Stand Alone Air Cleaners: Evaluation and Implications

Matthew Ward, Jeffrey A. Siegel, Richard L. Corsi
Center for Energy & Environmental Resources, The University of Texas at Austin, 10100 Burnet Road (R7100), Austin, Texas 78758

ABSTRACT

Stand alone (portable) air cleaners may be an efficient means for rapid removal of indoor fine particles, with potential use for shelter-in-place strategies following acts of bio-terrorism. In this study, a screening model was developed to ascertain the potential significance of size-resolved particle removal using portable air cleaners relative to filtration in HVAC systems, deposition to indoor surfaces, and air exchange. The air exchange rate, volumetric flow rate through the HVAC system, and size-resolved particle removal efficiency in the HVAC filter were varied. The effectiveness of portable air cleaners depends on size specific clean air delivery rates CADR. Since these values were not readily available in the published literature, we used experiments to determine ranges of CADR based on three air cleaners that had been in use in residential homes. Experiments were completed in a well-mixed 11-m^3 stainless-steel chamber. Incense sticks were burned for five minutes during each experiment, resulting in a poly-disperse aerosol with a wide range of fine particle diameters. Particle number concentrations were measured for seven ranges of particle diameter consistent with those expected for biological warfare agents. The effects of chamber air exchange, deposition, and coagulation were separated from filtration by analysis of dynamic mass balances and decay curves for experiments that included and excluded air cleaners. The CADR for the three air cleaners ranged from 221 to 306 m^3/hr in the diameter range of 0.1 - 0.2 μm, and from 272 to 363 m^3/hr in the diameter range of 1.0 - 2.0 μm. Using these values and the screening model it was determined that 1 to 3 portable air cleaners can be effective for shelter in place following bio-aerosol releases, with maximum reductions in particle concentrations as high as 90% relative to conditions in which an air cleaner is not employed. The effectiveness of air cleaners for shelter in place was predicted to decrease with increasing particle size, due to increasing competition by particle deposition with indoor surfaces and removal to HVAC filters.

INTRODUCTION

Growing public concerns regarding acts of terrorism has led to actions ranging from government advice to reduce residential air exchange rates through selective use of duct tape, to subsequent public demands for tape products and protective breathing devices. There is clearly a need for an improved understanding of potential human exposure to chemical and biological warfare agents following a terrorist attack, as well as rapid-response shelter-in-place (SIP) measures that the public can take to minimize their exposure to such agents.

Stand alone (portable) air cleaners containing High Efficiency Particle Arrestor (HEPA) filters may be effective at rapidly removing fine biological particles from residential indoor air following an act or bio-terrorism, and thus serve as a tool for SIP strategies. Numerous researchers have studied the effectiveness of portable air filters for the removal of particles from residential indoor air.[1-6] However, past studies have often focused on reductions in large particles associated with pet allergens, pollen, and dust mites.[1,2,4,6] Furthermore, many of the studies related to allergens are based on implicit measures of filter effectiveness gleaned from surveys or health responses, as opposed to direct measurement of particle removal efficiency.[5] Those for which changes in particle concentration before and after employment of portable air cleaners are measured generally consider only total particle number or mass concentration, without size resolution.[1,2,4] Nevertheless, the effectiveness of portable air cleaners for reductions in indoor particle and allergen levels have been noted to be significant. Mean particle levels associated with dust mites were reduced by approximately 70% following the employment of air cleaners containing HEPA filters in nine homes.[1] In a separate study of nine homes with dogs, commercial air cleaners with HEPA filters were able to reduce airborne dog allergen, *Can f 1*, by upwards of 90%.[4] By several metrics (questionnaire responses, emergency room visits, workdays missed by parents, expenditures on allergy medications, etc.), the use of air cleaners in the bedrooms of 90 children with perennial allergic rhinitis were effective.

