

AIR CLEANERS FOR GASEOUS CONTAMINANTS

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THE purpose of gas-phase (molecular) filtration is to remove air contaminants that could adversely affect the occupants, processes, or contents of a space. The effects are problematic 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. More information on gaseous contaminants and odors can be found in Chapters 11 and 12 of the 2017 *ASHRAE Handbook—Fundamentals*.

Indoor gaseous contaminant levels can sometimes be reduced with ventilation air drawn from outdoors, diluting the contaminants to acceptable levels. However, available outdoor air itself 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, as specified in ASHRAE *Standard* 62.1's IAQ procedure, 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 contaminants must also be removed by gaseous contaminant removal equipment, which is frequently different from particulate filtration equipment.

This chapter covers design procedures for gaseous contaminant air-cleaning systems for occupied spaces only. Procedures discussed are appropriate to address odors and gaseous irritants. Removal of contaminants for the express purpose of protecting building occupants (whether against deliberate attack or industrial accidents) or to protect artifacts (e.g., 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 61. Aspects of air-cleaning design for museums, libraries, and archives are included in Chapter 24, and removal of gaseous contaminants from industrial processes and stack gases is covered in Chapter 30 of the 2016 *ASHRAE Handbook—HVAC Systems and Equipment*.

1. TERMINOLOGY

In particular, gaseous contaminant control technology performance is a function of (1) the specific contaminant, (2) its concentration, (3) airflow rate, and (4) environmental conditions. The terminology related to gaseous contaminant air-cleaning equipment is specific to the field, and some terms that are familiar from particle filtration differ slightly in this context.

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

Absorption. Transport and dissolution of a sorbate into an adsorbent to form a homogeneous mixture having the characteristics of a solution. It is important to distinguish absorption from the surface phenomenon of **adsorption**, which is one of the most important processes in operation of air cleaners that remove gaseous contaminants.

Activated Carbon. Carbon, usually in the form of granules, treated to enhance its surface area and consequent ability to adsorb gases through a highly developed pore structure.

Activity. Mass of contaminant contained in a physical adsorbent at saturation, expressed as a percentage or fraction of the adsorbent 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 bed filters are changed for efficiency reasons well before the adsorbent 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 receptivity.

Adsorbent. Any solid having the ability to concentrate significant quantities of other substances on its surface.

Adsorption. Process in which the molecules of a gas or vapor adhere by physical or chemical processes to the exposed surface of solid substances (both the outer surface and inner pore surface) with which they come into contact.

Adsorption, Chemical (Chemisorption). Binding of a contaminant to the surface of an adsorbent by forces with energy levels approximately those of a chemical bond. Chemisorption is an irreversible process.

Adsorption, Physical. Attraction of a contaminant to the surface, both outer surface and inner pore surface, of adsorbent media by physical forces (Van der Waals forces). Physical adsorption is a reversible process.

Adsorption Capacity. The amount (mass or moles) of a selected contaminant that can be contained in the media of a gas-phase air-cleaning device under given test conditions and end point.

Adsorbent, Regenerated. Adsorbent material which, after saturation, may be treated to recover its adsorption properties and thereby enabled for reuse.

Adsorption Isotherm. A curve obtained by plotting, at constant temperature, the quantity of adsorbate against the concentration of the substance in the original gas or solution.

Breakthrough. Point in the operating cycle of a gas-phase air-cleaning device at which the effluent contaminant concentration becomes measurable. Thereafter, the effluent concentration may rise rapidly.

Breakthrough Curve. Plot of contaminant penetration through the air cleaner versus time for a particular challenge concentration and airflow.

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 a physical adsorbent or chemisorbent 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 chemisorbent, the media is exhausted. (Some commercial devices are designed to allow some of the challenge gas to bypass the adsorbent. These devices break through immediately, and breakthrough time, as defined here, does not apply.)

Capacity. See **Adsorption Capacity**.

CAS Number. An identification number unique to each individual chemical, specified by the Chemical Abstracts Service (CAS), a division of the American Chemical Society (ACS).

Catalyst. Any substance that, when present in a small quantity, significantly 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. The disproportionate or uneven flow of fluid (gas or liquid) through passages of lower resistance that 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 (Air) Stream. Test contaminant(s) of interest diluted to the specific concentration(s) of the test prior to filtration.

Chemisorbent Media. Media formed when an adsorbent such as activated alumina, zeolite, or activated carbon is treated with a chemical reagent such as potassium permanganate, potassium hydroxide, or phosphoric acid. Adsorbates are removed by a reaction with the chemical reagent.

Concentration. Quantity of one substance dispersed in a defined amount of another. Concentrations of contaminants in air are usually expressed as parts per million by volume (ppmv) or as milligrams of contaminant per cubic metre of air (mg/m^3).

Density, Apparent (Bulk Density). Mass under specified conditions of a unit volume of a solid physical adsorbent or chemisorbent, including its pore volume and interparticle voids.

Desorption. Process by which adsorbed molecules leave the surface of a physical adsorbent and reenter the fluid stream. This process is the opposite of adsorption.

Efficiency. See **Removal Efficiency**.

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

Equilibrium Capacity. See **Adsorption Capacity**.

HEPA Filter. High-efficiency particle air filter that has performance compliant with requirements of filter class ISO 35H to ISO 45H (per ISO 29463-1).

Mass Transfer Zone. Depth of physical adsorption or chemisorption media required to remove essentially all of an incoming contaminant; dependent on type of media, media granule size, 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 physical adsorbent (or chemisorbent) used in gaseous contaminant air-cleaning equipment. Also used to refer to a material (e.g., a nonwoven) that contains a physical adsorbent or chemisorbent.

Penetration. Ratio of contaminant concentration downstream of the media bed to the upstream (challenge) concentration, sometimes expressed as a percentage. Related to fractional efficiency by the expression $\text{Efficiency} = (1 - \text{Penetration})$. 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 absolute (static) pressure between two points in an airflow system, caused by frictional resistance to airflow in a duct, filter, or other system component such as a media bed or air-cleaning device.

Reactivation. Treatment of carbon with elevated temperature and steam to remove the volatiles that have been adsorbed on the carbon, so that the adsorbent can be reused.

Regeneration. The process of treating carbon thermally or chemically to extend its life.

Removal Efficiency. Fraction or percentage of a challenge contaminant that is removed by the air-cleaner media bed at a given time. Removal efficiency is also known simply as "efficiency."

Residence Time. Theoretical time period that a contaminant molecule is within the boundaries of the media bed of a physical adsorbent or chemisorbent. The longer the residence time, the higher the efficiency. For gaseous contaminant removal equipment, residence time is computed as

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

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 ft² 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 media beds in series increase residence time and thus performance. Because gaseous contaminant air cleaners all tend to have approximately the same granule size, residence time is a generally useful indicator of performance. In some engineering disciplines, the media volume 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. A minimum 0.07 s residence time for physical adsorbents, and 0.1 s for chemisorbents, provides for a minimum 95% contact time.

Different ways of arranging the media, different media, or different media granule sizes all can change the effective residence time because of their effect on the volume of the bed occupied by the media. The geometry and packaging of some 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 that a particular physical adsorbent or chemisorbent performs the same as a traditional deep-bed air cleaner, but no standard test exists to verify such a rating.

Retentivity. Measure of the ability of a physical adsorbent or gas-phase air-cleaning (GPAC) device to resist desorption of an adsorbate. It is usually stated as a percentage or fraction of the adsorbent mass and calculated as the residual capacity (fraction remaining) after purging the adsorbent with clean, conditioned air, following the challenge breakthrough. Retentivity is generally less than activity.

Sorbate. A material that has been or is capable of being taken up by another substance through either absorption or adsorption.

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

Vapor (Vapor-Phase Contaminant). Substance whose vapor pressure is less than the ambient pressure at ambient temperature but is present in the gas phase by evaporation or sublimation.

Volatile Organic Compound (VOC). Chemical belonging to the medium-volatility subset of the organic compounds that can be

Table 1 Emissions of Selected Toxic Compounds from Mainstream and Sidestream Smoke of Cigarettes

Contaminant	Contaminant CAS Number	Mainstream Smoke (MS)	Sidestream Smoke (SS)	SS/MS Ratio*
		Range, $\mu\text{g}/\text{cigarette}$	Range, $\mu\text{g}/\text{cigarette}$	
“Tar”		6100-48,700	10,500-34,400	0.91
Carbon monoxide	630-08-0	11,000-40,700	31,500-54,100	1.87
Nicotine	54-11-5	500-3320	1900-5300	2.31
Acetaldehyde	75-07-0	596.2-2133.4	1683.7-2586.8	1.31
Isoprene	78-79-5	288.1-1192.8	743.2-1162.8	1.33
Acetone	67-64-1	258.5-828.9	811.3-1204.8	1.52
Nitric oxide	10102-43-9	202.8-607.1	1000-1600	2.79
Hydrogen cyanide	74-90-8	98.7-567.5	190-350	0.77
Methyl ethyl ketone	78-93-3	72.5-230.2	184.5-332.6	1.49
Acrolein	107-02-8	51.2-223.4	342.1-522.7	2.53
Toluene	108-88-3	48.3-173.7	134.9-238.6	1.27
Propionaldehyde	123-38-6	46.8-144.7	151.8-267.6	1.06
Hydroquinone	123-31-9	27.7-203.4	49.8-134.1	0.94
Catechol	120-80-9	28.1-222.8	64.5-107.0	0.85
Benzene	71-43-2	28.0-105.9	70.7-134.3	1.07
1,3-Butadiene	106-99-0	23.6-122.5	81.3-134.7	1.3
Butyraldehyde	123-72-8	28.8-95.6	138.0-244.9	2.68
Formaldehyde	50-00-0	12.2-105.8	540.4-967.5	14.78
Crotonaldehyde	123-73-9	11.6-66.2	62.2-121.8	1.95
Ammonia	7664-41-7	9.8-87.7	4000-6600	147
Phenol	108-95-2	7.0-142.2	121.3-323.8	9.01
Acrylonitrile	107-13-1	7.8-39.1	24.1-43.9	1.27
m-Cresol + p-Cresol	108-39-4/106-44-5	7.3-77.3	40.9-113.2	4.36
Pyridine	110-86-1	2.8-27.7	195.7-320.7	16.08
Styrene	100-42-5	4.5-19.3	23.2-46.1	2.6

Source: Modified from IARC (2004).

*Median value for sidestream/mainstream smoke ratios for 12 commercial cigarette brands.

present in indoor air under normal indoor atmospheric conditions of temperature and pressure; specifically, an organic compound with a saturation vapor pressure greater than 0.01 psi at 77°F.

2. 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 0.04%) and water vapor (up to 3.5%). In addition, trace quantities of inert gases (neon, xenon, krypton, helium, etc.) are always present.

