseous contaminant control designer 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 name (e.g., aldehydes). Investigation may allow a rough estimate of contaminant generation rate based on quantity of product used daily or weekly.

Experimental measurements of air cleaner performance are usually not available, but it can be estimated using the equations presented in the section on Use of 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 chemisorption velocity.



- A. Granular media tray, refillable or disposable
 B. Granular media module, refillable or disposable
 C. Side access adsorber housing with granular media trays or modules
 D. Composite media in flanged unitary adsorber, disposable
 E. Granular media serpentine cell, refillable
 F. Adsorbent-infused panel filter, disposable
 G. Honeycomb panel adsorber, disposable

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

The performance of air cleaners 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 having or potentially having a health impact, 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 an economical and acceptable mode of operation.

The first step in design is selecting an appropriate adsorption medium. Next, the location of the air cleaner in the HVAC system must be decided. Then the air cleaner must be sized such that sufficient media is used to achieve design efficiency and capacity goals and to estimate media replacement requirements. Finally, the commercial equipment that most economically meets the needs of the particular 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 aid in reducing 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

[Table 6](#) lists some physical adsorption and chemisorption media used for indoor air applications. Activated carbon, impregnated activated carbon, and potassium permanganate-impregnated alumina are the three adsorbents used most widely. Activated carbon is by far the most popular because of the wide range of contaminants it can adsorb.

[Table 7](#) is a general guide to the relative effectiveness of unimpregnated activated carbon on a range of odors and compounds

Table 6 Adsorption and Chemisorption Media Used in HVAC Systems

Material	Impregnant	Typical Vapors or Gases Captured
Physical adsorbents		
Activated carbon	None	Organic vapors, ozone, acid gases
Activated alumina	None	Polar organic compounds ^a
Silica gel	None	Water, polar organic compounds ^a
Molecular sieves (zeolites)	None	Carbon dioxide, iodine
Chemisorbers		
Activated alumina	KMnO ₄	Hydrogen sulfide, sulfur dioxide
Activated carbon	I ₂ , Ag, S	Mercury vapor
Activated carbon ^b	I ₂ , KI ₃ , amines	Radioactive iodine, organic iodine
Activated carbon	NaHCO ₃	Nitrogen dioxide
NaOH + Ca(OH) ₂	None	Acid gases
Activated carbon	KI, I ₂	Mercury vapor

^aPolar organics = alcohols, phenols, aliphatic and aromatic amines, etc.

^bMechanism may be isotropic exchange as well as chemisorption.

under typical average air purification duty conditions. The table is widely used in the industry, but it is only a guide. 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.

Some chemically reactive gases such as ammonia or formaldehyde are not adsorbed well by standard activated carbon, but specially impregnated carbon can be used successfully. These gases are noted with an asterisk (*) in [Table 7](#). The capacity index values in the table were developed from data obtained at concentrations well above those encountered indoors. The ratings are noted below and remain useful for comparative purposes. With that qualification, the ratings have the following meaning:

- 4 Activated carbon has a high capacity for these materials, adsorbing 20 to 40% of its mass of the contaminant. (They average 30% at high concentrations.) At indoor concentrations, the capacities are about 8 to 15%. More than 70% of the materials listed fall into this category.
- 3 Activated carbon has a satisfactory capacity for these materials, adsorbing 10 to 25% of its mass of the contaminant (averaging 17% at high concentrations, lower at indoor concentrations).
- 2 Activated carbon has a relatively low adsorption capacity for these materials, and its use is borderline.
- 1 Activated carbon has a very low or negligible capacity for these materials and is generally not recommended.

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. A graphical representation of the media and equipment selection process is shown in [Figure 5](#).