Cheng *et al.*[2] studied the effectiveness of a portable air cleaner containing a HEPA filter on the removal of pollen and fungal spores in a single-family home with different ventilation rates within the rooms where the air cleaners were located. At low air exchange rates (< 0.2/hr) the air cleaner was observed to have a marked effect on pollen and fungal spore concentrations, with a rapid decrease (within one hour) to less than 10% of initial values. The overall effectiveness of the air cleaner decreased as room ventilation rate increased.

Several researchers have used more controlled laboratory studies to better understand the effectiveness of portable air cleaners for different types of particles.[7-9] Shaughnessy *et al.*[9] used a clean air test chamber to test various types of portable air cleaners and observed that HEPA based systems demonstrate higher efficiencies than electret filter systems, ionizers and ozone generators for particle removal. Experiments were completed using dust particles, particles associated with environmental tobacco smoke, fungal spores and pollen. Foarde *et al.*[8] described a test method to determine the clean air delivery rate (CADR) for a portable air cleaner challenged with a microbial aerosol. The method was a modification of the Association of Home Appliance Manufacturers (AHAM) Standard AC-1 "*Standard Method for Measuring Performance of Portable Household Electric Cord-Connected Air Cleaners*", which focuses on determination of CADR for three types of particle classes - smoke, dust and pollen. These protocols rely on chamber testing and particle decay in the absence and presence of an air cleaner. Foarde *et al.*[7] also developed a method to measure single-pass microbial particle reduction using a portable air cleaner. The method was tested on two bacteria, two fungi, and a virus which collectively encompasses the range of particle sizes associated with biological warfare agents.

In this study, we developed a simplified (screening) model to assess the potential effectiveness of portable air cleaners as a rapid response SIP tool. The competition between portable air cleaners, building air exchange rate, removal by filtration in HVAC systems, and particle deposition was explored. The effectiveness of portable air cleaners was characterized by the ratio of indoor particle counts in different size ranges for cases involving 0 to 3 air cleaners. The assessment was facilitated through experimental determination of size-resolved clean air delivery rates (CADR) for three common residential air cleaners, each containing HEPA filters. Descriptions of the model development, parameter estimation, experimental determination of CADR, and assessment results are presented herein.

MODEL DEVELOPMENT

A screening model based on steady-state conditions in a well-mixed residential dwelling was developed for this assessment. A description of resulting mathematical equations and parameter selection are described in this section.

Model Equations

A particle mass (or number) balance for a residential dwelling is presented in Equation 1. The term on the left-hand-side of Equation 1 represents the change in particle mass (or particle number) as a function of time. The first two terms on the right-hand-side (RHS) of Equation 1 represent particle penetration into the home via infiltration from the outdoor atmosphere and particle exhaust from indoor to outdoor air, respectively. The third term on the RHS of Equation 1 represents particle removal by filtration in an HVAC system. The fourth term represents particle removal by collective deposition mechanisms on indoor surfaces. The last term on the RHS represents particle removal by a portable air cleaner, i.e., the focus of this study. Note that Equation 1 must be applied to each particle size in the indoor environment, since several of the parameters are dependent on particle size.

It is important to recognize the simplifying assumptions associated with Equation 1. These include the treatment of the indoor environment as a well-mixed reactor, treatment of all removal in the HVAC system via filtration only (no model representation of removal via deposition to components of the HVAC system such as cooling coils, fan blades, and duct walls), and no consideration of particle interaction with one another, i.e., coagulation effects that tend to shift particle size distributions.

