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What Is an Effective Portable Air Cleaning Device? A Review

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The use of portable air cleaning devices in residential settings has been steadily growing over the last 10 years. Three out of every 10 households now contain a portable air cleaning device. This increased use of air cleaners is accompanied by, if not influenced by, a fundamental belief by consumers that the air cleaners are providing an improved indoor air environment. However, there is a wide variation in the performance of air cleaners that is dependent on the specific air cleaner design and various indoor factors. The most widely used method in the United States to assess the performance of new air cleaners is the procedure described in the American National Standards Institute (ANSI)/Association of Home Appliance Manufacturers (AHAM) AC-1-2002. This method describes both the test conditions and the testing protocol. The protocol yields a performance metric that is based on the measured decay rate of contaminant concentrations with the air cleaner operating compared with the measured decay rate with the air cleaner turned off. The resulting metric, the clean air delivery rate (CADR), permits both an intercomparison of performance among various air cleaners and a comparison of air cleaner operation to other contaminant removal processes. In this article, we comment on the testing process, discuss its applicability to various contaminants, and evaluate the resulting performance metrics for effective air cleaning.

Keywords air cleaner, clean air delivery rate, effectiveness, gas, particle, portable air cleaner

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The use of air cleaning to control exposures to residential indoor air contaminants is not a new concept. Peshkin and Beck(1) described a "new" portable filter, incorporating the use of "filters of high efficiency" as a treatment method for asthma patients. Crisp and Green(2) found that electrostatic air cleaning devices were effective as a treatment for 61 patients. Kranz(3) found that considerable local improvement to allergy patients was possible using a portable air cleaner of very high efficiency. One study published in the *Lancet*(4) described the use of a portable air purifier incorporating activated carbon and a "paper" filter blending cellulose and asbestos fibers for the treatment of bronchial and asthmatic patients (asbestos would not be permitted in such applications today). As a whole, defining the benefits afforded by the air cleaners in these early studies was necessarily limited by the technology available at the time in assessing both environmental and clinical improvements.

The practice of air cleaning using "portable" type devices, as reflected by the studies cited above is not a new development; however, it was not until the late 1970s and early 1980s that a wide variety of air cleaners for the consumer market began appearing. Many of these products were promoted as being capable of removing tobacco smoke, odors, dust, pollen, and other indoor pollutants—both gas- and particle-phase. The most popular types of these products were known as "table-top" air cleaners, consisting of small devices with low-flow fans pulling air through a filter and circulating it back into the room. Even though most of these devices were ineffective in terms of particle removal,(5) their marketing proved that portable air cleaners could be sold in the consumer market, thus paving the way for larger stand-alone air cleaners with more elaborate removal technologies.(6)

The sale and marketing of portable air cleaners for homes has increased considerably in the last decade. A recent survey of homes across the United States revealed 3 out of every 10 households own at least one type of air cleaning device.(7) The "present-day" realm of portable air cleaners embodies all electric appliances (which can be moved from room to room) intended for the removal of contaminants from indoor air. Such appliances include floor-type, stand-alone units, table-type units (designed to be placed on a table, counter, or desk top), wall-type units (designed to be wall mounted or attached to the wall and plugged in accordingly), and combination-type (designed to operate in one or more orientations—wall, floor, or table).

Air cleaners are, by definition, designed to reduce contaminant concentrations in indoor air. The methods for removing contaminants vary, depending on the contaminant phase and the design of the air cleaner. Typical particle removal methods include but aren't limited to drawing air though various filter media, electrostatic precipitation, and air ionization, with subsequent collection of particles on various indoor or air cleaner surfaces. For gas-phase species, sorption and chemical reaction are typical removal methods. The details of these various removal mechanisms are beyond the scope of this article but can be found in the published literature and in the product literature provided by air cleaner manufacturers. Fans are often used to provide mechanically driven air movement through an air cleaner, but neither the definition of an air cleaner nor the testing protocol developed by the Association of Home Appliance Manufacturers (AHAM) and recognized by the American National Standards Institute (ANSI)[8] requires that a fan be used.

About the same time that air cleaner sales began increasing in the 1970s and 1980s, it was recognized that there were no uniform testing methods that could be applied to give consumers a means of making performance-based choices. Lawrence et al.[9] reported on the potential benefits of portable air purifiers; operational and evaluation variables that require consistency to discern the effectiveness of the units were also noted. Whitby et al.[10] made reference to the lack of standard methods for testing/rating air cleaning devices and expressed concern regarding the "sweeping and general" claims being used by manufacturers of the devices. Consumers Union[11] reported over 40 years ago on the need for validation of these "claimed results" and on the lack of published results on the effectiveness of the air cleaners.

Two early papers described essentially the same evaluation methodology and reported on the performance of some of the then-available consumer portable air cleaners.[5,10] Whitby et al.[10] reported on a "dynamic method" for measuring smoke, hydrocarbon gas removal, and odorant emission rate developed and applied to the evaluation of six different air purifiers. Offermann et al.[5] discussed a similar method used to evaluate 11 air cleaning devices for control of environmental tobacco smoke particles. The Whitby paper focused on an "efficiency-volume product" term, which is analogous to the "effective cleaning rate" term coined by Offermann to describe the effectiveness of the air cleaning device in providing "clean" air with respect to a specific contaminant (expressed as a volumetric flow rate) to a given space.

The methodology described in these two papers formed the basis for the first published ANSI/AHAM standard AC-1[12] and for subsequent air cleaner performance evaluations published by AHAM and by Consumers Union.[13–15] The AHAM term "clean air delivery rate" (CADR) was created in lieu of the previous terms employed by Whitby and by Offermann to describe the equivalent volume of clean air provided to the space by an air cleaner. In addition, other researchers have evaluated and used this performance metric for other types of air cleaners and found the approach to be valid and useful in estimating the effects of the devices in various room sizes or in comparing air cleaning with ventilation as an indoor quality control technique.[16–25] The application and results are described later in this article.

PERFORMANCE EVALUATION METHODOLOGY

Concentrations of contaminants in indoor air are dynamic and result from the competition between various source and removal processes. These processes can be described by a simple mass-balance model, where the key assumption is that the indoor space is well mixed. For most residential environments and for the time scales of interest (of order hours), this is a reasonable assumption well borne out by the many model-measurement comparisons of indoor pollutant behavior since this approach was first introduced.[26,27] Mathematically, the "well-mixed box" equation is:

$$\frac{dC_i}{dt} = S/V + P\lambda_v C_o - \Lambda C_i \qquad \textbf{(1)}$$

The first two terms on the right-hand side of Eq. 1 describe the source terms. The first is the volumetric source term describing any indoor contaminant emission source, where S is the emission rate in mass per unit time and V is the volume of the indoor space. The second is infiltration of contaminants from outdoors, where λ_v is the air infiltration rate (in units of inverse time), P is the penetration factor, and C_o is the outdoor contaminant concentration. The last term in Eq. 1 describes the indoor removal processes, where Λ represents all first-order removal processes (in units of inverse time) and C_i is the indoor contaminant concentration. The removal processes can be broken down into their constituent parts, for example

$$\Lambda = \lambda_v + \lambda_d + \lambda_{ac} \qquad \textbf{(2)}$$

where λ_d is the removal rate due to deposition onto surfaces and λ_{ac} is the removal rate due to air cleaner operation.