Sizing Gaseous Contaminant Control Equipment

[Tables 6](#) and [7](#) provide guidance in the selection of sorbent media. Both manufacturers' guidance and adsorbent performance

Table 7 General Guide to Activated Carbon Relative Capacity Index for Odors

Acetic acid	4	*Corrosive gases	3	*Hydrogen sulfide	1	Paper deteriorations	4
Acetone	3	Creosote	4	Industrial wastes	3	Paradichlorobenzene	4
*Acetylene	1	Decaying substances	4	Ink odors	3	Paste and glue	4
*Acrolein	3	Deodorants	4	Iodine	4	Pentane	3
Acrylic acid	4	Detergents	4	Irritants	4	Perfumes & cosmetics	4
Adhesives	4	Dichloroethane	4	Isopropyl acetate	4	Pet odors	4
Alcoholic beverages	4	Dichloroethylene	4	Isopropyl alcohol	4	Phenol	4
*Amines	2	Diesel fumes	4	Isopropyl ether	4	Phosgene	3
*Ammonia	2	Diethyl ketone	4	Kerosene	4	Pitch	4
Amyl acetate	4	Dimethylsulfide	4	Kitchen odors	4	Plastic	4
Amyl alcohol	4	Disinfectants	4	Lactic acid	4	Propane	2
Amyl ether	4	Embalming odors	4	Liquid fuels	4	*Propylene	2
Animal odors	3	Epoxy	4	Liquor odors	4	Radiation products	2
Anesthetics	3	Ethane	1	Lubricating oils/greases	4	Rancid oils	4
Aniline	4	Ether	3	Lysol	4	Resins	4
Asphalt fumes	4	Ethyl acetate	4	Masking agents	4	Reodorants	4
Automobile exhaust	3	Ethyl alcohol	4	Medicinal odors	4	Ripening fruits	4
Benzene	4	Ethyl chloride	3	Menthol	4	Rubber	4
*Bleaching solutions	3	*Ethylene	1	Mercaptans	2	Sewer odors	4
Bromine	4	Ethylene dichloride	4	Methane	1	Smog	4
Butane	2	Ethyl ether	3	Methyl acetate	3	Smoke	4
Butyl acetate	4	Ethyl mercaptan	3	Methyl acrylate	4	Solvents	3
Butyl alcohol	4	Essential oils	4	Methyl alcohol	3	Stoddard solvent	4
Butyl chloride	4	Eucalyptole	4	Methyl bromide	3	Styrene monomer	4
Butyl ether	4	Exhaust fumes	3	Methyl butyl ketone	4	*Sulfur dioxide	2
Butyric acid	4	Fertilizer	4	Methyl chloride	3	*Sulfur trioxide	2
Carbolic acid	4	Film processing odors	3	Methylene chloride	4	Sulfuric acid	4
*Carbon dioxide	1	Floral scents	4	Methyl ethyl ketone	4	Tar	4
Carbon disulfide	2	Food aromas	4	Mildew odor	3	Tetrachloroethane	4
Carbon monoxide	1	*Formaldehyde	2	Mixed odors	4	Tetrachloroethylene	4
Carbon tetrachloride	4	*Formic acid	3	Naphtha (coal tar or petroleum)	4	Toluene	4
Cheese odors	4	Fuel gases	2	Naphthalene	4	Toluidine	4
*Chlorine	3	Fumes	3	Nicotine	4	Trichloroethane	4
Chlorobenzene	4	Gasoline	4	*Nitric acid	3	Trichloroethylene	4
Chlorobutadiene	4	Hospital odors	4	Nitrobenzenes	4	Turpentine	4
Chloroform	4	Household smells	4	*Nitrogen dioxide	1	Urea	4
Chloropicrin	4	Hydrogen	1	Nitroglycerine	4	Uric acid	4
Cigarette smoke odor	4	*Hydrogen bromide	1	Octane	4	Valeric acid	4
Citrus/fruit odors	4	*Hydrogen chloride	1	Odorants	4	Varnish fumes	4
Cleaning compounds	4	*Hydrogen cyanide	1	Organic chemicals	4	Vinegar	4
Coal smoke odor	3	*Hydrogen fluoride	1	Ozone	4	Vinyl chloride	2
Combustion odor	3	*Hydrogen iodide	1	Paint and redecorating odors	4	Xylene	4
Cooking odors	4	*Hydrogen selenide	1	Palmitic acid	4		

Adapted with permission. ©1995 Barnebey and Sutcliffe Corporation.