Equation 1. Equation for particle concentration in a well-mixed house.

$$V\frac{dC}{dt} = pQC_o - QC - \eta_f Q_f C - v_d AC - \eta_{pf} Q_{pf} C$$

where:

V = volume of house (m^3)
C = indoor particle mass or number concentration (mg/m^3 or $\#/m^3$)
C_o = outdoor particle mass or number concentration (mg/m^3 or $\#/m^3$)
t = time (hr)
p = fractional particle penetration efficiency (-)
Q = volumetric infiltration rate into and out of house (m^3/hr)
η_f = fractional removal efficiency associated with HVAC filter (varies with particle size) (-)

Q_f = volumetric flow rate of air through HVAC system (m^3/hr)
v_d = surface-integrated particle deposition velocity (varies with particle size) (m/hr)
A = collective area of all indoor surfaces (m^2)
η_{pf} = fractional removal efficiency for portable air cleaner (varies with particle size) (-)
Q_{pf} = volumetric flow rate of air through portable air cleaner (m^3/hr)

The clean air delivery rate, CADR, is defined as the product of η_{pf} and Q_{pf}. CADR is a function of particle size.

By dividing through by volume and factoring all terms that include indoor concentration allows Equation 1 to be re-written as Equation 2.

Equation 2. Simplification of Equation 1 with lumped parameter α.

$$\frac{dC}{dt} = p\lambda C_o - \alpha C$$

where:

λ = rate of air exchange between the indoor and outdoor atmospheres (1/hr)
$$\alpha = \lambda + \eta_f \frac{Q_f}{V} + v_d \frac{A}{V} + \eta_{pf} \frac{Q_{pf}}{V}$$

All other variables are as described for Equation 1.

Separation and integration of Equation 2 with the simplifying assumption of a constant outdoor particle concentration leads to a time-dependent solution for indoor particle concentration as described by Equation 3.

Equation 3. Solution to Equation 2 for time-dependent indoor particle concentration.

$$\frac{C(t)}{C_o} = \frac{p\lambda}{\alpha}\left(1 - e^{-\alpha t}\right)$$

where:

C(t) = indoor particle mass or number concentration at time t (mg/m^3 or #/m^3)

All other variables are as described for Equations 1 and 2.

As time becomes large (usually assumed as > 3/α) Equation 3 approaches the steady-state solution for time equals infinity as described by Equation 4. This solution is clearly inappropriate for a dynamic plume of particles associated with the release of a biological warfare agent, e.g., for which C_o would likely vary considerably with time. However, it is appropriate for purposes of comparing the *relative* effectiveness of portable air cleaners in comparison to other particle removal mechanisms in a home.

Equation 4. Steady-state solution to Equation 3.

$$\frac{C(\infty)}{Co} = \frac{p\lambda}{\alpha} = \frac{p\lambda}{\lambda + \eta_f \frac{Q_f}{V} + v_d \frac{A}{V} + \eta_{pf} \frac{Q_{pf}}{V}}$$

where:

$C(\infty)$ = indoor particle mass or number concentration at steady-state (mg/m^3 or #/m^3)

All other variables are as described for Equations 1 and 2.

For purposes of comparing the relative effectiveness of portable air cleaners as a shelter-in-place tool, we consider a parameter Γ as defined by Equation 5. This parameter was used to determine the relative effectiveness of portable air cleaners for various particle sizes relative to scenarios in which such air cleaners are not employed. As is depicted in Equation 5, the relative effectiveness of portable air cleaners as a shelter-in-place tool depend not only parameters that define the air cleaner itself, but also the magnitude of air exchange rate, removal by filtration in an HVAC system, and particle deposition. All but the air exchange rate in the denominator of Equation 5 depend on particle diameter and, as such, the relative effectiveness (Γ) of portable air cleaners as a shelter-in-place tool should also depend on particle size. For a given particle size, Γ varies from a value of 1 for a completely ineffective air cleaner, and approaches 0 for an ideal air cleaner.