When performing air cleaner testing in a room-size chamber, sufficient concentrations of the test contaminant are introduced into the chamber so that concentrations due to any infiltrating contaminant can essentially be neglected. The actual testing commences after the contaminant source is turned off, so S = 0. Thus, during testing Eq. 1 reduces to

$$\frac{dC_i}{dt} = -\Lambda C_i = -(\lambda_v + \lambda_d + \lambda_{ac})C_i \qquad \textbf{(3)}$$

The solution to Eq. 3 is

$$C_i(t) = C_i(0)\exp(-\Lambda t) = C_i(0)\exp[-(\lambda_v + \lambda_d + \lambda_{ac})t] \qquad \textbf{(4)}$$

It is useful to rearrange the terms in Eq. 4 and take the natural log of both sides

$$\Lambda = \lambda_v + \lambda_d + \lambda_{ac} = \frac{\ln(C_i(0)/C_i(t))}{t} \qquad \textbf{(5)}$$

In practice, $C_i(0)$ is the contaminant concentration at the start of the analysis, usually chosen to be at the time when conditions in the test chamber are well mixed, and t is the elapsed time between the starting concentration, $C_i(0)$, and the concentration at time t, $C_i(t)$.

Equation 5 provides the basis for determining the removal rate of contaminants due to these three processes. Tests conducted without an air cleaner operating in the chamber yield removal due to ventilation and deposition. If measurement of an inert tracer gas is used as part of the test, contaminant removal due to ventilation and to deposition can be determined independently. An identical test with the air cleaner operating (usually performed after the test chamber is reloaded with contaminant) will then provide a measure of the removal rate due to the air cleaner operation combined with the other removal processes.

To explicitly account for room size, the ANSI/AHAM standard defines CADR as

$$\begin{aligned} \text{CADR} &= \text{V}(\Lambda_{AC} - \Lambda_{noAC}) = \text{V}(\lambda_v + \lambda_d + \lambda_{ac} - \lambda_v - \lambda_d) \\ &= \text{V}\lambda_{ac} \end{aligned} \quad \textbf{(6)}$$

As can be seen in Eq. 6, CADR is based on the measured difference in decay or removal rates with the air cleaner in operation and with no air cleaner operation. The units of CADR are flow, that is, volume per unit time. This provides a useful comparison against the ventilation rate when stated in terms of flow. The CADR is significant since it is a measure of operation of the air cleaner taking into account both the efficiency of the filter and mixing characteristics within a space that may include short circuiting (short-circuiting is the re-entrainment of some of the "cleaned" air from the outlet of the air cleaner into the inlet of the device rather than mixing completely with the air within the chamber). As such, the CADR gives a more representative means of characterizing the performance in a real environment rather than a measure of the single pass efficiency alone, such as might be noted by a manufacturer.(16) Note that the relationship between CADR and the filtration efficiency (ε) is CADR $= \varepsilon * Q_{ac}$, where Q_{ac} is the volumetric airflow through the device.

AHAM currently makes use of the CADR as a means of rating the particle removal performance of portable air cleaners on the market. Three particle types have been selected for these evaluations: environmental tobacco smoke (ETS) (particle size range, 0.09–1.0 μm diameter); dust (particle size range, 0.5–3.0 μm diameter); and paper mulberry pollen (particle size range, 5–11 μm diameter). The results of the most recent AHAM testing of 156 commercially available air cleaners(28) are summarized in Figure 1. The mean CADR values for all three test aerosols are essentially the same, ~160 ft^3/min (270 m^3/hour), and more than 90% of the air cleaners tested have CADRs between 60 and 300 ft^3/min (100–500 m^3/hour). Note, we have chosen to discuss CADR in the units used by AHAM (ft^3/min) and have provided the metric equivalents, as appropriate.

CADR and its predecessor names, "efficiency volume product" and "effective cleaning rate," as stated earlier, have been used in a number of published papers documenting studies of various air cleaners for both particles and gases. The AHAM CADR approach is also cited by the American Lung Association and the Environmental Protection Agency (EPA) as an appropriate performance indicator for evaluating the effectiveness of air cleaners used in the home or in similar applications.(29,30)

Shaughnessy et al.,(19) in a study of various portable air cleaners and their effectiveness on a number of different particle types, demonstrated similar particle removal efficiencies for

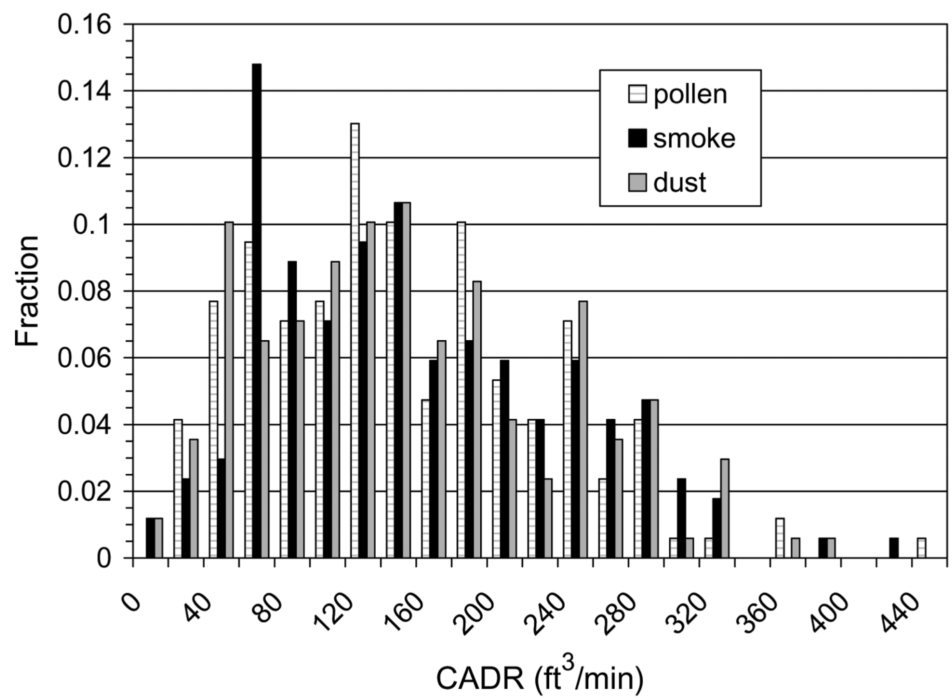

FIGURE 1. Distribution of particle air cleaner performance measured as the clean air delivery rate (CADR) for three test aerosols, as reported by AHAM(28) for 156 air cleaners

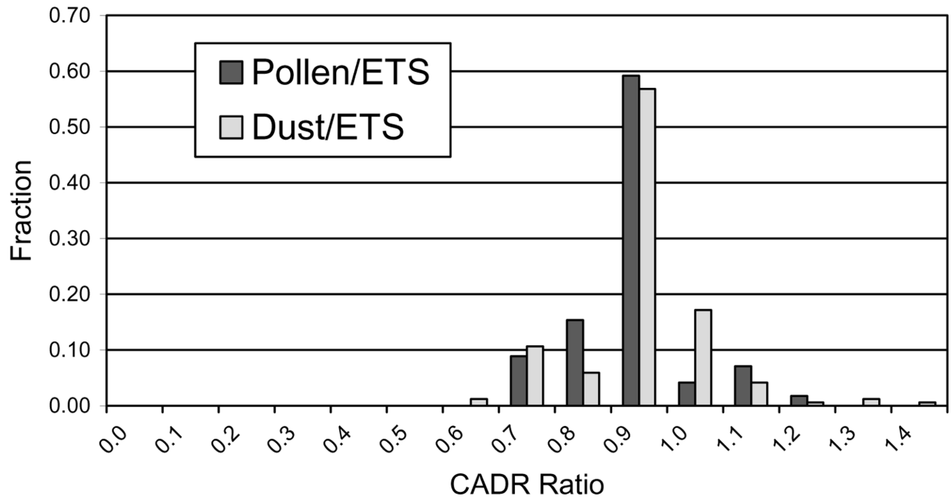

FIGURE 2. Distribution of the ratio of air cleaner performance reported for dust and pollen, compared to that for environmental tobacco smoke (ETS) for the same air cleaners shown in Figure 1. Approximately 85% of these ratios lie between 0.8 and 1.2.