Gases and vapors other than these natural constituents of air are usually considered to be gaseous 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 11 in the 2017 *ASHRAE Handbook—Fundamentals*. However, for convenience, data on some of the contaminants in cigarette smoke (Table 1), and some common contaminants emitted by building materials (Table 2), indoor combustion appliances (Table 3), office equipment (Table 4), and occupants (Table 5) are provided here.

Table 6 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 the type of raw information on which air-cleaning system designs can be based in addition to indicating which parameters to measure. 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 and provided in the appendix of *ASHRAE Standard 62.1* and *62.2*.

A recirculating air-handling schematic is shown 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 processes adding contaminants a to the space divided by the summation of ventilation and other processes removing contaminants b . The steady-state concentration C_{ss} for a single component can be expressed as (Meckler and Janssen 1988)

$$C_{ss} = a/b = \frac{\text{Contaminant insertion into space}}{\text{Contaminant removal from space}} \quad (2)$$

where

C_{ss} = steady-state contaminant concentration, $\mu\text{g}/\text{m}^3$

a = contaminants inserted into space, $\mu\text{g}/\text{s}$

b = contaminants removed from space, $\mu\text{g}/\text{s}$

For the occupied space, the parameters for insertion of the contaminant into the occupied space are

Table 2 Example Generation of Gaseous Contaminants by Building Materials

Contaminant	CAS Number	Emission Factor Averages (ranges), $\mu\text{g}/(\text{h}\cdot\text{m}^2)$					
		Acoustic Ceiling Panels	Carpets	Fiberboards	Gypsum Boards	Paints on Gypsum Board	Particle Boards
4-Phenylcyclo-hexene (PCH)	4994-16-5		8.4 (n.d.-85)				
Acetaldehyde	75-07-0		2.8 (n.d.-37)	9.0 (n.d.-32)			28 (n.d.-55)
Acetic acid	64-19-7			8.4 (n.d.-26)			
Acetone	67-64-1	12 (n.d.-33)		35 (n.d.-67)	37 (n.d.-110)	35 (n.d.-120)	
Ethylene glycol	107-21-1			140 (n.d.-290)		19 (n.d.-190)	160 (140-200)
Formaldehyde	50-00-0	5.8 (n.d.-25)	3.6 (n.d.-41)	220 (n.d.-570)	6.8 (n.d.-19)		49 (n.d.-97)
Naphthalene	91-20-3		11 (n.d.-59)	3.0 (n.d.-8.2)			
<i>n</i> -Heptane	142-82-5			21 (n.d.-53)			
Nonanal	124-19-6	4.9 (1.7-11)	11 (n.d.-68)		10 (n.d.-28)	3.7 (n.d.-24)	
Toluene	108-88-3			19 (n.d.-46)			
TotalVOC (TVOC)*	N/A	32 (3.2-150)	1900 (270-9100)	400 (52-850)	15 (n.d.-61)	2500 (170-6200)	420 (240-510)

Contaminant	CAS Number	Emission Factor Averages (ranges), $\mu\text{g}/(\text{h}\cdot\text{m}^2)$					
		Plastic Laminates and Assemblies	Non-Rubber-Based Resilient Flooring	Rubber-Based Resilient Flooring	Tackable Wall Panels	Thermal Insulations	Wall Bases (Rubber-Based)
1,2,4-Trimethylbenzene	95-63-6			210 (n.d.-590)			
2-Butoxy-ethanol	111-76-2		2.7 (n.d.-24)	1.6 (n.d.-24)			
Acetaldehyde	75-07-0		11 (n.d.-49)				
Acetone	67-64-1	75 (4.8-150)	120 (n.d.-830)			12 (1.8-21)	220 (30-400)
Butyric acid	107-92-6		0.51 (n.d.-5.1)				
Dodecane	112-40-3			1.3 (n.d.-20)			
Ethylene glycol	107-21-1		38 (n.d.-210)				
Formaldehyde	50-00-0	13 (n.d.-29)	6.8 (n.d.-79)			5.9 (0.35-14)	32 (3.6-61)
Naphthalene	91-20-3		3.4 (n.d.-14)	5.6 (n.d.-28)	6.6 (6.6)		
<i>n</i> -Butanol	71-36-3						100 (n.d.-200)
Nonanal	124-19-6		5.7 (n.d.-19)	1.4 (n.d.-11)		1.8 (0.57-4)	
Octane	111-65-9						150 (n.d.-300)
Phenol	108-95-2	9.4 (4.4-19)	35 (n.d.-310)				340 (n.d.-680)
Toluene	108-88-3		5.1 (n.d.-12)				
Undecane	1120-21-4						140 (13-270)
TVOC*	N/A	160 (6.3-310)	680 (100-2100)	15000 (1500-100000)	270 (100-430)	7.5 (0.57-26)	7100 (1200-13000)

Source: CIWMB (2003).

n.d. = nondetectable N/A = not applicable

*TVOC concentrations calculated from total ion current (TIC) from GC/MS analysis by adding areas of integrated peaks with retention times greater than 5 min, subtracting from sum of area of internal standard chlorobenzene-d5, and using response factor of chlorobenzene-d5 as calibration.

Table 3 Example Generation of Gaseous Contaminants by Indoor Combustion Equipment

	Generation Rates, $\mu\text{g}/\text{Btu}$					Typical Heating Rate, Typical Use, Vented or Unvented Fuel			
	CO ₂ 124-38-9	CO 630-08-0	NO ₂ 10102-44-0	NO 10102-43-9	HCHO 50-00-0	1000 Btu/h	h/day	Unvented	Fuel
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		200	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. (1985), and Wade et al. (1975).

$$a = NG_O + Q_i C_x + G + (E_v P Q_v C_x) / f - k_n A \quad (3)$$

where

- N = number of occupants
- G_O = generation rate of contaminant by an occupant, $\mu\text{g}/(\text{s}\cdot\text{person})$
- Q_i = infiltration flow, m^3/s
- C_x = outdoor concentration of contaminant, $\mu\text{g}/\text{m}^3$
- G = generation rate of contaminant by nonoccupant sources, $\mu\text{g}/\text{s}$
- E_v = ventilation effectiveness (fraction of supply air passing through bypass boundary zone into occupied space)
- P = HVAC filter penetration by contaminant, fraction
- Q_v = ventilation airflow, m^3/s
- f = $1 - P(1 - E_v)$ = factor arising from mixing outdoor and recirculated air in the air-handling unit, fraction

k_n = difference of k_d and k_s = net deposition on surfaces for the contaminant, $\mu\text{g}/\text{h}\cdot\text{m}^2$

A = surface area inside the occupied space on which contaminant can be adsorbed or desorbed, m^2

The parameters associated with removal of contaminant from the space are

$$b = Q_L + Q_h + N Q_O (1 - P_O) + (E_v Q - Q_v) (1 - P) / f + Q_e \quad (4)$$

where

- Q_L = leakage (exfiltration) flow, m^3/s
- Q_h = hood flow, m^3/s
- N = number of occupants
- Q_O = average respiratory flow for single occupant, m^3/s

Table 4 Gaseous Contaminant Emission Rates, µg/h-unit from Office Equipment

	Desktop Computers				Laptop Computer		Laser Printers		Inkjet Printer	
	Pre-Operational Phase**		Active Operational Phase**		Pre-Operational Phase	Active Operational Phase	Idle Phase	Active Printing Phase**	Idle Phase	Active Printing Phase
Ozone								(n.d.-1750)*		
Hexamethyl-cyclotrisiloxane							14.4	135.82	12.27	29.22
Octamethyl-cyclotetrasiloxane	18.48	(n.d.-35.3)	8.40	(n.d.-26.1)		1.07	5.18	116.84	2.23	4.57
Decamethyl-cyclopentasiloxane	64.16	(26.8-82.4)	38.95	(20.7-84.4)	14.03	24.97	2.73	113.11	0.87	1.87
Dodecamethyl-cyclohexasiloxane	171.44	(66.4-422)	147.63	(44.5-240)	20.19	92.93				
Tetradecamethyl-cycloheptasiloxane	26.18	(9.8-69.1)	55.94	(19.7-90.5)	1.33	8.83				
Hexadecamethyl-cyclooctasiloxane	3.09	(n.d.-8.9)	25.56	(7.0-44.7)						
Hexanal							3.09	343.06	1.31	2.99
Octanal							7.56	116.4		
Nonanal							2.74	192.04		
D-Limonene							0.5	69.04		
Toluene	8.00	(5.9-10.4)	46.65	(22.0-74.0)		11.28	1.06	55.77	0.38	0.3
Ethylbenzene	5.10	(0.86-11.4)	27.21	(5.7-50.9)		0.77	0.29	70.42	0.11	0
m/p-Xylene	5.54	(n.d.-15.1)	36.97	(6.2-74.7)			0.45	102.19		
o-Xylene	2.60	(n.d.-6.4)	17.61	(3.5-33.5)			0.22	58.51		
Styrene	7.27	(2.3-12.5)	13.21	(3.4-33.2)			0.68	79.97	1.36	1.24
1,2,3-trimethyl-benzene	0.42	(n.d.-1.4)	3.77	(1.2-9.1)		0.19	0.41	135.19		
Benzaldehyde			1.88	(n.d.-7.5)			1.2	85.23	1.24	1.75
1,3-diethyl-benzene,	0.26	(0.08-0.53)	0.66	(0.46-0.96)		0.07	0.47	104.62		
2-ethyl-1-Hexanol	7.04	(n.d.-12.6)	13.79	(5.4-19.8)	2.22	11.65	0.98	66.66	2.26	2.11
Dodecane	2.28	(1.2-3.9)	3.92	(1.8-5.3)	1.87	3.53	0.24	42.68		
Acetophenone	2.11	(n.d.-3.7)	6.51	(4.9-8.9)			0.9	42.02	1.93	2.18
Phenol	11.83	(7.0-16.7)	39.61	(28.7-69.1)	2.25	7.6	2.03	63.85	3.12	3.19
Tridecane							0.39	154.29		
Tetradecane	6.10	(2.9-14.2)	10.85	(6.0-21.2)	2.08	4.94	1.31	531.82	1.51	1.09
Pentadecane							0.52	217.51	2.41	1.73
Hexadecane	3.36	(1.4-8.0)	8.35	(3.9-18.2)	0.7	2.02	0.14	31.94	2.4	1.74

Source: Modified from Maddalena et al. (2011).