Equation 5. Parameter defining effectiveness of portable air cleaner.

$$\Gamma = \frac{C(\infty)_{pf}}{C(\infty)_{nopf}} = \frac{\left\{\lambda + \eta_f \frac{Q_f}{V} + v_d \frac{A}{V}\right\}}{\left\{\lambda + \eta_f \frac{Q_f}{V} + v_d \frac{A}{V} + \eta_{pf} \frac{Q_{pf}}{V}\right\}}$$

where:

$C(\infty)_{pf}$ = indoor particle concentration at steady-state with air cleaner(s) (mg/m^3 or #/m^3)
$C(\infty)_{nopf}$ = indoor particle concentration at steady-state without air cleaner(s) (mg/m^3 or #/m^3)

Equations 4 and 5 comprise the screening model and metric, respectively, used for this assessment of portable air cleaners as possible tools to be employed for residential shelter-in-place strategies. Key parameters that were used in the assessment are described in the following sub-section.

Parameter Selection

In order to determine the model parameters for Equations 4 and 5, we used experimental data to determine $\eta_{pf}Q_{pf}$ and values from the literature to determine all of the other parameters. The experiments are described in the next section. We are interested in a particle size range from 0.1 to 2 µm which is the range of interest for many biological agents of terror. These particles are also likely to be the most persistent in indoor environments because they have very long characteristic removal times by gravitational settling, and they are too large to be substantially removed by Brownian diffusion.

The volume of a typical home was selected by considering the typical home area from the 2001 American Housing Survey[10] of 157 m^2 and multiplying it by an assumed ceiling height of 2.4 m, for a volume of 377 m^3.

Based on the work of Liu and Nazaroff[11], the penetration factor (p) was assumed to be unity for all particle sizes of interest.

The air exchange rate (λ) was determined from a study of 2,844 American homes by Murray and Burmaster[12]. We chose the median value of 0.5/hr for our Base Case and also considered the 10% and 90% values of 0.2/hr and 1.3/hr for bounds on this parameter.

The term $v_d A/V$ is often referred to as the deposition loss rate. We adopted size-dependent deposition loss rates as summarized by Riley *et al.*[13], based on their review of the published literature.

The HVAC filter efficiency (η_f) was determined for a typical residential furnace filter from experiments by Hanley *et al.*[14]. We also considered the case of a new electret filter [15].

The flow through the air handler (Q_f) was determined by assuming a 3.5 ton air conditioner and considering measured results to determine the recommended HVAC flow of 2,040 m^3/hr. We considered two cases of HVAC control: in the first case the HVAC blower runs continuously (typically done for ventilation), in the second case, the blower cycles on and off and runs for an average of 10 minutes every hour.

For the purposes of comparison, we define a base case combination of the four varied parameters:

- Air exchange rate, $\lambda = 0.5$/hr
- HVAC filter efficiency, η_f as a function of particle diameter from standard (i.e. low-efficiency) furnace filter from Hanley *et al.*[14]
- HVAC flow rate, $Q_f = 340$/hr (i.e. cycling 10 minutes every hour)
- Single portable air cleaner with average CADR as a function of particle size from experiments described below.

EXPERIMENTAL DETERMINATION OF CADR

Several researchers have quantified the effectiveness of portable air cleaners for removing respirable particles indoors. For example, Offerman *et al.*[16] tested the effectiveness of portable air cleaners for removing particulate matter associated with cigarette smoke. Their experiments involved a 35 m^3 indoor air quality research house to observe indoor particle concentration decay with air cleaners in operation. The HEPA device used in their experiments had a CADR of 306 ± 14 m^3/h for particles with a mass median diameter of 0.45 μm. Niu *et al.*[17] calculated CADRs for 27 different portable air cleaners based on measured PM_{10} decay of house dust inside an effectively air tight 6.4 m^3 stainless steel chamber. Their best-performing device had a CADR of 235 ± 24 m^3/h and used a HEPA filter. Both of these studies controlled for particle removal mechanisms not associated with the cleaning device, including deposition and infiltration.

There is limited information in the published literature regarding size-resolved CADRs for portable air cleaners for particle sizes in the ranges of interest. Therefore, it was necessary to conduct experiments to determine size-resolved CADR for use in the model developed in this paper.