the same general particle size range regardless of whether the particles were inert or biological (viable/nonviable) in origin. In addition, those devices exhibiting effectiveness in the smallest particle-size range (tobacco smoke particles) displayed similar CADRs as the particle size increased with other types of test particle. The most recent AHAM performance data (shown in Figure 1), cast as the removal ratio of dust to ETS and pollen to ETS, show very little difference in CADRs associated with removal of dust and pollen when compared with ETS (Figure 2). Approximately 85% of the ratios lie between 0.8 and 1.2.

In addition to the AHAM compilation of particle air cleaner performance currently updated quarterly, Consumers Union, an independent product testing firm, periodically reports in the monthly *Consumer Reports* magazine results of their evaluations of air cleaners.[13–15] The most recent *Consumer Reports* ratings[15] ranked 18 of the top "room" air cleaners on the market. Fourteen of the top 15 air cleaners on their list were equipped with high-efficiency particulate air (HEPA) filters.

EFFECTIVENESS OF AIR CLEANING

While CADR is used to describe the performance of an air cleaner with respect to contaminant removal, the benefit of using an air cleaner needs to be assessed in the context of its actual use. In particular, what CADR value provides an acceptable level of air cleaning? For example, the air cleaner removal rate must compete with other removal processes that occur within the space. Other removal mechanisms within the space include surface deposition (for particles) or sorption (for gases), indoor air reactions (typically for gases), and ventilation (outdoor air exchange).

The concept of air cleaner effectiveness has been used to examine acceptable values for CADR. Effectiveness, ε, has been defined by Nazaroff[22] as the difference in indoor concentration due to air cleaning ($C_{noAC} - C_{AC}$,) compared with the "no cleaning" case, C_{noAC}

$$\varepsilon = \frac{C_{noac} - C_{ac}}{C_{noac}} \tag{7}$$

Returning to Eq. 1 and solving the equation for steady-state conditions (i.e., $dC_i/dt = 0$), yields, with some rearrangement of terms

$$C_i = \frac{S/V + \lambda_v PC_o}{\Lambda} = \frac{S + V\lambda_v PC_o}{V(\lambda_v + \lambda_d + \lambda_{ac})} \tag{8}$$

For the case with no air cleaner operating, $\lambda_{ac} =,0$ and Eq. 8 is

$$C_{noac} = \frac{S + V\lambda_v PC_o}{V(\lambda_v + \lambda_d)} \tag{9}$$

and when the air cleaner is operating (and recalling the definition of CADR in Eq. 6)

$$C_{ac} = \frac{S + V\lambda_v PC_o}{V(\lambda_v + \lambda_d) + CADR} \tag{10}$$

Using these two equations and Eq. 7, we obtain a relationship between effectiveness and the contaminant removal processes

$$\varepsilon = \frac{CADR}{V(\lambda_v + \lambda_d) + CADR} = \frac{CADR/[V(\lambda_v + \lambda_d)]}{1 + CADR/[V(\lambda_v + \lambda_d)]}. \tag{11}$$

The closer the effectiveness is to 1, the more ideal the performance of the air cleaner is in removal of the contaminant. Figure 3 shows air cleaner effectiveness as a function of the ratio between CADR and the other removal processes—ventilation and (for particles) deposition, CADR/[$V(\lambda_v + \lambda_d$]. The AHAM performance recommendation (effectiveness) of 80% reduction in steady-state particle concentrations, shown as a dotted line in Figure 3 (AHAM Recommended), requires that this ratio be a factor of 4 (i.e., particle removal rate by

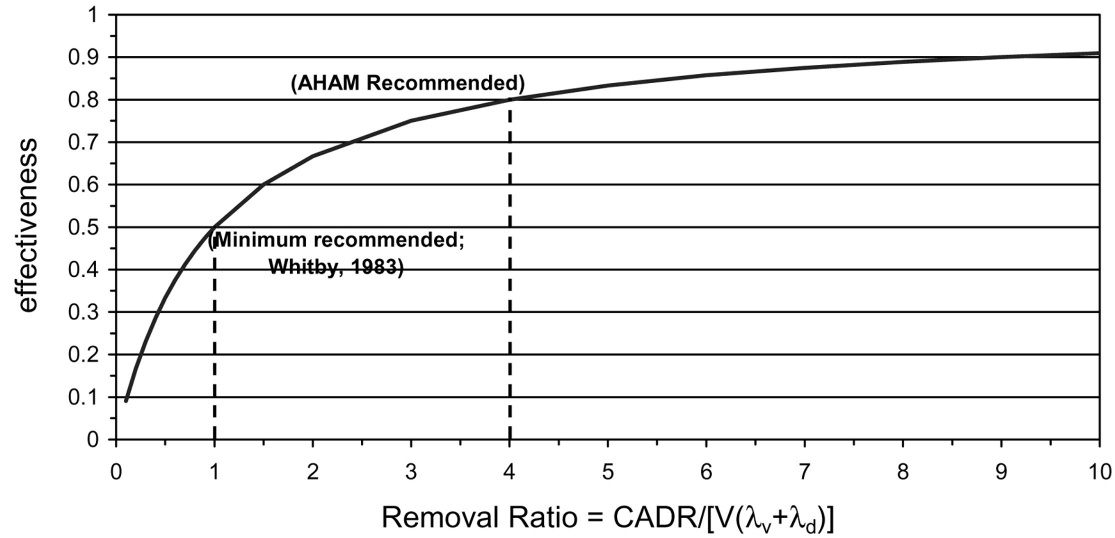

FIGURE 3. Effectiveness of airborne contaminant removal as a function of the ratio between air cleaner performance and the other removal processes, ventilation, and deposition (for particles) (adapted from Nazaroff)[22]

air cleaning is four times the removal rate by ventilation and deposition combined). As an illustration, the combination of ventilation rate and particle deposition rate is ~1.05 $hour^{-1}$ (representative of typical ventilation rate of 1 $hour^{-1}$ and deposition rate for small particles of 0.05 $hour^{-1}$), thus for a room size of 15 × 15 × 8 ft (=1800 ft^3 or 51 m^3), the combined removal rate is 30 ft^3/min, leading to a minimum CADR of 120 ft^3/min (200 m^3/hour). As can be seen in Figure 3, to achieve an effectiveness of 90%, the removal ratio more than doubles. In the above example, the required CADR increases to nearly 270 ft^3/min (460 m^3/hour).