*The range of the reported ozone emission rates of laser printers

**The use of "n.d." in place of a value indicates that no data was available for the minimum of a range

Table 5 Emission Rates of Selected Gaseous Compounds from Human Occupants

Contaminant	Contaminant CAS Number	Emission Rate, µg/hr-person
Carbon dioxide	124-38-9	32.8×10^6
Carbon monoxide	630-08-0	0.20×10^6
Ammonia	7664-41-7	1342
Hydrogen sulfide	7783-06-4	119
Decamethylcyclopentasiloxane (D5)	541-02-6	3350
Acetone	67-64-1	1060
Acetic acid	64-19-7	329
Isoprene	78-79-5	162
Methanol	67-56-1	156
Acetaldehyde	75-07-0	114
Dodecamethylcyclohexasiloxane (D6)	540-97-6	105
6-Methyl-5-hepten-2-one	110-93-0	99.3
Ethanol	64-17-5	94.9
Formic acid	64-18-6	48.5
Propionic acid/hydroxyacetone	79-09-4/ 116-09-6	40.4
4-oxopentanal	626-96-0	36.9
Octamethylcyclopentasiloxane (D4)	556-67-2	21
Toluene	108-88-3	7.7

Data compiled from Tang et al. (2016); Tang et al. (2015); and Wang (1975)

P_O = penetration of contaminant through human lung, fraction

Q = total flow, m³/s

Q_v = ventilation (makeup) airflow, m³/s

P = filter penetration for contaminant, fraction

Q_e = exhaust airflow, m³/s

The steady-state contaminant concentration is of interest for both system design and filter sizing. Laying out the equation for the steady-state concentration with all of the parameters, Equation (2), with substitutions of Equations (3) and (4), becomes

$$C_{ss} = \frac{NG_O + Q_i C_x + G + (E_v P Q_v C_x) / f - k_n A}{Q_L + Q_h + N Q_O (1 - P_O) + (E_v Q - Q_v) (1 - P) / f + Q_e} \quad (5)$$

The following assumptions are made for this model:

- No removal of contaminant by HVAC system elements (with the exception of the filter) and ductwork
- No contaminant interactions in the air
- No removal of contaminants by occupants other than through breathing
- Occupied space is perfectly mixed

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

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

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

where

- C_θ = concentration in space θ minutes after a change of conditions
 C_0 = concentration in space at time $\theta = 0$
 V = volume of the ventilated space, m^3
 b = volume per unit time
 θ = time

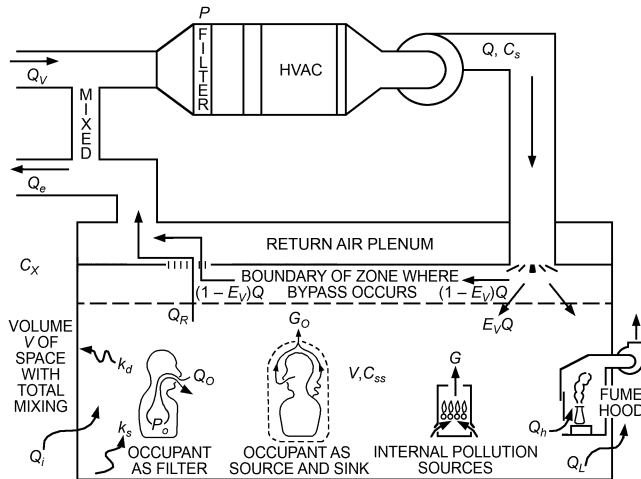
with C_{ss} given by Equation (2), and b by Equation (4).

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

$$C_{ss} = \frac{NG_O + G + [(E_v P Q_v C_x)/f] + k_n A}{NQ_O(1 - P_O) + [(E_v Q - Q_v)(1 - P)/f] + Q_e} \quad (7)$$

Even if there is no 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 most structures infiltration and exfiltration are never zero. The only inhabited spaces operating on 100% recirculated air are space capsules, undersea structures and vehicles, and structures with life support (to eliminate carbon dioxide and carbon monoxide and supply oxygen).

Outdoor air contaminant concentrations and the emission rates of the internal sources are generally unsteady in nature. Buildings



- A = surface area inside occupied space on which contaminant can be adsorbed or desorbed, m^2
 V = volume of occupied zone, m^3
 C_{ss} = steady state contaminant concentration in occupied zone, $\mu g/m^3$
 C_s = concentration of contaminant in supply air, $\mu g/m^3$
 C_x = outdoor concentration of contaminant, $\mu g/m^3$
 G = generation rate for contaminant by nonoccupant sources, $\mu g/s$
 G_O = generation rate for contaminant by an occupant, $\mu g/(s \cdot person)$
 N = number of occupants
 E_v = ventilation effectiveness (fraction of supply air passing through bypass boundary zone into occupied space), fraction
 f = $1 - P(1 - E_v)$ = factor arising from mixing of outdoor and recirculated air in air-handling unit, fraction
 k_s = contaminant emission rate for occupied zone surfaces, $\mu g/h \cdot m^2$
 k_d = contaminant deposition rate for occupied zone surfaces, $\mu g/h \cdot m^2$
 k_n = difference of k_d and k_s = net deposition on surfaces for contaminant, $\mu g/h \cdot m^2$
 P = HVAC filter penetration by contaminant, fraction
 P_O = fraction of contaminant exhaled from human lung, fraction
 Q = total supply airflow, m^3/s
 Q_e = exhaust airflow, m^3/s
 Q_v = ventilation airflow, m^3/s
 Q_h = hood airflow, m^3/s
 Q_i = infiltration airflow, m^3/s
 Q_L = leakage (exfiltration) airflow, m^3/s
 Q_O = average respiratory airflow for single occupant, m^3/s

Fig. 1 Recirculatory Air-Handling System with Gaseous Contaminant Modifiers

may also have multiple rooms within a building zone, 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 and emission velocities k_d and k_s 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 the deposition velocity on surfaces to zero. Computer programs (e.g., CONTAM by NIST at www.nist.gov/services-resources/software/contam, IAQX by U.S. EPA at www.epa.gov/air-research/simulation-tool-kit-indoor-air-quality-and-inhalation-exposure-iaqx) are available to handle these calculations. Details on multi-zone modeling and computational fluid dynamics (CFD) modeling can also be found in Chapter 13 of the 2017 *ASHRAE Handbook—Fundamentals*.

The assumption of bypass and mixing used in the model presented here can be used to approximate the multiple-room case, because gaseous contaminants are readily dispersed by airflow. Also, a gaseous contaminant diffuses from a location of high concentration to one of low concentration, even with low rates of turbulent mixing.

Quantities appropriate for the flows in Equations (2) to (5) are discussed in the sections on Local Source Management and Dilution Through General Ventilation. Infiltration flow can be determined approximately by the techniques described in Chapter 16 of the 2017 *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 (2017); DeFrees and Amberger (1987) describe a variation on the blower-door technique useful for large structures.

To assist in understanding how the equations can be applied, an example is included for the steady-state concentration C_{ss} , in this case, toluene. The example conditions are for an occupied conference room of $20 \times 40 \times 10$ ft containing 100 people (the bypass zone above is of undetermined height and does not need to be specified further). The following parameters are used, and the calculation is performed in SI units:

- A = surface area inside ventilated space on which contaminant can be adsorbed, $260.13 m^2$
 E_v = ventilation effectiveness = 0.8
 G = generation rate for contaminant by nonoccupant sources, $0.0 \mu g/s$
 G_O = generation rate for contaminant by an occupant, $0.00639 \mu g/(s \cdot person)$
 k_n = deposition velocity on a for contaminant, $3 \mu g/h \cdot m^2$
 N = number of occupants, 100
 C_x = outdoor concentration of contaminant, $20 \mu g/m^3$
 P = filter penetration for contaminant, 0.75
 P_O = penetration of contaminant through human lung, 0.5
 Q = total flow, $0.8 m^3/s$
 Q_O = average respiratory flow for a single occupant, $8 L/min = 1.33 \times 10^{-4} m^3/s$
 Q_v = ventilation (makeup) airflow, $8 L/s \cdot person = 0.008 m^3/s$; for 100 people, $Q_v = 0.8 m^3/s$

Using these parameters, the steady-state concentration from Equation (7) becomes

$$\begin{aligned}
 C_{ss} &= \frac{(100)(0.00639) + [(0.8 \times 0.75 \times 0.8 \times 20)/0.85]}{(100)(0.0001333)(0.5) + [(0.8 \times 0.8 - 0.8)(0.25)]/0.85 + 0.8} \\
 &= \frac{11.933}{0.759} = 15.7 \mu g/m^3
 \end{aligned}$$

Table 6 Typical U.S. Outdoor Concentration of Selected Gaseous Air Contaminants

Inorganic Air Contaminants ^a					
Inorganic Name	CAS Number	Period of Average	Arithmetic Mean Concentration		
			µg/m ³	ppb	
Carbon monoxide	630-08-0	1 year (2008)	2000	2	
Nitrogen dioxide	10102-44-0	1 year (2008)	29	15	
Ozone	10028-15-6	3 years (2006-08)	149	76	
Organic Air Contaminants ^b					
VOC Name	CAS number	Number of Sites Tested	Frequency Detected (% of Sites)	Arithmetic Mean Concentration	
				(µg/m ³)	(ppb)
Chloromethane	74-87-3	87	99	2.6	1.3
Benzene	71-43-2	67	99	3.0	0.94
Acetone	67-64-1	67	98	8.6	3.6
Acetaldehyde	75-07-0	86	98	3.4	1.9
Toluene	108-88-3	69	96	5.1	1.4
Formaldehyde	50-00-0	99	95	3.9	3.2
Phenol	108-95-2	40	93	1.6	0.42
<i>m</i> - and <i>p</i> -Xylenes	1330-20-7	69	92	3.2	0.74
Ethanol	64-17-5	13	92	32	17
Dichlorodifluoromethane	75-71-8	87	91	7.1	1.4
<i>o</i> -Xylene	95-47-6	69	89	1.2	0.28
Nonanal	124-19-6	40	89	1.1	0.19
2-Butanone	78-93-3	66	88	1.4	0.48
1,2,4-Trimethylbenzene	95-63-6	69	87	1.2	0.24
Ethylbenzene	100-41-4	69	84	0.9	0.21
<i>n</i> -Decane	124-18-5	69	80	0.97	0.17
<i>n</i> -Hexane	110-54-3	38	75	1.7	0.48
Tetrachloroethene	127-18-4	69	73	1.1	0.16
4-Ethyltoluene	622-96-8	69	72	0.53	0.11
<i>n</i> -Undecane	1120-21-4	69	70	0.6	0.094
Nonane	111-84-2	69	66	0.59	0.11
1,1,1-Trichloroethane	71-55-6	66	65	0.88	0.16
Styrene	100-42-5	69	61	0.39	0.092
Ethyl acetate	141-78-6	66	58	0.43	0.12
Octane	111-65-9	68	56	0.44	0.094
1,3,5-Trimethylbenzene	108-67-8	69	56	0.41	0.083
Hexanal	66-25-1	40	53	0.65	0.16

^aSource: EPA (2009). Note that only statistically viable datasets were used to calculate the national average concentrations, so the numbers may not be fully representative.

^bSource: EPA (2016b).