To determine CADR, factors influencing particle concentration in a large stainless steel test chamber containing one of several operating air cleaners were identified and categorized into factors associated with the specific air-cleaner design, and factors associated with the test space. By comparing temporal decays in particle concentration with and without an air cleaner operating, factors associated only with the air cleaners were isolated from other factors and combined into a single parameter (CADR) for each of seven different particle size ranges.

Air cleaner design factors were identified as follows: air cleaner flow rate (Q_{pf}, m^3/hr), the volumetric flow rate of air through the air cleaner; air cleaner filter efficiency (η_{pf}), the fraction of particles removed from air flowing through the air cleaner; short circuit, the ratio of particle concentration entering the air cleaner to ambient particle concentration; and filter bypass, the portion of air cleaner flow passing unfiltered through cracks between the filter and housing. In an ideal well-mixed reactor, short circuit would equal unity. Therefore, we have neglected short circuit. In good quality air cleaners, the filter is clamped into the housing with an airtight seal, and bypass is negligible. In this study, all of the tested air cleaners had gasketed filters, thus we neglected bypass.

Factors associated with the test chamber were identified as the following: chamber volume (V, m^3); chamber infiltration rate (Q, m^3/hr), the volumetric rate of air infiltration into and out of the test chamber; penetration efficiency (p), the portion of particles not arrested in the process of infiltrating the test chamber; and deposition/coagulation (K), the loss of particles due to collisions with interior surfaces and other particles. Whereas deposition is usually modeled as an area reaction and coagulation as a volume reaction, we represent deposition plus coagulation as a single first order volume reaction, $-KVC$ as in Offerman *et al.*[18]. This simplification is justified because, in a well-mixed chamber, deposition/coagulation with and without an air cleaner operating can be assumed equal.

Change in number concentration with time can be described by a particle number balance on the test chamber as shown in Equation 6 in which each factor influencing concentration is represented.

Equation 6. Equation for particle number concentration in the test chamber.

$$V\frac{dC}{dt} = pQC_o - QC - KVC - \eta_{pf}Q_{pf}C$$

where:

C = indoor particle mass or number concentration (#/m^3)
C_o = outdoor particle mass or number concentration (#/m^3)
K = particle deposition/coagulation constant (1/hr)
t = time (hr)

All other variables are as described previously.

Concentrations were orders of magnitude larger inside the test chamber than out during the experiments. Therefore, C_o was assumed to be zero. By dividing Equation 6 by V and combining like terms, Equation 6 can be written as Equation 7.

Equation 7. Simplification of Equation 6.

$$\frac{dC}{dt} = -\gamma C$$

where:

$\gamma = \lambda + K + \eta_{pf}Q_{pf} / V$
λ = Air exchange rate (1/hr)

Separation and integration of Equation 7 leads to a time-dependent solution for test chamber particle concentration as described by Equation 8.

Equation 8. Solution to Equation 7 for time-dependent test chamber particle concentration.

$$C(t) = C(0)\left(e^{-\gamma t}\right) \rightarrow \ln\left[\frac{C(t)}{C(0)}\right] = -\gamma t$$

Thus, γ is the slope of the natural logarithm of the particle concentration curve normalized by an initial concentration, $C(0)$. Obtaining γ from experimental data, CADR can be calculated by Equation 9.

Equation 9. Air cleaner CADR calculation.

$$CADR = V(\gamma_{ac} - \gamma_{nac}) = V\left[(\lambda + K + \eta_{pf}\frac{Q_{pf}}{V}) - (\lambda + K + 0) \right] = \eta_{pf} Q_{pf}$$

Where:

γ_{ac} = -ln[$C(t)$ / $C(0)$] / t with an air cleaner operating
γ_{nac} = -ln[$C(t)$ / $C(0)$] / t with no air cleaner operating.