In contrast, reducing the effectiveness to 67% is equivalent to setting the removal rate by air cleaning equal to twice that due to the combination of ventilation and deposition. Similarly, for an effectiveness of 50% the air cleaning removal rate is equal to that due to ventilation and deposition combined, shown as dashed line in Figure 3.[10] These have implications for the application of air cleaners with various CADR values, as discussed in the next section.

As stated above, AHAM has a performance recommendation (effectiveness) of 80% reduction in steady-state particle concentrations related to air cleaner operation. The degree of air cleaner effectiveness necessary to have a meaningful effect on contaminant concentrations in the indoor space has been the subject of discussion for many years. Whitby et al.[10] in their early development of the dynamic model for evaluating air cleaners placed a great deal of emphasis on the significance of "efficiency-volume product" (equivalent to CADR) provided by the air cleaner to the space, a key index of performance. Whitby et al. stated that for a device to be effective in air cleaning, the unit must provide a minimum of one air change per hour (of cleaned air) to the room intended for use. For a typical small room of 15 ft × 15 ft × 8 ft, this would relate to a minimum CADR value of 30 ft^3/min. Whitby and colleagues noted that ventilation must be considered as the critical factor in the consideration of the potential for an air cleaner to impact the concentration of pollutants in the air. Their analysis focused on removal of small particles (ETS) where the removal rates due to deposition would be small compared with ventilation. As illustrated in Figure 3, the effectiveness related to Whitby's recommendation would afford only a 50% reduction in steady-state particle concentrations.

In practice, many air cleaning devices on the market today have rated CADR values, with respect to particle removal, significantly higher than the minimum suggested by Whitby et al. for an occupied space. AHAM's recommended effectiveness of 80% equates to the air cleaner being capable of providing an equivalent (volume of clean air) of 4–5 air changes per hour for the specific room size. For the previous example room size of 15 ft × 15 ft × 8 ft, this would relate to a minimum CADR value of 120 ft^3/min. Figure 4 provides a graphic representation of CADR values necessary to meet the AHAM recommended 80% effectiveness value and Whitby's suggested 50% value. These calculations are based on reducing small particle concentrations.

These same principles for judging the performance of an air cleaning device have been adopted on an international basis as well. The Swedish Asthma and Allergy Association (SAAA)[31] guidelines state that the equivalent airflow rate related to an air cleaner (equivalent airflow rate is another term for CADR) must be suited to the size of the room. They also emphasize the importance of competing with other removal processes such as ventilation in their guidance. They concur with the AHAM guidance that an 80% reduction in contaminant concentration is necessary to produce meaningful reductions in contaminant concentrations indoors. The guidance is mainly based on particle removal; however, the SAAA clearly states that the same guidelines are applicable for gas-adsorption-based air cleaners, with related gas-phase removal terms to be taken into account.

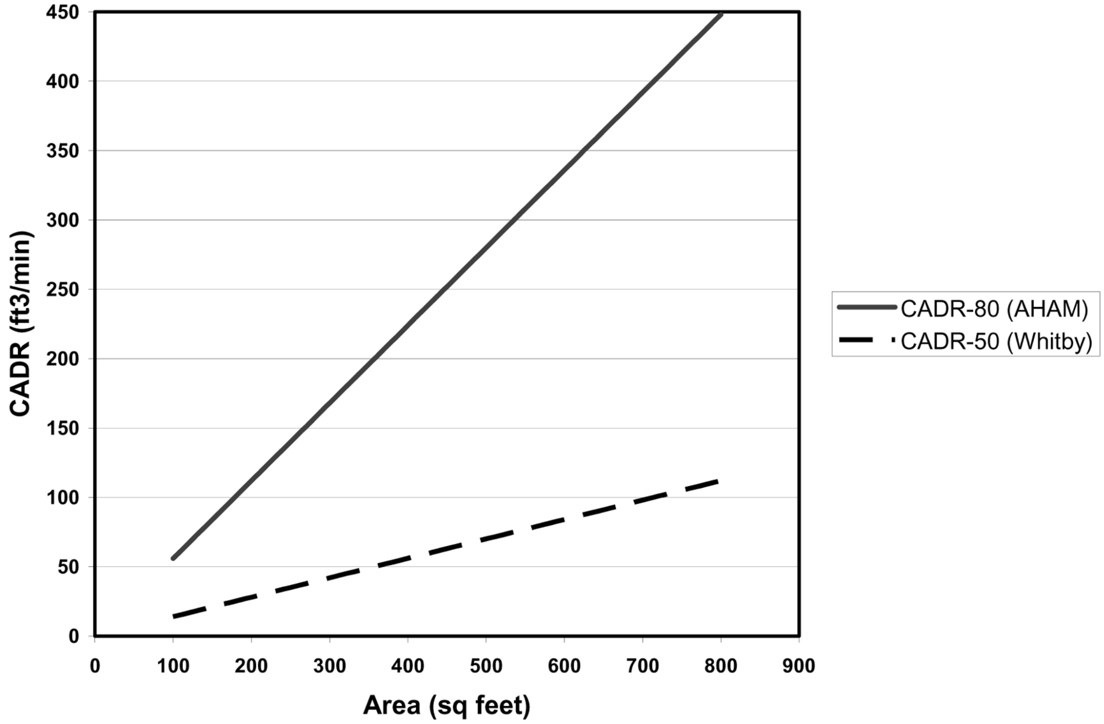

FIGURE 4. Clean air delivery rate as a function of indoor floor area for two effectiveness values: 80% as recommended by AHAM, and 50% based on Whitby et al.[10] Graph applies to removal of smaller particles, less than ~1 micron in size, and is based on a ceiling height of 8 ft.

APPLICATION OF AIR CLEANING TO PARTICLES

As discussed earlier, the AC-1 protocol is based on testing the performance of air cleaners against three types of aerosols (ETS, dust, and pollen) representing different particle sizes.[8] And, as also noted earlier, the AHAM CADR results show only a minor dependence on test particle size (Figure 2). On the other hand, the effectiveness of particle air cleaning depends on particle size, as described by Eq. 11. The variation in particle deposition rate as a function of particle size is shown in Figure 5. This figure represents average deposition losses measured in a room-size chamber under various experimental