These calculations can help in determining the space concentration of the contaminant but can also be used in determining changes in filtration to modify that concentration.

3. PROBLEM ASSESSMENT

Consensus design criteria (allowable upper limit for any contaminant) do not exist for most nontoxic chemicals. Chapter 10 of the 2017 *ASHRAE Handbook—Fundamentals* discusses health effects of gaseous contaminants and explains the various exposure limits used to protect industrial workers indoors. It also provides limited guidance on acceptable indoor air concentrations in commercial buildings and residences. Chapter 11 of that volume discusses the nature and non-health-related effects of gaseous contaminants, as well as providing some guidance on measuring their concentrations.

Ideally, design for reduction of exposure to gaseous contaminants is based on accurate knowledge of the identity and concentration (as a function of time) of the contaminants and other chemical species that are present, as well as the sources of each contaminant and behavior of the contaminant in the space. This knowledge may come from estimates of source strength, modeling, direct measurement of the sources, or from direct measurements of the contaminant levels in the indoor air. Unfortunately, definitive assessment is seldom

possible, so often careful observation, experience, and judgment must supplement data as the basis for design. For instance, certain molecular contaminants may have distinctive odor levels, or have known sources in different geographical regions.

Two general design cases exist: (1) ventilation systems in newly constructed 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 in the section on Gaseous Contaminants, must be used. To estimate the contaminants, identify contaminant-generating activities, estimate and sum the building sources, and identify outdoor air contaminants. Gaps in measured contaminant load data must be filled with estimates or additional measurements. Once contaminant loads are identified, design can begin.

To address a particular problem in an existing system, special measurements may also be required to identify the contaminant. Assessing the problem can become an indoor air quality investigation, which may include building inspection, occupant questionnaires, and local sampling and analysis. The *Building Air Quality Guide* (EPA 1991) is a useful basic guide for such investigations. Once the contaminant 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 2017 *ASHRAE Handbook—Fundamentals*, Chapter 11 discusses sampling and measurement techniques for industrial and nonindustrial environments, and Chapter 12 covers evaluating odor levels.

Results of sampling and analysis identify contaminants and their concentrations at particular places and times or over known periods. 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 contaminants. The degree of formality applied depends on the perceived severity of potential effects.

4. CONTAMINANT REDUCTION STRATEGIES

Four contaminant reduction strategies may be used to improve the indoor air quality in a building: (1) elimination of sources or reduction of their emissions, (2) local hood usage with exhaust or recirculated air cleaning, (3) dilution with increased general ventilation, and (4) general ventilation air cleaning with or without increased ventilation rates. For indoor contaminant sources, the first three are usually favored because of cost considerations. Reducing concentrations by general air cleaning is more difficult, because it is applied after the contaminants are fully dispersed and at their lowest concentration. The section on Contaminant Removal by Ventilation Air Cleaning discusses the fourth strategy of general ventilation air cleaning in more detail, so it will not be addressed in this section.

Elimination or Reduction of Emissions

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). Radon gas levels can be reduced by installing traps in sewage drains, sealing, and subsurface ventilation to prevent entry of the gas (EPA 1987, 1993). 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 in place of a more troublesome one. Growth of mildew and other organisms that emit odorous contaminants can be restrained by eliminating or reducing condensation and applying fungicides and bactericides, provided they are registered for the use and carefully chosen to have low offgassing potential.

Local Source Management

Local source management is more effective than using general ventilation when discrete sources in a building generate substantial amounts of gaseous contaminants. If these contaminants are toxic, irritating, or strongly odorous, local capture 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 is larger than that required for gaseous contaminants; otherwise, the problems of capture are the same for both gases and particles.

Capture hoods are normally provided with exhaust fans and stacks that vent to the outdoors. Hoods use 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 of outdoor air. This practice must be limited to hoods exhausting the most innocuous contaminants because of the risk of filter failure. Design of effective hoods is described in ACGIH (2013) and in Chapter 33 of this volume.

Dilution Through General Ventilation

In residential and commercial buildings, the chief use of local source hooding and exhaust occurs in kitchens, bathrooms, and occasionally around specific point sources such as diazo printers. Where there is no local removal of contaminants, the general ventilation distribution system can sometimes provide contaminant concentration reduction through dilution. These systems must meet both thermal load requirements and contaminant concentration standards. Complete mixing and a relatively uniform air supply per occupant are desirable for both purposes. The air distribution guidelines in Chapters 16, 20, and 21 of the 2017 *ASHRAE Handbook—Fundamentals* are appropriate for contamination reduction by general ventilation. Airflow requirements set by *ASHRAE Standard 62.1* must be met.

When local exhaust is combined with general ventilation, a proper supply of makeup air must balance the exhaust flow for any hoods present to maintain the desired over or underpressure in the building or in specific rooms. Supply fans may be needed to provide enough pressure to maintain flow balance. For instance, 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 19 covers clean spaces in detail.

5. CONTAMINANT REMOVAL BY VENTILATION AIR CLEANING

If eliminating sources, local hooding, or dilution cannot reduce contaminant concentrations to desired levels, or are only partially effective, the air must be cleaned. Designing an air-cleaning system requires understanding of the capabilities and limitations of the processes involved.

Complete and permanent removal of every contaminant is often not necessary. Intermittent nuisance odors, for instance, can often be managed 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. Design goals are discussed at greater length in the section on Air Cleaner System Design.

Gaseous Contaminant Removal Processes

Many chemical and physical processes remove gases or vapors from air, but those of highest current 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 removal processes have been proposed, but currently have limited application in HVAC work, and are only briefly discussed.

Physical Adsorption. Physical adsorption is a surface phenomenon similar in many ways to condensation. Contaminant gas

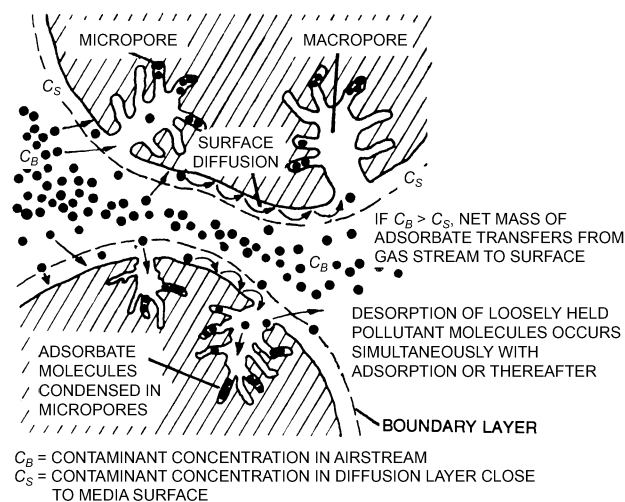


Fig. 2 Steps in Contaminant Adsorption

molecules strike a surface and remain bound to it (adsorbed) for an appreciable time by molecular attraction (van der Waals forces). Therefore, high surface area is crucial for effective adsorbents. Surfaces of gaseous contamination 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 or activated to develop microscopic pores, greatly increasing the area available for molecular contact. These internal pores account for the majority of available surface area in most commercially available adsorbents. Typical activated alumina has a surface area of 1 to 1.6×10^6 ft² per pound; typical activated carbon has a surface area from 4 to 8×10^6 ft²/lb. Pores of various microscopic sizes and shapes form minute traps that can fill with condensed contaminant molecules.

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 beaded or pelletized media have slightly lower pressure drops per unit depth of sorbent than those composed of granular or flaked media. On the other hand, the surface area with smaller particles of the adsorbent is more accessible to the contaminant.

Several steps must occur in physical 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 or even reemission of collected contaminants.
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.

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 adsorbent bed or when another contaminant arrives that either binds more tightly to the adsorbent

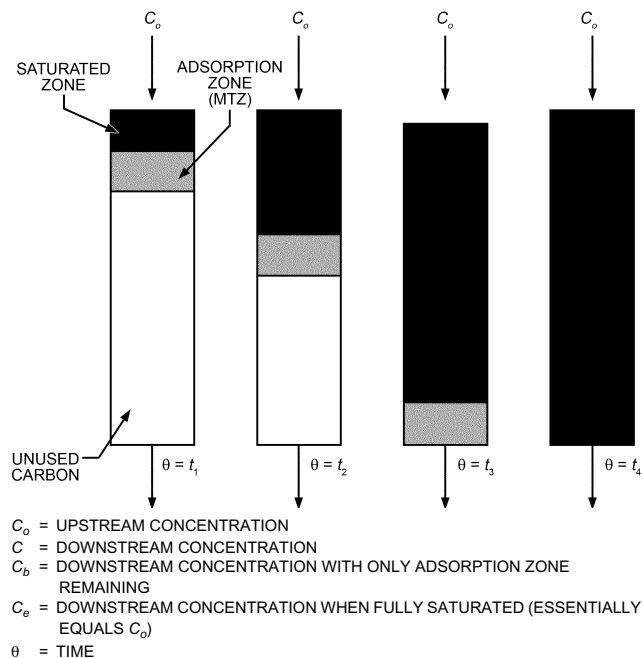


Fig. 3 Dependence of Contaminant Concentration on Bed Depth and Exposure Time

surface or is present at a much higher concentration. Complete desorption usually requires adding thermal energy to the bed.

Providing a sufficient depth of adsorbent and contact time is very important in achieving efficient contaminant removal. When a contaminant is fed at constant concentration and constant gas flow rate through an adsorbent bed of sufficient depth, the gas stream concentration within the bed varies with time θ and bed depth, as shown in Figure 3. In fixed-bed adsorption, at any given time, the bed can be divided into three zones: (1) the saturated zone containing adsorbent nearly saturated (spent) with the contaminants, (2) the adsorption zone, and (3) a zone with unused adsorbent. Distribution of contaminant in an adsorbent 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 of the MTZ, all contaminant has already been adsorbed. 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.

The minimum bed depth is based primarily on the length of the **mass transfer zone (MTZ)**, which, at fixed conditions such as temperature, partial pressure, and flow rate, is related to the rate of adsorption. The movement of the MTZ through the adsorbent bed can also be graphically represented as a **breakthrough curve** (Figure 4). When the leading edge of the MTZ reaches the outlet of the bed, the concentration of the contaminant suddenly begins to rise. This is referred to as the **breakthrough point**. Past the breakthrough point, the downstream concentration is at less than 0.1% of the upstream, just as the slope of the curve increases until it reaches an exhaustion point where the bed becomes fully saturated. If the adsorbent bed depth is shorter than the required MTZ, breakthrough will occur almost immediately, rendering the system ineffective. 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

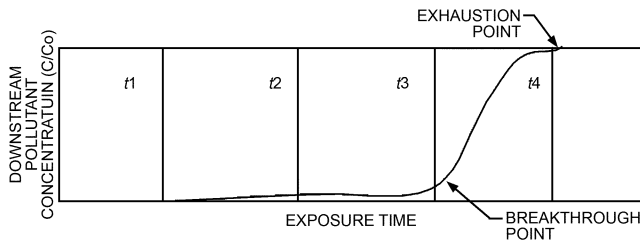


Fig. 4 Breakthrough Characteristics of Fixed-Bed Adsorbents

could be very short, or more significant, depending on contaminant and media. However, not all adsorbent/contaminant combinations show as sharp a breakthrough as in Figure 4. Breakthrough curves can be used to calculate a number of different properties of the adsorbent system such as breakthrough capacity, degree of utilization, usage rate etc.