*Requires impregnated carbon.

Equations (1) through (6) are used to size equipment. A manufacturer's guidance is often followed because the 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 calculation of the expected indoor concentration at various breakthroughs and efficiencies.
4. Obtain a measurement or estimate of the 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 (<0.2 mg/m³). 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 extremely fine aerosol particles, 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.

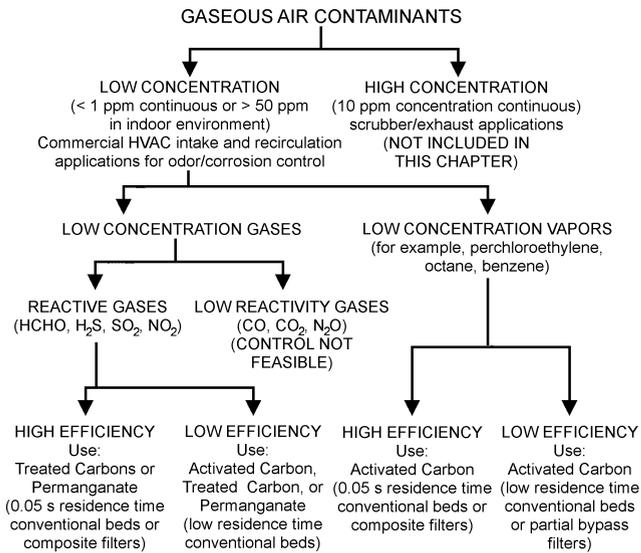


Fig. 5 Media and Equipment Selection Schematic
(Adapted with permission. ©1992 Extraction Systems, Inc.)

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, Owning and Operating Costs](#), provides general information on performing an economic analysis. [Table 8](#) 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

Table 8 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	Disposal of spent gaseous contaminant filter media
Motor	Added electric power
Controls	Maintenance labor
Plenum	
Spare media holding units	
Floor space	

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 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. Adsorbent beds 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 generated during the operation. Hooding, dust masks, and gloves are all required to refill adsorbent 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. Adsorbent 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 the media at start-up is likely, or where vibration of the adsorber bank may cause the granular media to shed particles. These filters are frequently 25 to 30% efficiency filters, but higher efficiencies may be needed in some applications.

Equipment Mass. Adsorption equipment is much heavier than particulate filtration equipment, so supporting structures and frames must be designed accordingly. A typical 600 by 600 mm adsorber consisting of a permanent holding frame and sorbent-loaded trays has an installed mass of approximately 90 kg.

Eliminate Bypass. Adsorbent 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 and

between individual holding frames. Granular media retainers, such as trays or modules, must be loaded with media per manufacturers' recommendations to eliminate the possibility of 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 is 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 is to be installed.

Pressure Gages. Provided 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 is 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

critical installations, "coupons" plated with precious metals 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. Standardized methodology for these tests is not available.

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). Spent carbon is regenerated in special high-temperature kilns in the absence of oxygen to drive off the contaminants it has acquired. 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 the 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 the 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 mass of the contaminant. However, if the sorbent were loaded to 8% by mass 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 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 rapidly raise 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 Testing

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.

Field Testing

Up- and downstream measurements are evaluated by converting them to efficiency or fractional penetration and comparing them to measurements made at installation. Efficiency is most directly interpreted if there is a single contaminant with a relatively constant challenge concentration. For multiple contaminants at multiple concentrations, judgment and experience are needed to interpret downstream measurements. Media samples can be evaluated by the manufacturer for remaining life in fractions of the original capacity.

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