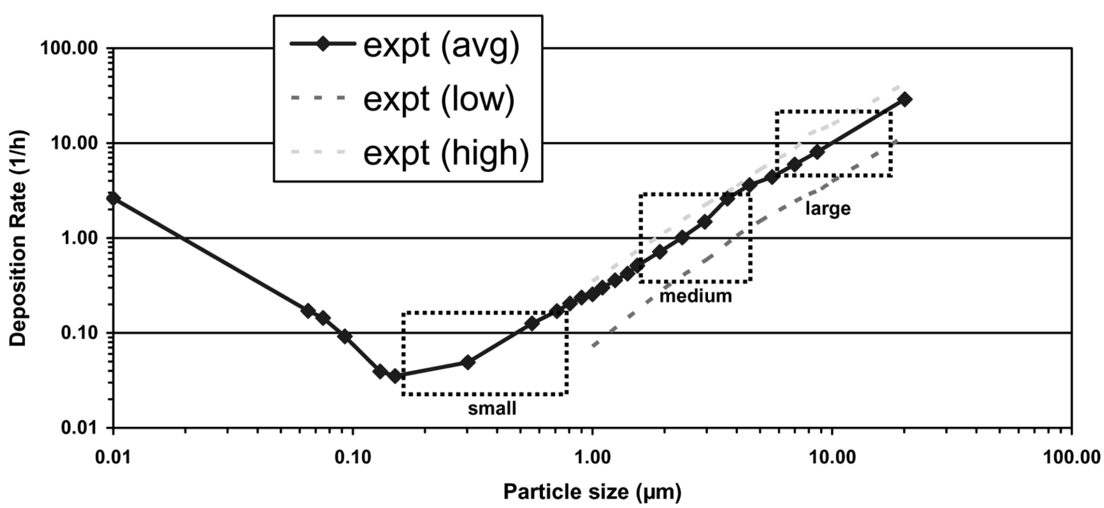

FIGURE 5. Particle removal by deposition as a function of particle size. Data are from Thatcher et al.[40] and Xu et al.,[41] as reported by Fisk et al.[38] The dashed lines show the upper and lower bounds of the measurements reported by Thatcher. The rectangles designate those particle sizes used in the present analysis, where "small" refers to the particle size region associated with the peak in the ETS mass distribution. The rectangle labeled "medium" refers to the size region associated with some allergens and with larger ambient aerosols. The rectangle labeled "large" refers to the size region associated with pollens, with sources of asthma such as cat antigen, and allergens such as dust mites.[38,39]

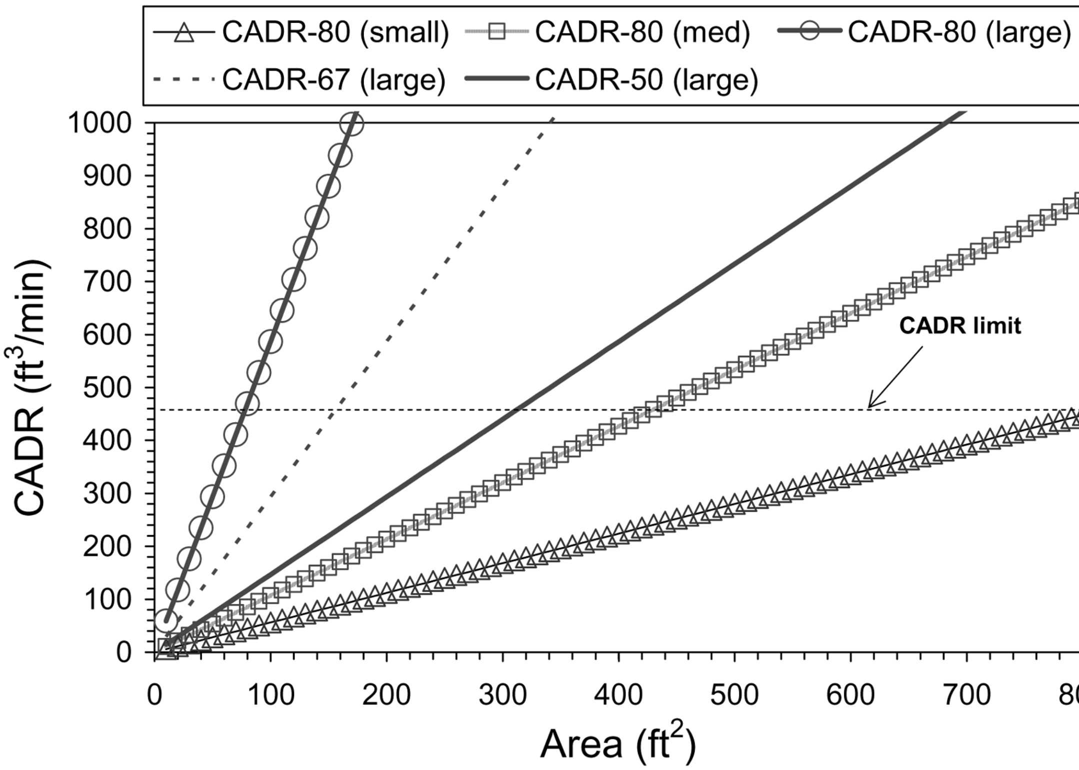

FIGURE 6. Clean air delivery rate as a function of indoor floor area and particle size. Volume is calculated based on a ceiling height of 8 ft. CADR-80, -67, and -50 are, respectively, the CADR values based on 80%, 67%, and 50% reduction in particle concentrations due to air cleaner operation. The particle size categories are those described in the text.

conditions (furnishing level and internal air velocity). As can be seen, deposition loss rates vary over almost three orders of magnitude as particle sizes range from ~ 0.2 to over 10 μm.

Three particle size regions are designated in Figure 5, representing three different types of aerosols of interest: (1) small: particles less than 0.8 micron, for example, ETS; (2) medium: particles ranging from 1–4 microns, for example, house dust, some allergens such as cat allergen; and (3) large: particles ranging from 6–20 microns, for example, pollen and allergens, such as dust mite and cockroach feces. The average deposition removal rates associated with these groups of particles are $\sim$0.05, $\sim$1, and $\sim$ 10 per hour, respectively. When compared with typical residential ventilation rates ($\sim$ 1 per hour)[32] particle deposition losses for small particles have little impact on the particle removal ratio described in Eq. 11. On the other hand, losses due to deposition of medium-size particles are about the same as those due to ventilation. Finally, large particles deposit at rates that are much higher than the equivalent loss rate due to ventilation.

These differences in particle deposition losses have an important effect on the resulting CADR needed to meet the effectiveness criterion. We recast Eq. 11 in terms of height, hour, and floor area, A, a more commonly used descriptor of room size than is room volume, to yield

$$\mathrm{CADR} = \mathrm{hA}\frac{\varepsilon(\lambda_v + \lambda_d)}{1 - \varepsilon} \quad \textbf{(12)}$$

Using this equation and the ventilation and particle deposition parameter values described above, we develop the relationship between room size, CADR, and particle-size category, as shown in Figure 6; for these calculations we have assumed a ceiling height of 8 ft (2.4 m). Three lines display CADR as a function of indoor space area calculated for small, medium, and large particle categories, based on an air cleaner effectiveness of 80% applied to each particle-size category. For small particles, a room area of 400 ft^2 (37.2 m^2) requires an air cleaner with a CADR value of 225 ft^3/min (383 m^3/hour). For particles in the medium size category, an air cleaner with a CADR of 425 ft^3/min (722 m^3/hour) is needed for the same size room. Only one of the air cleaners listed by AHAM[28] has a CADR for dust above 425 ft^3/min.