Multiple contaminants produce more complicated penetration patterns: individually, each contaminant might behave as shown in Figure 4, but each has its own time scale. The better-adsorbing contaminants are captured in the upstream part of the bed, and the poorer-adsorbing are adsorbed further downstream. As the challenge continues, the better-adsorbing compound progressively displaces the other, meaning the displaced component can leave the adsorbent 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, generally present at much higher concentrations than typical indoor contaminants, altering adsorption parameters by reducing the amount of the first contaminant that can be held by the bed 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 adsorption into the water layer at high relative humidities.

Chemisorption. The three steps described for physical adsorbents also apply to chemisorption. However, the third step in chemisorption involves chemical reactions with electron exchange between the contaminant molecule and the chemisorbent. 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 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 new contaminants.
- 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 chemisorbent media are formed by coating or impregnating a highly porous, nonreactive substrate (e.g., activated alumina, zeolite, or carbon) with a chemical reactant (e.g., acids, bases, or oxidizing chemicals). The reactant will eventually become exhausted, but the substrate may have physical adsorption ability that remains active when chemisorption ceases.

General Considerations. Physical adsorption and chemisorption are the removal processes most commonly used in gaseous

Table 7 Comparison of Physical Adsorption and Chemisorption

Physical Adsorption	Chemisorption
Forces operating are weak van der Waal's forces.	Forces operating are similar to those of a chemical bond.
Heat of adsorption is low (about 20 to 40 kJ mol ⁻¹).	Heat of adsorption is high (about 40 to 400 kJ mol ⁻¹).
No compound formation takes place.	Surface compounds are formed.
Process is reversible; desorption of gas occurs by increasing temperature or decreasing pressure.	Process is irreversible.
Process does not require any activation energy.	Process requires activation energy.
Adsorption decreases with increase of temperature.	Adsorption increases with increasing temperature.
Process is not specific in nature: all gases are adsorbed on all solids to some extent, though some compounds are adsorbed better than others.	Process is semispecific in nature and occurs only when there is some possibility of compound formation between the gas being adsorbed and the solid adsorbent.
Process forms a multimolecular layer.	Process forms a unimolecular layer.

Adapted from www.thebigger.com/chemistry/surface-chemistry/distinguish-between-physical-adsorption-and-chemisorption/

contaminant filtration. In most cases, the processes for both involve media supplied as granules, flakes, 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 are traditionally a few millimetres in all dimensions, typically on the order of 4 × 6 or 4 × 8 U.S. mesh pellets or flakes. Table 7 summarizes the differences between physical adsorption and chemisorption.

Other Processes. Although physical adsorption and chemisorption are the most frequently used, 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 30 of the 2016 *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 VOCs other than hydrocarbons or other reactions can produce undesirable by-products such as nitrogen-, sulfur-, and chlorine-containing gases. 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, especially if removal of undesirable by-products is required. Availability of waste heat significantly improves CatOx cost competitiveness. CatOx systems have potential application in security and protection applications.

Photocatalysis (or photocatalytic oxidation [PCO]) uses light (usually ultraviolet [UV]) and a photocatalyst to perform **reduction-oxidation (redox)** chemistry on the catalyst's surface as first observed and reported by Fujishima and Honda (1972). The photocatalyst can be granular, bulk, or unsupported, or it can be supported as a thin film on media such as glass, polymer, ceramic, or metal. However, supported photocatalysts are generally used for air treatment. 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. For this material, ultraviolet light with wavelengths less than 380 nm 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, product formation, and desorption. With appropriate light intensity and sufficiently long residence time, photocatalysis can almost completely oxidize a wide variety of organic compounds such that the exit gas stream contains mostly carbon dioxide and water (Obee and Brown 1995; Obee and Hay 1999; Peral and Ollis 1992; Peral et al. 1997; Tompkins et al. 2005a). In cases of incomplete oxidation, particularly when chlorinated compounds are present as reactants, multiple by-products may be formed (d'Hennezel et al. 1998; Farhanian and Haghghat 2014). ASHRAE research project RP-1134 exhaustively reviewed the literature on UV photocatalysis (Tompkins et al. 2005a, 2005b).

Currently, with recent catalyst, lamp, and reactor design developments, UV-PCO can be used as a gas-contaminant removal technology (Chen et al. 2005). A study conducted for an in-duct UV-PCO system utilizing honeycomb monoliths with VOC mixtures found in indoor air showed single pass VOC removal efficiencies ranging from 19 to 85%, with the oxidation rates approximately following: alcohols and glycol ethers > aldehydes, ketones, and terpene hydrocarbons > aromatic and alkane hydrocarbons > halogenated aliphatic hydrocarbons (Hodgson et al. 2005). A time dependent mathematical model has recently been developed to predict the performance of an in-duct PCO air cleaner under realistic indoor conditions (Zhong et al. 2013). In most residential and commercial building applications, reduction of levels is likely to be most effective when the air contaminants can be passed through the UV-PCO filters multiple times. In an HVAC application, the preferred location for a UV-PCO filter is in the return or mixed air, where gas contaminants pass through the filter many times in a given time period. UV-PCO can be an attractive because of its promise of reduced maintenance (no filters and/or adsorption media to maintain and dispose of periodically) and ability to treat a wide variety of airborne chemicals.

Sometimes, the UV-PCO unit is followed by a gas-phase media section that can adsorb any partially oxidized molecules to prevent them from recirculating back into the occupied space (Hodgson et al. 2007). A further extension of UV-PCO being studied is use of UVV (i.e., low-energy UV light with wavelength close to the visible limit of 400 nm) along with UVC (short-wavelength UV light; wavelength of 100 to 280 nm) to generate radicals such as ozone, hydroxyls, and peroxides, which increase contaminant destruction efficiency and hence air-cleaner single-pass efficiency. A downstream gas-phase media section is necessary in this case to destroy these radicals and prevent them from passing into occupied spaces.

Air ionizers (ion generators) may be effective under some circumstances for particulate, VOC, and odor removal. Most ionization technologies are based on the principle of corona discharge (or non-thermal plasma) and can be classified into three categories: needle-point ionization, bipolar ionization, and ozone generators. Air ionization involves the electronically induced formation of positive and/or negative ions, including reactive oxygen species (ROS) that react rapidly with airborne VOCs and particulate species. Manufacturers of these systems suggest that reactive oxygen species can be present as oxygen radicals, activated oxygen, superoxide or diatomic oxygen, trivalent oxygen, or oxygen cluster ions. Most ionization systems are prone to generate NO_x and ozone, which is harmful to humans, and require control systems to maintain ozone levels below safe limits or should be avoided (ASHRAE 2015). There are limited peer-reviewed studies on the effectiveness of ionization systems to remove VOCs and odors in a single pass moving air stream.

Ozone is sometimes 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 2016a). 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 ozone to combat ETS in indoor air is not recommended. In addition, reaction of ozone with both indoor contaminants and building and HVAC surfaces can produce secondary contaminants such as small particles and aldehydes (Morrison et al. 1998; Vartiainen et al. 2006; Wang and Morrison 2006).

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 microbes or chemicals, and the risk of unexpected or undetected failure make it unsuitable for cleaning air circulated to people.

Odor counteractants and odor masking products do not remove the contaminant(s) responsible for problem odors from the air; they may apply only to specific odors and have limited effectiveness. They also add potential contaminants to the air.

6. EQUIPMENT

The purpose of gas-phase filtration equipment is to expose the chosen filtration media or device to the air to be filtered. In most cases, the filtration method uses granular media material, supplied either in bulk, or incorporated into a filter device that can be refillable or disposable. Typically, the gas filter has a particulate prefilter and afterfilter.

The most common retaining structure places the granular media between perforated retaining sheets or screens, as shown in Figures 5A, 5B, 5C, 5D, 5F, and 5H. The perforated retainers or screens must have holes smaller than the smallest particle of the media, and are typically made of aluminum; stainless, painted, plated, or coated steel; plastics; and kraftboard. Figure 5I represents a bonded flat panel filter.

Media may also be retained in fibrous filter or other porous support structures, and very fine media can be attached to the surface or within the structure of some particulate filter media, as shown in Figures 5E and 5G.

Effect of Media Size. Filtration devices that use small-diameter media generally have higher initial efficiency than the same media in larger particles, because of the larger exposed surface area. Devices that use larger-diameter media generally provide more overall filtration capacity because of the greater mass of media exposed to the air to be filtered.

Equipment Configurations. The typical media-holding devices shown in Figure 5 vary in thickness from 0.625 in. to as much as 6 in. Though they can be mounted perpendicular to the airflow (Figure 5A), they more often hold the media at an angle to the airstream

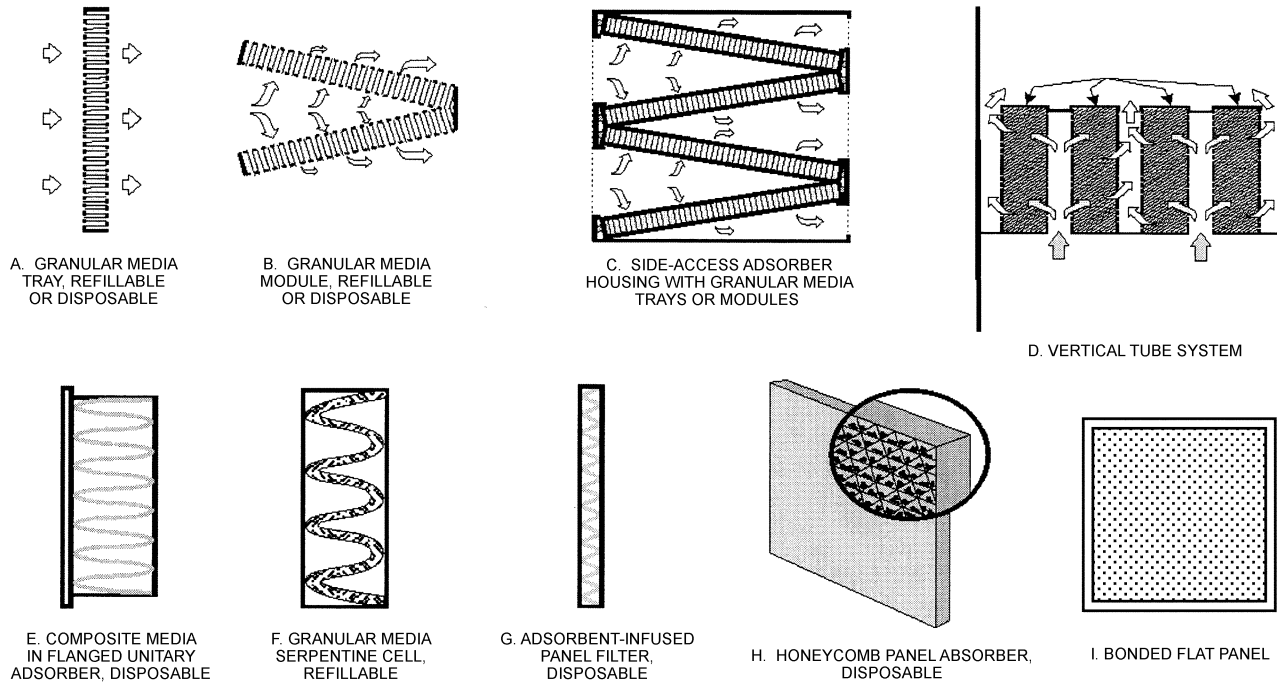


Fig. 5 Sectional and Schematic Views of Typical Physical Adsorbent and Chemisorbent Configurations

(Figures 5B to 5F) to increase the face area and thereby reduce pressure drop and increase residence time.