For large particles, the CADR value required to achieve an 80% reduction in particles for a 400 ft^2 room is over 2300 ft^3/min (3900 m^3/hour), which is well beyond any portable air cleaner tested by AHAM (the largest CADR listed for pollen is 400 ft^3/min–680 m^3/hour). Conversely, an air cleaner with a 400 ft^3/min rating for pollen can provide an 80% reduction in big particles for a room with an area less than 70 ft^2 (6.5 m^2). If the effectiveness criterion is relaxed to 67% or to 50% for the large particle category, for a room size of 400 ft^2, the CADR for large particles is still more than 1100 ft^3/min (1870 m^3/hour) or 580 ft^3/min (985 m^3/hour), respectively. Conversely, an air cleaner with a pollen CADR of 400 ft^3/min can provide a 67% reduction in the concentration of large particles in a room

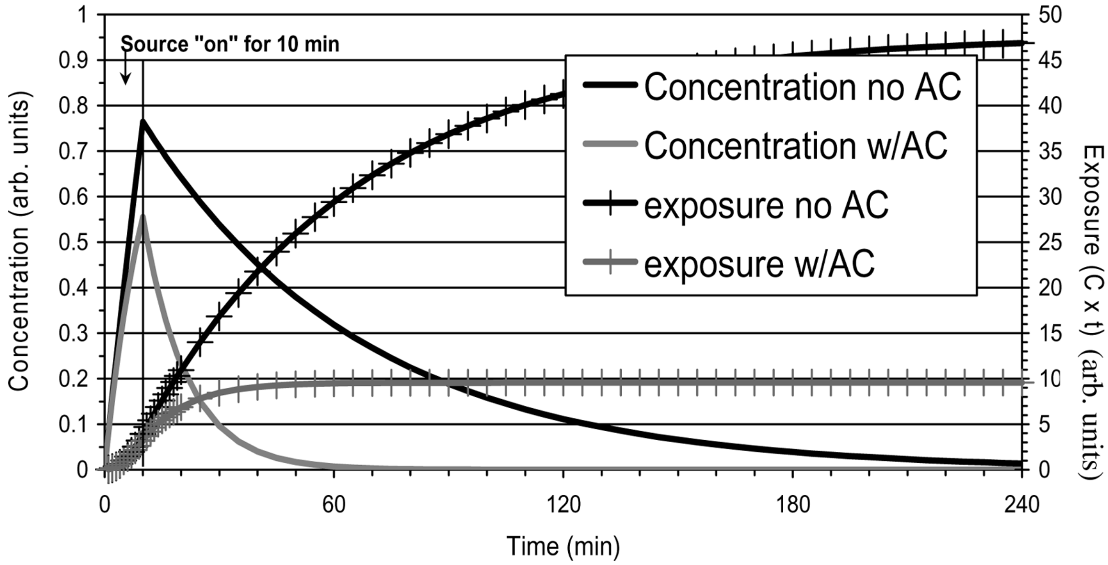

FIGURE 7. Particle concentrations and exposures (calculated as concentration × time) as a function of time in a typical indoor space with and without air cleaning. This illustration is based on a steady 10-min release of "small" particles into a 150 ft^2 space (1200 ft^3), with a ventilation rate of 1 $hour^{-1}$, and a particle deposition rate of 0.05 $hour^{-1}$ (see Figure 4). The CADR for the air cleaner is 84 ft^3/min, based on the 80% reduction criterion.

smaller than 140 ft^2 (13 m^2), or a 50% reduction in a ~270 ft^2 room (25 m^2).

The discussion thus far has used steady-state concentrations of particles indoors for the illustrative calculations and comparisons. Not all indoor particle concentrations—especially those that might arise from episodic sources like cigarette smoking, cooking, etc.—will be relatively constant with time. We examine the dynamic effects of single and multiple particle release periods in Figures 7 and 8. The source profile and the particle size chosen for this illustration are typical of sidestream smoke as the source of ETS. The particle concentration profile is reduced by operation of the air cleaner. At the end of the 10-min release period, the concentration ratio is ~0.7; by 60 min, the ratio is ~0.02. In terms of exposure—the integral of concentration over time—the ratio (air cleaner on vs. air cleaner off) is ~0.8 at 10 min and ~0.3 at 60 min. Eventually, the exposure ratio reaches 0.2, which is consistent with the 80% effectiveness of the air cleaner assumed for this illustration. This exposure ratio as a function of time is shown in Figure 8, labeled as "single source CADR-80 (small)."

When the same particle source is operated periodically, in this case for 10 min every hour, the resulting exposure ratio is shown in Figure 8 also, labeled as "repeat source CADR-80 (small)." A similar pair of exposure ratio curves is shown for a large particle example, labeled CADR-50. In these cases, a deposition removal rate of 10 $hour^{-1}$ and a CADR-50 of 220 ft^3/min (374 m^3/hour) were used. This CADR value was used because there are no tested air cleaners with a CADR for large particles large enough to yield an 80% removal rate for a room size of 150 ft^2(14 m^2). As can be seen from both pairs of curves, the repeated source has only a modest effect on the exposure ratio as compared with the single source. It is also worth noting the different inherent time constants for small vs. large particle removal. The total removal rate for the small particles, with 80 % effective air cleaning, is ~5 $hour^{-1}$, while for the large particles, with only 50% effective air cleaning, the total removal rate is ~22 $hour^{-1}$ in these examples.

APPLICATION OF AIR CLEANING TO GASES

Although AHAM and others have used the CADR concept to evaluate the performance of air cleaners in reducing particulate matter concentrations, the CADR methodology is by no means restricted to particulate matter as an analyte. Rather, the approach utilizing a well-mixed chamber and the assumption of first-order decay is easily extended to the removal of gas-phase compounds. Axley[(33)] provided a detailed mathematical analysis and discussion of the sorption processes relevant to gas-phase air cleaning and compares the results of the more detailed simulations with those arising from a first-order decay process. He found for the simulated challenge compound, toluene, that the results of his more detailed analyses were compatible with the CADR methodology.

Whereas the extension of the CADR approach to gases is straightforward conceptually, there are practical considerations that must be addressed in establishing standardized test procedures. A key question is which gas-phase compounds should be included in the assessment process. Important gas-phase indoor contaminants include ozone, oxides of nitrogen and sulfur, and a wide range of volatile organic compounds (VOC). Over 300 different chemical compounds have been identified—not all of which are seen in a single indoor environment, nor are all equally important.[(34)] The challenge is

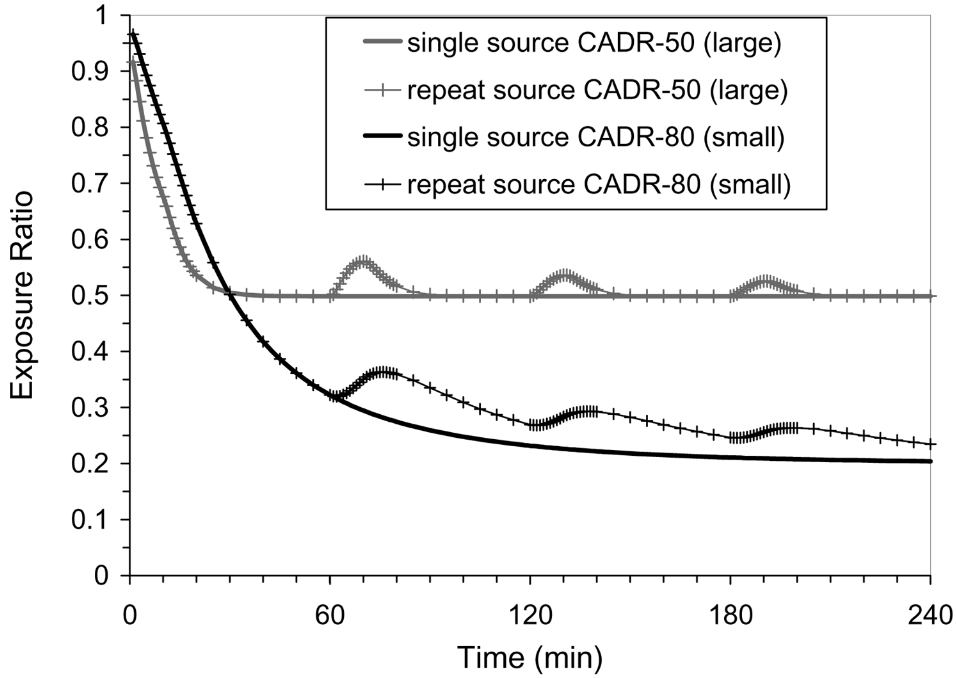

FIGURE 8. Exposure ratios as a function of time for two different release profiles and two different CADR-particle size combinations. The exposure ratio for CADR-80 and a single release is based on the exposure curves shown in Figure 7. The same calculations are shown for a repeated source, which was again a steady release for 10 min at 1, 2, and 3 hours after the initial release. A similar pair of exposure ratio curves are shown for a large particle example, using CADR-50 (see text).

to identify compounds representative of these various indoor contaminants. Toluene has been suggested as a representative of total volatile organic compounds[35] and this compound has been used in several studies of air cleaner performance, as discussed in more detail below.

VanOsdell[34] developed a recommended challenge mixture of eight VOCs, along with SO_2, NO_2, O_3, CO, and CH_4. The eight VOCs are proposed as representing the chemical classes indicted in parentheses: toluene (aromatic), hexanal (aldehyde), n-hexane (alkane), 2-butanone (ketone), dichloromethane (light chlorinated hydrocarbon), tetrachloroethylene (heavy chlorinated hydrocarbon), isobutanol (alcohol), and formaldehyde (also an aldehyhde and an important indoor air contaminant). A similar list of VOCs was used by Daisey and Hodgson[16] and by Chen et al.[25] in their respective studies of air cleaners.

A second important issue is the time-dependent behavior of the air cleaner and the cleaner lifetime. A notable difference between gas-phase removal and particle removal is that when a filter-based device becomes loaded with particles, it continues to remove the particles, albeit at a reduced airflow rate; in many cases there is a slight improvement in removal efficiency. In the case of an air cleaner that uses a sorption bed to remove the gas-phase fraction from the air, when the bed is loaded, breakthrough of the contaminant begins to occur back into the room. Thus, the breakthrough time and loading characteristics of the individual gas-phase removal device must be determined and included in the test results. Finally, when air cleaning involves chemical transformation, there are potential issues regarding reaction by-products.

Published results evaluating air cleaner performance against gas-phase contaminants in typical residential or commercial settings are limited. Daisey and Hodgson[16] examined the initial efficiencies of four commercially available portable air cleaners designed primarily for particle removal but with activated carbon positioned after the particle filter materials. Results of these tests are summarized in Table I. As part of the study, one filter containing 115 g of carbon was retested after having been operated for 150 hours in a residence occupied by nonsmokers. The resulting CADR values were less than half of those observed in the initial testing for all of the challenge compounds. In addition, the authors observed that nitrogen dioxide (NO_2) was converted to nitric oxide (NO) and emitted into the room air rather than absorbed; NO_2 sorption had been observed in the initial testing.

Niu et al.[24] also examined the initial performance of portable particle air cleaners containing activated carbon. Nineteen air cleaners were used in this study; they evaluated only removal rates of toluene as the gas-phase compound. The results are summarized in Table I. Particle removal rates were also studied and the ratio of the gas and particle CADR values compared. For the cleaners with the highest CADR values for toluene removal, only two had initial removal ratios above 50% (54% and 97%). Extended use testing was done on four cleaners, consisting of operation for 2 hours in a smoky environment (incense smoke) and for two, an additional 80 hours

TABLE I. Summary of Initial Air Cleaner Performance for Gas-Phase Contaminants, by Air Cleaner Type (entries are CADR in ft^3/min).

Compound[C]	Ref. 16 Carbon (sorption)	Ref. 24 Carbon (sorption)	Carbon (sorption)	Ref. 19 Ionization	Ozone	Carbon (sorption)	Ref. 25[A] Botanical	UV-PCO
Number of Devices Tested	4	19	12	1	1	9[B]	1	1
NO_2	3–46		NE; 6–96	NE	6			
Formaldehyde			1–55	NE	NE	0.8–24	4.6	13
Dichloromethane	NE					0.3–97	NE	2
n-Hexane						2.4–328	NE	4.5
2-Butanone	NE; 5–29					2–329	NE	11
n-Heptane	2–29							
Toluene	2–27	1–12				6.4–337	NE	14
Tetrachloroethylene	1–26					4.7–373	0.1	5.4
2-Butanol						3.7–345	3	47
Hexanal	3–23					11–370	4.9	56
n-Dodecane						13–333	0.9	32

Note: The values show the range of non-zero CADR values (ft^3/min) measured in the tests. NE indicates that no effect was seen in one or more air cleaners in the group.
[A] Reported CADR values are averages based on a 12-hour test.
[B] The highest CADR values listed here are for the UV-PCO device that incorporated a ~9 cm thick carbon adsorber. When operated without the carbon bed, the UV-PCO device produced no significant removal.
[C] VOC listed in order of decreasing vapor pressure (vp); the first three have vp $>$ 100 mm Hg (at 23°C); compounds 4 through 8 have vp between 10 and 100 mmHg; the last two have vp of 10 mmHg or less.

of operation in a freshly painted room. In all but one case, toluene removal dropped to zero on retesting. For the fourth air cleaner, the CADR for toluene was reduced by more than a factor of four.

Twelve air cleaners representing four types of particle air cleaning technology were studied by Shaughnessy et al.,[19] using both particles and gas-phase compounds as challenge materials. Of the latter, two were generated as part of the environmental tobacco smoke evaluation (nicotine and vinyl pyridine). The other two test gases were formaldehyde and nitrogen dioxide. The particle removal methods included filter media (both HEPA and electret), electrostatic precipitators, ionizers, and ozone generators. One of the devices combined both ionization and an electret filter, which were tested independently and in combination. All but one ionizer and one of the ozone generators also contained activated carbon. The formaldehyde (HCHO) and NO_2 results are summarized in Table I.

CADR values for nicotine removal ranged from "no effect" to 22 ft^3/min (37 m^3/hour) for one of the ozone generators. Although this ozone generator contained 450 g of carbon, some of the reduction in nicotine concentration was likely due to air chemistry, as the ozone generator without the carbon had a CADR for nicotine of 6 ft^3/min (11 m^3/hour). No secondary byproduct analyses were conducted as part of these tests; however, the production of gas- and particle-phase byproducts through the interaction of ozone with gas-phase compounds has been observed.[36] Vinyl pyridine measurements were conducted in only a few tests, and the resulting CADR values ranged from 6 to 55 ft^3/min (10 to 94 m^3/hour).

Chen et al.[25] evaluated 15 air cleaners using a mixture of representative VOCs. The air cleaners covered a wide range of technologies, including both portable stand-alone and in-duct devices. The air cleaning methods included use of sorption (activated carbon, carbon-zeolite mixtures impregnated with KI, and carbon and activated alumina impregnated with $KMnO_4$); ultraviolet-photocatalytic oxidation (UV-PCO); ozone oxidation; air ionization; and a "soil-botanical" filter. Most of the testing was done using a mixture of 16 VOCs covering six categories of chemicals, ranging from HCHO, with a high vapor pressure and low boiling point, to n-dodecane with a low vapor pressure and high boiling point. For three air cleaners using air ionization or ozone, the terpene d-limonene was added to the VOC mixture. None of these air cleaners produced significant removal of the challenge VOCs, except for the d-limonene, whose reactions with ozone have been described elsewhere.[36] Two of the commercially available UV-PCO devices did not perform well against the challenge VOC mixture; neither produced significant reductions in VOC concentrations. When the activated carbon was added to one of these devices, the combined unit worked very well, which was apparently due to sorption on the carbon.