The honeycomb panels in Figure 5H hold the media in small channels formed by a corrugated spacer material, faced with a plastic mesh material. Though they usually have a low pressure drop, these are often in a holding frame configured at an angle to the airflow, as in Figure 5C.

Most of these devices are removed from the airstream, to either be refilled, or replaced. An exception is the vertical tube system, shown in Figure 5D. It is filled with bulk media, usually from plastic pails or large bags, fed in through top-access hatch(es). Expended media is removed by vacuuming from the same hatches, or from bottom hatches or hoppers.

Bypass. Performance of any air cleaner installation is limited by the airflow integrity of the total installation. A 100% efficient filter mounted in a housing that allows unintentional bypass is not truly a 100% efficient filter. Designers should consider the desired overall efficiency and ensure that the housing and filter together meet performance goals. One method of detecting significant unintentional bypass is to measure whether the filter achieves its rated pressure drop at full flow; if the pressure drop is low, bypass is likely.

7. 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 overall mechanical design. The overall mechanical design may be carried out according to ASHRAE *Standard* 62.1's IAQ procedure rather than using the ventilation procedure.

The gaseous contaminant air-cleaning system designer ideally should have the following information:

- A clear goal concerning what level of air cleaning is needed based on the application
- Exact chemical identity of the contaminants present in significant concentrations (not just the ones of concern)

- Rates at which contaminants are generated in the space and are transported to air cleaner system.
- 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

This information is usually difficult to obtain, though *Standard* 62.1's IAQ procedure provides some guidance. The first three items can be obtained by sampling and analysis, but funding is usually not sufficient to carry out adequate sampling 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 application or published guidance (e.g., Rock [2006] for environmental tobacco smoke) can be very helpful.

Experimental measurements of air cleaner performance can now be carried out using ASHRAE *Standard* 145.2 for individual contaminant gases. Alternatively, performance can be estimated, using Equations (2) to (7), when the exact chemical identity of a contaminant is known. The chemical and physical properties influencing a contaminant's removal by air-cleaning devices can usually be obtained from handbooks and technical publications. Contaminant properties of special importance are relative molecular mass, normal boiling point at standard temperature and pressure (STP), 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 with no subsequent desorption or release of by-products. For any chemical that may affect health, the design goal is to reduce the concentration to below the level of health concerns. Again, desorption

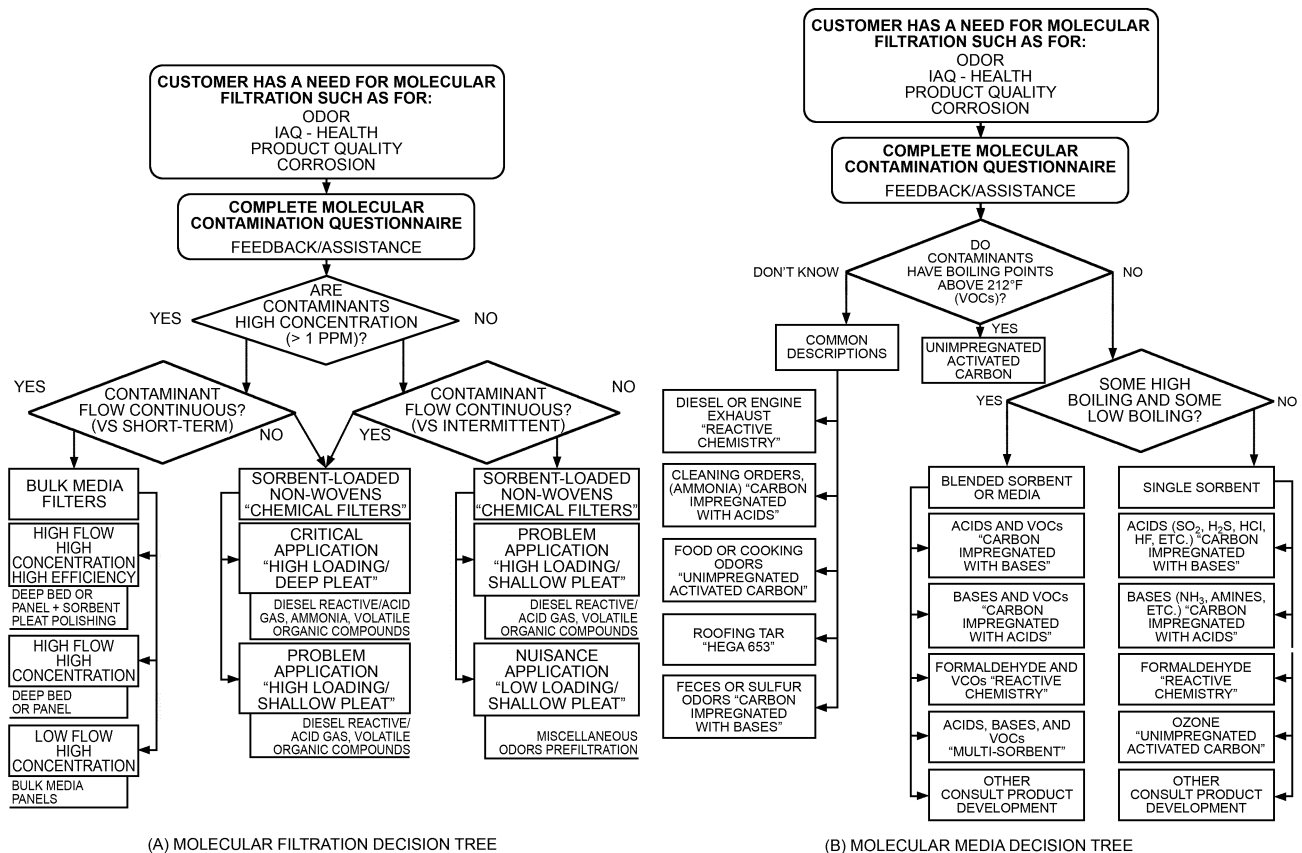


Fig. 6 Filtration and Media Selection Methods

back into the space must be minimized. For odor management, 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 physical or chemical adsorption medium. Next, the air cleaner's location in the HVAC system must be decided and any HVAC concerns addressed. 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.

Media Selection

Media selection is clear for many general applications; however, some complex gas mixtures in critical applications may require bench testing to determine if capacity and efficiency values are suitable for the application. In general, gaseous contaminants that have boiling points greater than 120°F and molecular weights over 50 can be removed by physical adsorption using standard activated carbon. Those with a lower boiling points and molecular weights usually require chemisorption or addition of a catalyst for complete removal. Figure 6 shows the media and filtration selection process.

In practice, different uses 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 8 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-remove 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, particularly for physical adsorbents and permanganate media.
- **Temperature.** A temperature increase decreases adsorption in a physical adsorbent, whereas it increases the reaction rates of chemisorbents.
- **Humidity.** For physical adsorbents, the effect of humidity (generally for > 50% rh) depends on the contaminant. Carbon capacity for water-miscible solvents increases; capacity for immiscible or partially miscible solvents decreases. Some humidity is usually required for effective operation of chemisorbents.
- **Concentration.** Increased contaminant concentration improves adsorption for both physical and chemical adsorbents.

Table 9 provides a general guide to selecting media commonly used to remove particular chemicals or types of chemicals. The media covered are permanganate-impregnated media (PIM), activated carbon (AC), acid-impregnated carbon (AIC), and base-impregnated carbon (BIC). The numeral 1 indicates the best media to use, and 2 the second choice. As was true of Table 6, some difference

Table 8 Typical Contaminants in Commercial Applications

Commercial Application	Contaminants/Species
Activated Carbon or Carbon/Permanganate-Impregnated Media 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, perfumes, floral scents, odorous fumes, moldy odors, paint fumes, furniture, ETS, NO _x , SO _x , O ₃ , mercaptans, valeric acid, formaldehyde
Activated Carbon/Permanganate-Impregnated Media 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 Media Barber shops, dining rooms	Mixed gases, ETS, food odors
Carbon/Permanganate Blend or Permanganate-Impregnated Media Embalming rooms, fruit/vegetable storage, greenhouses	Multiple organics; organic gases poorly sorbed by activated carbon Multiple organics, formaldehyde, ethylene
Activated Carbon or Permanganate-Impregnated Media/Acid-Impregnated Carbon Blend Garbage disposal areas	Mixture of volatile organics and inorganics with ammonia
Permanganate-Impregnated Media Autopsy rooms, banks (vault area), fish markets, hospitals (autopsy), morgues	Volatile organic gases poorly adsorbed by activated carbon Formaldehyde, trimethyl amine
Permanganate-Impregnated Media/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

in opinion exists as to which media is best, and chemicals for which there is disagreement are tagged with an exclamation point. Where information is unavailable, media can be evaluated for their ability to remove specific gases using ASHRAE *Standard* 145.1.

Air Cleaner Location and Other HVAC Concerns

Outdoor Air Intakes. Proper location of the outdoor air intake is especially important for applications requiring gaseous contaminant filters because outdoor contaminants can load the filters and reduce their operating lifetime. Outdoor 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 46 for more information on air inlets.