Chen et al.[25] observed variations in the CADR with time over their 12-hour test period, with some sorption-based cleaners showing a decrease in CADR with time. In contrast, one of the UV-PCO devices showed an increased CADR with time, potentially due to competition for adsorption sites among the constituents of the challenge mixture. As a result, a 12-hour average CADR was computed; the results from these tests are summarized in Table I for selected VOC.

TABLE II. Particle Removal Effectiveness for Different Room Sizes and Air Cleaner CADR Values

Room Dimension (= area; volume, where height = 8 ft)	CADR (ft^3/min)	Effectiveness (%)[A] Small-Size Particles $\lambda_{dep} = 0.05$ hour^{-1}	Medium-Size Particles $\lambda_{dep} = 1$ hour^{-1}	Large-Size Particles $\lambda_{dep} = 10$ hour^{-1}
5 × 6 (= 30 ft^2; = 240 ft^3)	10	70	56	19
	40	90	83	48
	80	95	91	65
	150	97	95	77
	300	99	97	87
9 × 12 (= 108 ft^2; = 864 ft^3)	40	73	58	20
	80	84	74	34
	150	91	84	49
	300	95	91	65
	350	96	92	69
	450	97	94	74
12 × 18 (= 216 ft^2; = 1728 ft^3)	80	73	58	20
	150	83	72	32
	300	91	84	49
	350	92	86	52
	450	94	89	59
18 × 24 (= 432 ft^2; = 3456 ft^3)	150	71	57	19
	300	83	72	32
	350	85	75	36
	450	88	80	42
20 × 30 (= 600 ft^2; = 4800 ft^3)	300	78	65	25
	350	81	69	28
	450	84	74	34

Note: Values based on assumed ventilation rate of 1 hour^{-1}.
[A]Classification of particles based on approximate size = small: 0.1–0.8 micron; medium: 1–4 microns; large: 6–20 microns (see Figure 5).

A wide variation in the performance of carbon-based sorption devices has been observed in these tests, due in part to the variability in the quantity and physical arrangement of the activated carbon. It has also been noted that the vapor pressure is a key variable.[(25)] Both of these issues, along with the related issue of carbon bed depth (or, alternatively, the bed contact time) have been identified by the military in preparing filters for nuclear, biological, or chemical protection. For physical sorption using carbon, the vapor pressure should be less than 10 mmHg at the filter bed temperature. For gases with higher vapor pressures, reactions with impregnants become important removal mechanisms.[(37)]

DISCUSSION

Our analysis indicates that many of the particle air cleaners tested by AHAM[(28)] meet the 80% effectiveness criterion for small (e.g., ETS) particles when applied to the appropriate room size (Eq. 2 and Figure 6). On the other hand, meeting this criterion for larger particle sizes (e.g., particles with diameters 2 μm and greater) is more difficult even though the AHAM testing procedure includes both dust and pollen as test aerosols. In the case of filter-based air cleaners, filtration efficiency should improve in most cases as the particle size increases from submicron to supermicron particle diameters.[(38)] However, particle deposition losses also increase rapidly with increasing particle size, thus increasing the CADR needed to maintain the criterion of 80% reduction in steady airborne concentrations based on air cleaner performance alone.

The relationship among the three key elements affecting air cleaner efficacy—room size, CADR, and particle-size category—is presented in Figure 6 for specific air cleaner effectiveness categories. In Table II, the air cleaning effectiveness as a function of these parameters is displayed. The values in the table are based on Eq. 11. As noted earlier, for a given CADR, the effectiveness is strongly dependent on the particle-size category. For example, for a floor dimension of 5 × 6 ft, an air cleaner with a CADR of 40 ft^3/min will have a smoke removal effectiveness of 90%, but for pollen (large-size particles) the effectiveness is only 48%. Similarly, for the largest room size the air cleaner with the highest CADR rating has a smoke removal effectiveness of 74% and a pollen removal effectiveness of 34%. Recall from Figure 2, the CADR ratios for the air cleaners tested by AHAM are strongly clustered around 1.0, so for most air cleaners, their performance for dust or pollen is very similar to that for ETS.

Overall, the results in Table II underscore the need to consider which particle-size category is of greatest interest. For homes where ETS is the main concern, air cleaning effectiveness of 80% or greater can be achieved with moderate to large CADR ratings. On the other hand, for pollen control, only the combination of small room size and large CADR ratings will yield particle removal effectiveness of 80% or greater. For typical room sizes greater than 200 ft^2, removal effectiveness of 80% (for large-size particles, for example, pollen, dust mite, and cockroach allergen) cannot be feasibly achieved by air cleaners currently on the market due to the very high CADR values required to meet this performance goal. This may account for the finding, stated in the *Clearing the Air* report,[39] that there is limited evidence indicating that particle air cleaning is associated with a reduction in the exacerbation of asthma symptoms. The report goes on to state that "theoretical and empirical data suggest that air cleaners are most likely to be effective in reducing indoor concentrations of particles smaller than approximately 2 microns. However, much of the airborne allergen appears to be within larger particles."[39, pp. 384–385] This again, is consistent with our statements formulated above.

When considering the effectiveness of air cleaning for gas-phase contaminants, it is first apparent from Table I that many of the devices evaluated in the published literature have, at best, marginal CADR values (i.e., CADR < ca. 80 ft^3/min, using the values in Table II for a moderate size room with small losses to surfaces within the room). None of the devices examined by Daisey and Hodgson[16] approached this value, and only two devices examined by Shaughnessy et al.[19] exceeded this value for NO_2 removal. In this latter case, these were cleaners with the largest amount of carbon in the adsorption bed. The extensive comparisons made by Chen et al.[25] to various challenge gases yielded a large number of CADR values below 80 ft^3/min. Three carbon sorption based cleaners had CADR values above this number for a number of compounds. Of these, the best performer was the air cleaner containing both UV-PCO and carbon filtration, with CADR values above 350 ft^3/min. The testing showed the UV-PCO by itself was ineffective (for this air cleaner) and the authors attribute the good air cleaning performance to the ~9 cm thick carbon bed.

A second important consideration is how well the air cleaners perform over time as the filter bed loads or, as was observed with the UV-PCO device, the apparent presence of competing chemical compounds. These issues, along with the problem of production of reaction byproducts, make evaluation of gas-phase air cleaning complicated. Although, as suggested by Chen et al.,[25] the use of vapor pressure to aggregate some of the test chemicals could simplify some of the sorption-based air cleaner testing, experience with other technologies, such as UV-PCO, is still very limited.

In the case of the carbon-based devices examined in these recent papers, most of the air cleaners tested appear to have been designed primarily to address particle removal. It is possible that portable or in-duct air cleaners designed specifically to address gas-phase compounds using sorption methods will show greater and more consistent removal results.

Finally, it is important to remember that much of this discussion has used effectiveness as an important consideration. Recall (Eq. 7) that this is a relative measure of air cleaner efficacy. In some situations an 80% reduction, for example, in particle concentrations may not be sufficient to achieve an absolute concentration (and hence exposure) goal or requirement. Source control is and will always be the preferred approach to reduction of contaminants within an indoor setting, whereas air cleaning is representative of a supplemental means of managing airborne pollutants.

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