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

Air Cleaner Usage. The three principal uses for gaseous contaminant removal equipment in an HVAC system are as follows:

- *Outdoor air treatment.* Air-cleaning equipment can be located at the outdoor air intake to treat outdoor air only. This treatment is used principally when indoor gaseous contaminant concentrations are adequately reduced by outdoor air ventilation, but the outdoor air needs to be cleaned to achieve satisfactory indoor air quality. Note that air-cleaning media performance is a function of the temperature and relative humidity of the incoming air. Problems may arise when outdoor air temperature and relative humidity are either very low or very high. Consult the supplier for advice if the installation is in an extreme climate region.
- *Bypass or partial supply air treatment.* Intentional bypass can be achieved with a bypass duct and control damper or by installing

an air cleaner in a manner that allows substantial bypass. Partial supply air treatment may be appropriate where a specific threshold contamination level is targeted, when outdoor and indoor contamination rates are known, and the required level of reduction is small to moderate.

- *Full supply air treatment.* Full treatment achieves the best contaminant concentration reduction, 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 keep indoor contaminants such as bioeffluents at low levels. Full or bypass treatment of the supply air may be appropriate, depending on the source strength.

Sizing Gaseous Contaminant Removal Equipment

A number of issues need to be taken into account during equipment sizing. These include

- Nature of contaminant(s) to be removed
- Average and peak concentrations of contaminant(s)
- Efficiency of the media used
- HVAC considerations, including layout and space available for equipment installation; equipment location; whether air is indoor, outdoor, or supply; and volume airflow and air velocity through the section

The more undesirable the contaminant of concern, and the greater its concentration, the greater the quantity of media required for removal, and the larger the air cleaner installation. Media efficiency

Table 9 Media Selection by Contaminant

Gaseous Contaminant	PIM	AC	AIC	BIC	Gaseous Contaminant	PIM	AC	AIC	BIC	Gaseous Contaminant	PIM	AC	AIC	BIC
Acetaldehyde	1	2			Dichlorofluoromethane		1			Methyl formate	2	1		
Acetic acid (!)	1	2		2,1	R-114 (see note)		1			Methyl isobutyl ketone	2	1		
Acetic anhydride (!)	1,2	1		2	Diethylamine	2	1			Methyl sulfide	1			
Acetone (!)	1	2			Dimethylamine		1	2		Methyl vinyl ketone	2	1		
Acetylene	1				Diocetyl phthalate		1			Naphtha		1		
Acrolein	1	2			Dioxane	1	2			Naphthalene		1		
Acrylic acid (!)	1	1		2	Ethanol	1	2			Nicotine	1	2		
Allyl sulfide	1	2			Ethyl acetate	2	1			Nitric acid				1
Ammonia (NH ₃)			1		Ethyl chloride (!)	1,2	2,1			Nitric oxide (NO)	1			2
Aniline	2	1			Ethylene (C ₂ H ₄)	1				Nitrobenzene		1		
Arsine	1				Ethylene oxide	1	2			Nitrogen dioxide	1			2
Benzene		1			Ethyl ether	2	1			Nitromethane	1			
Borane (!)	1	2,2			Ethyl mercaptan (!)	1,1	2		2	Nitrous oxide				1
Bromine		1			Formaldehyde	1				Octane (!)	2	1,1		
1,3 Butadiene	1	2			Gasoline	1				Ozone (O ₃) (!)	2	1,1		
Butane		1			General halocarbons		1			Perchloroethylene	2	1		
2-Butanone	1	2			General hydrocarbons	2	1			Peroxy acetyl nitrate (PAN)		1		
2-Butoxyethanol	2	1			General VOC	2	1			Phenol	2	1		
Butyl acetate (!)	1,2	2,1			Heptane		1			Phosgene	2	1		
Butyl alcohol	2	1			Hydrogen bromide		2		1	Phosphine	1			
Butyl mercaptan	2	1			Hydrogen chloride		2		1	Putrescine	1	2		
Butylene	2	1			Hydrogen cyanide	1				Pyridine (!)	1	1		
Butyne	2	1			Hydrogen fluoride	1			1	Skatole	2	1		
Butyraldehyde	2	1			Hydrogen iodide	2				Silane	1			
Butyric acid		1		2	Hydrogen selenide					Stoddard solvent	1			
Cadaverine	2	1			Hydrogen sulfide	1			1	Stibine	1			
Camphor		1			Iodine		1			Styrene (!)	2	1,1		
Carbon dioxide (CO ₂)	Carbon w/catalyst				Iodoform	2	1			Sulfur dioxide	1			1
Carbon disulfide	2	1			Isopropanol	2	1			Sulfur trioxide	1			1
Carbon monoxide (CO)	Carbon w/catalyst				Kerosene		1			Sulfuric acid		2		1
Carbon tetrachloride	1				Lactic acid		1			Toluene		1		
Chlorine (Cl ₂)				1	Menthol	2	1			Triethylamine	2		1	
Chloroform		1			Mercury vapor		Impregnated AC			Trichlorethylene		1		
Creosote (!)	1,2	2,1			Methanol	2	1			1,1,1, trichloroethane (!)	1	2,1		
Cyclohexane		1			Methyl acrylate	2	1			R-11 (see below)		1		
Cyclohexanol	2	1			Methyl bromide (!)	2,1	1			Turpentine	2	1		
Cyclohexanone	2	1			Methyl butyl ketone (!)	1,2	2,1			Urea (!)	2	1,1		
Cyclohexene		1			Methyl cellosolve acetate	2	1			Uric acid (!)	1	1		2,2
Decane		1			Methylchloroform		1			Vinyl chloride		1		
Diborane	1				Methylcyclohexane		1			Xylene		1		
Dichlorobenzene		1			Methylene chloride		1							

1 = primary media selection for contaminant; 2 = secondary media selection.

PIM = permanganate-impregnated media; 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 to identify these cases.

depends on the residence time of contaminant(s) in the air cleaner, which in turn depends on media bed depth and HVAC air velocity.

There are two common sizing approaches: testing and calculations with Equations (2) to (7), or following manufacturers' guidance.

Available Test Methods and Equations. ASHRAE *Standard* 145.1 provides a method for testing granular media at small scale in a laboratory, and can be used to compare media performances against specific contaminants. ASHRAE *Standard* 145.2 provides a method of testing a 2 × 2 ft filter under laboratory conditions and can supply more direct evaluation of potential air cleaning installations. Equations (2) to (7) can be used to size equipment, though the contaminant concentration data required to use the equations effectively may be difficult to obtain.

General procedures for developing a specification for an air cleaner installation are as follows:

1. Choose a physical or chemical adsorbent suited to the contaminant(s) using testing or taking guidance from Tables 6 and 7.
2. Pick an appropriate efficiency for the adsorbent (complete removal or partial bypass), depending on the contaminant(s).
3. Choose a desired operating adsorbent 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 breakthrough time at adsorbent use conditions as developed in step 3.
5. Determine the change-out rate for the adsorbent as set by the breakthrough time.
6. Match the computed design requirements to available air cleaning equipment and specify.

Manufacturers' Design Guidance. Most manufacturers of air-cleaning system components offer selection guidance. Some of the approaches for traditional granular beds are summarized here. Note that inclusion of this information or exclusion of other approaches 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.

Manufacturers with laboratory testing facilities may evaluate and specify filters by measuring the initial removal efficiency of the whole filter installed in its frame (similar to the ASHRAE *Standard* 145.2 test), and measure 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.

In situations where multiple contaminants at low concentrations occur, such as in most IAQ investigative work and applications, neither the total load nor specific contaminant can typically be determined. In these cases, a broad-based air-cleaner design approach is usually recommended, consisting of two media banks: activated carbon, followed by permanganate-impregnated media. Sometimes these two media are combined into one bank because of space or pressure drop limitations.

- For light-duty applications, the recommendation is to use particulate filter media infused with carbon and/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.

A useful approach for carbon-based air cleaners divides HVAC and IAQ applications into three categories and recommends specific 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 management, which corresponds to a partial bypass design.

Another form of manufacturer's guidance of activated carbons is shown in Table 10, which gives suggested packed-bed residence time ranges, developed for the 6 × 4 mesh coconut shell carbon typically used in packed beds, for various applications. Mesh size is frequently used to specify granular media. The mesh size is closely related to the U.S. sieve size (the smallest sieve that the granule will pass through), and inversely related to the dimensions of the

Table 10 Suggested Mesh 4 × 6 or 4 × 8 Coconut Shell Carbon Residence Time Ranges

Application	Residence Time, ^a s
HVAC odor management applications for indoor air quality	
Light duty recirculation	0.03 to 0.07
Light duty – medium duty	0.07 to 0.10
Heavy duty	0.06 to 0.14
Cleanroom corrosion reduction	
Recirculation	0.03 to 0.07
Intakes	0.03 to 0.14
Industrial corrosion reduction (refineries, wastewater, pulp, etc.)	0.12 to 0.28+
Corrosive/reactive low-level exhaust applications	0.12 to 0.28+
Toxic gas removal	Not applicable
Museums	
Standard applications	0.07 to 0.12
Recirculation applications	0.06 to 0.10
Critical air intake	0.28+
Critical recirculation application	0.12 to 0.28+
Nuclear applications ^b	0.12 to 0.28+

Notes: ^aAll 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.

^bNuclear Grade Carbons are most often an 8 × 16 mesh

Source: Data from ©1992 Extraction Systems, Inc.

granule. A table with more information can be found in Chapter 11 of the 2017 *ASHRAE Handbook—Fundamentals*. Residence times in Table 9 are appropriate for moderate to thick beds of large-particle carbons, but do not apply universally to commercial adsorbents. 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 9, 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. A test can be performed per ASHRAE *Standard* 145.1 to compare filters (e.g., fiber-bonded filters to a granular adsorber) and determine what is best suited for an application.

Special Cases

Ozone reaches an equilibrium concentration in a ventilated space without a filtration device. It does so partly because ozone molecules react in air to form oxygen, but also because of reactions with people, plants, ductwork, and materials in the space. This oxidation is harmful to all four things, and therefore natural ozone decay is not a satisfactory way to remove ozone, except possibly 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 when radon is inhaled, where they emit alpha and beta particles that are potentially cancer causing. 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. Reduction of radon emission at the source by sealing entry points or depressurizing the source location like subslab ventilation are the accepted methods of reducing exposure to radon.

Museums, libraries, archives, and similar applications are special cases of air cleaner design for protection, and may require very efficient air cleaning; see Chapter 24 for specifics.

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 IAQ 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 60.

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. If no information is available, ASHRAE *Standard* 145.2 provides a procedure for measuring pressure drop across a full-scale gaseous air cleaner in a laboratory setting. 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 outdoor air only and outdoor 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 humidity, because high humidity degrades the performance of carbon adsorbents.

Table 11 Items Included in Economic Comparisons Between Competing Gaseous Contaminant Removal 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
Sensors and controls	
Plenum	Added electric power
Spare media holding units	Maintenance labor
Floor or duct space	

Economic Considerations

Capital and operating costs for each competing system should be identified. Chapter 38 provides general information on performing an economic analysis. Table 11 is a checklist of filtration items to be considered in such an analysis. It is important that the fan maintain adequate flow and overcome the pressure drop 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.

8. 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 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. Physical and chemical adsorbent filters are both much heavier than particulate filters. Suitable lifting equipment must be available during installation and removal to prevent injury.

At some point, granular activated carbon (GAC) becomes exhausted, and it is necessary to rebed the media. Depending on how the GAC was used, it may be considered nonhazardous and can be removed by the user or a service company. Hazardous media may be toxic, ignitable, corrosive, or reactive; see guidelines in 40 CFR 261 (2012; www.ecfr.gov).

It is the responsibility of the generator to determine the nature of the spent carbon waste. A carbon profile should be performed to characterize it as either hazardous or nonhazardous. A spent carbon profile is required to ensure that the spent carbon is safely recycled or disposed of in compliance with federal, state, and local regulations. Disposal of hazardous waste is governed by Resource Conservation and Recovery Act (RCRA; www.epa.gov/rcra).

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

9. INSTALLATION, START-UP, AND COMMISSIONING

This section provides general guidance on installing gaseous contaminant removal equipment. Manufacturers can provide complete installation details and drawings. Following the manufacturer's instructions will ensure that the equipment is installed properly and that it operates as designed.

Particulate Filters. Physical adsorbents and chemisorbents cannot function properly if their surfaces are covered and their pores clogged with particulate matter. UV-PCO system performance is also degraded unless protected by prefilters. A particulate filter with a minimum efficiency reporting value (MERV) of at least 8 (per ASHRAE *Standard* 52.2) should be installed ahead of the adsorbent bed to capture dirt and dust and to allow the adsorbent to capture gas-phase contaminants. Weschler et al. (1994) reported that carbon service life for ozone removal was lengthened by using an improved prefiltration. A secondary, higher-efficiency particulate filter is often desirable in critical and dusty installations. If the air is extremely dirty (e.g., from diesel exhaust or fumes), the filter should have a much higher efficiency rating. A minimum of a MERV 14 particulate filter is recommended for such applications.

Final filters downstream of the installation are often used in critical applications where dust from media at start-up is likely, or where vibration of the adsorbent bed may cause granular media to shed particles. These filters should have a minimum MERV 8 rating, but as noted, a secondary and/or higher-efficiency filter may be needed in some applications. Consult the equipment manufacturer for their recommendation.

Equipment Weight. Physical and chemical adsorption equipment is much heavier than particulate filtration equipment, so supporting structures and frames must be designed accordingly. A typical filter with a face area of 24 by 24 in. consisting of a permanent holding frame and sorbent media can have an installed weight of approximately 30 to 400 lb, depending on its depth and configuration. The manufacturer can provide system weights for the selected equipment.

Minimize or Eliminate Unintentional Bypass. Unintentional bypass can degrade the installed performance of a gas filter. Adsorbent beds and ducts must be tightly sealed to prevent bypass of contaminants. Before installation, and periodically during operation, visually inspect filters and replace any that are damaged. Install the filter according to the airflow direction indicated. Check to be sure that filters are properly seated and to ensure that the bank of filter frames is rigid and reinforced to avoid collapse. It is good practice to caulk all seams between individual holding frames. Granular media settles and compacts over time, and trays or modules must be loaded with media and installed following manufacturers' recommendations to eliminate bypass through the media bed. In addition, ensure that all doors, seams, and joints downstream of the adsorbent bed are properly sealed to prevent contaminated air from entering the system.

When to Install Media. Proper timing for installing adsorbent beds 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 adsorbents will adsorb paint and solvent vapors and other contaminants before the building is ready for occupancy. In some situations, adsorption of vapors and gases in the ventilation system before official start-up may be desired or needed. However, adsorbent life will be reduced correspondingly. If sorbent media are not used until the building is ready for occupancy, the unremoved contaminants may seriously reduce the initial indoor air quality of the building and the usable life of the bed. Thus, shortened life is an acceptable trade-off for the quality of air at the time of occupancy (NAFA 2012). 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 adsorbent bed pressure drop. Gas-phase adsorbents typically can have significant pressure drop, and failing to account for this detail will negatively affect fan airflow. The specifications should clearly state when media are to be installed.

Pressure Gages. If upstream filtration is adequate, adsorbent pressure drop will not increase during normal operation, unless media settling and compacting occurs. A pressure gage is therefore not normally needed for a particulate filter bank. However, a gage can be useful to detect fouling or unintentional bypass. If the prefilters or final filters are installed immediately adjacent to the adsorbents, 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 in under Operation and Maintenance.) The installation should provide access ports to the fully mixed airstream both up- and downstream of the air cleaner. If media samples will be removed to determine remaining life of the gas filter, access must be provided to obtain those samples.

Start-Up and Commissioning

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

The commissioning authority may require an activity test on a random sample of media to determine if the new media meets specifications or suffered prior exposure that reduced its life. An in situ air sampling test may also be required on the adsorbent; however, no standard method for this test exists. See Chapter 44 for more on commissioning.

10. OPERATION AND MAINTENANCE

Bypass units and filters with adsorbent-infused fibrous media require frequent changing to maintain even low efficiency, but frequent maintenance is not required for complete removal units. Complete removal media units 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 physical and chemical 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 adsorbent bed or from a pilot cell placed in front of the bed. 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 copper or silver 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 removal and provides an indication of system life. A standardized methodology for these tests is described in Instrument Society of America (ISA) *Standard* 71.04.

Replacement and Reactivation

Regeneration of granular media is not the same as reactivation (regeneration), which is the process of 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 (or media changed), however chemisorber media 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.

11. ENVIRONMENTAL INFLUENCES ON AIR CLEANERS

Environmental conditions, particularly temperature and humidity, affect the performance of most gaseous contaminant removal equipment. Physical adsorbents such as activated carbon are particularly susceptible. The user should confirm performance for any air-cleaning 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 adsorbents, such as carbon, because of competition for adsorption 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. Both the chemical nature of the contaminant(s) and the concentration 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 removal system should be held within design limits.

The effect of relative humidity swings can be better understood by considering a hypothetical physical adsorbent with a saturation capacity for a contaminant 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 adsorbent could load up to 5% capacity. Should the humidity then swing back to 50%, the adsorbent could continue to adsorb up to 10% by weight of the contaminant. However, if the adsorbent 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 adsorbent 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 adsorbed contaminants displace weakly held contaminants.

All physical and chemical adsorption media have an 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* 52.2 MERV of 7 is recommended.

Vibration breaks up the granules to some degree, depending on the granule hardness, and causes media settling in some activated carbon filters. 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.

Physical adsorption and chemisorption media sometimes accelerate corrosion of metals they come into contact with. Consequently, media holding cells, trays, and modules should not be constructed of uncoated aluminum or steel. Painted steel or acrylonitrile butadiene styrene (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.

12. 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. It may be done 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 are ultimately needed to validate performance claims. Field tests under actual conditions are used to ensure that the air cleaners were also properly installed and to evaluate remaining media life.

Laboratory Tests of Media and Complete Air Cleaners

Small granular media samples have been tested in laboratories 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, and the contaminant concentrations are several orders of magnitude lower than those used in the testing.

Testing for Fundamental Media Properties. The test used to evaluate fundamental properties of physical adsorption media, measurement of the adsorption isotherm, is static. 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 then 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 (CCl₄) vapor, was widely used for specifying performance of activated carbon. 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 test procedures so that users accustomed to CCl₄ 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 sorption.

Small-Scale Dynamic Media Testing. ASHRAE *Standard* 145.1-2015 provides a flow-through test of physical and chemical

adsorption media at small scale (about 2 in. diameter test bed) and relatively high concentration (100 ppm). The test is intended to provide data for meaningful comparisons of media, provided that the same contaminant challenge gas is used for each test. *Standard 145.1* was 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 *Standard D3467*; Mahajan 1987, 1989; Nelson and Correia 1976).

Because physical adsorbent 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 a useful measure of filter performance on a single contaminant, and they do give a basis for estimates of filter penetrations and filter lives. Filter penetration data thus obtained can be used to estimate steady-state indoor concentrations in the preceding equations.

VanOsdell et al. (2006) presented data from ASHRAE research project RP-792 showing that, for a particular VOC adsorbed on activated carbon, tests at high concentration could be extrapolated to indoor levels. In addition, tests of a carbon with one chemical, toluene, were used to predict breakthrough 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 values.

A more recent ASHRAE research project, RP-1557 (Han et al. 2013), tested several physical and chemical adsorbent media against toluene, formaldehyde, ozone, and nitrogen dioxide. It found that relative performance at high-challenge-gas concentration corresponded with performance at low concentration. Some progress was also made in developing a mechanistic model for predicting low-concentration behavior for physical adsorbers.

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 exposing the test filter to unpolluted air and measuring downstream concentrations. Reaction products may be as toxic, odorous, or corrosive as captured pollutants.

Full-Scale Laboratory Tests of Complete Air Cleaners. Full-scale tests of in-duct air cleaners are the system test analogs of the media tests described previously. ASHRAE *Standard 145.2-2016* details a full-scale performance test for in-duct air cleaners in a laboratory setting. 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 removal 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 contaminant removal device to examine these uncertainties.

A useful quantity that can be calculated from data obtained during air-cleaner testing is the **clean air delivery rate (CADR)**. Most air cleaners do not remove 100% of the contaminant(s) that they are intended to mitigate. The CADR expresses this incomplete removal as delivery of a lesser amount of fully cleaned air. For an in-duct test, the CADR is calculated as the product of the single-pass efficiency and the airflow rate through the device. For a chamber test, the CADR is calculated as the product of the decay rate constant due to action of the air cleaner and the volume of the chamber. Units are those of airflow rate (i.e., cfm), allowing direct comparison between the impact of the air cleaner and use of ventilation air. Note that the CADR may be different for each of the gaseous contaminants that the air cleaner removes.

Field Tests of Installed Air Cleaners

Gaseous contaminant air cleaners are expensive enough to place a premium on using their full capacity (service life). For odor management applications, the most reliable measure of the continued usefulness of gaseous contaminant air cleaners may be a lack of complaints because of the low concentrations, and complaints often serve as early indicators of exhausted granular 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 the capacity of 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 taken over the filter area are more representative of the air cleaner than one larger sample. The sample needs to be handled and shipped carefully so that it remains representative of the in-place filter 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. Each has the potential to be superior in a given case. For indoor air applications with relatively constant contaminant sources, passive samplers are advantageous because they capture an integrated sample and are 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. Measurement of efficiency using 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 and Hendry (2005) attempted to use single-component analyses to evaluate air cleaners in the field. The up- and downstream samples were analyzed not for TVOC, but for particular chemicals (heptane, toluene, ethyl benzene, and formaldehyde). Bayer and Hendry found that the time variations of the challenge made the efficiency determinations so variable that the procedure could not be used reliably.

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