Chamber Experiments

Three portable air cleaners each equipped with HEPA filters were evaluated to determine their CADRs corresponding to seven particle diameter ranges between 0.1 to 2.0 µm. The air cleaners were selected to represent typical air cleaners costing between $200 and $400 that are available to consumers in most American cities. Filters of intermediate age (neither new nor requiring replacement) were selected for use in the experiments. Each air cleaner underwent testing in an 11 m^3 in stainless steel chamber in which two fans were placed to produce well-mixed conditions. The test chamber was equipped with a continuously running exhaust fan whereby a steady air exchange rate of 2.86 h^{-1} (as determined by a tracer gas test) was maintained throughout the experiment. This setup caused air to infiltrate into the chamber from the climate-controlled lab space via openings in the chamber walls and exhausted to the outdoors.

Temperature and relative humidity were monitored during the experiment and found to be approximately constant for the duration of the experiment, with values of 24-25 ^{o}C and 50%, respectively.

To produce a poly-disperse aerosol of fine particles, two sticks of incense were burned inside the chamber for five minutes then extinguished. Next, an air cleaner was activated. For the following 45 minutes particle counts were monitored every minute in air samples collected from a point six feet above the chamber floor. A Lasair optical particle counter was employed for determination of particle number concentrations. This procedure was repeated four times, once with no air cleaner operating and once with each of the three air cleaners operating.
Prior to the experiment the sampling train was calibrated to allow for particle deposition to the walls of the collection tube.

The particle counts for seven size ranges were recorded: 0.1-0.2, 0.2-0.3, 0.3-0.4, 0.4-0.5, 0.5-0.7, 0.7-1.0, and 1.0-2.0 µm. Approximately 40-50 sets of data points were collected for each air cleaner. Raw number counts were each divided by the volume of air taken in each sample to produce particle concentration in units of number per volume.

Analysis of Experimental Data

Upon lighting incense, particle concentrations in every size range reached their maximum levels rapidly. Thereafter, particle concentration decay occurred exponentially both with no air cleaner and with each air cleaner operating. Figure 1 shows the particle count in each size range for the duration of the experiment:

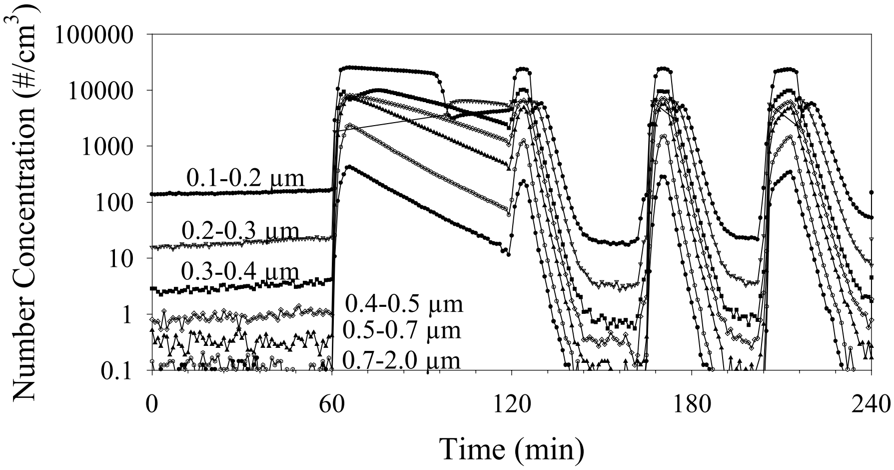


Figure 1: Particle number concentration as a function of time for seven size bins. Incense is burned for five minutes at t = 60, 120, 165, 205 minutes followed by air cleaner activation.

Particle number per cubic centimeter is plotted on a logarithmic scale with time. Since particle concentration decays exponentially the plots appear linear on the log scale. The first part of the scale shows ambient particle concentration for each size range followed by a sudden increase as the incense is burned. Then gradual decay occurs resulting from natural particle transport and air exchange. Next, a sharp increase followed by steep exponential decay resulting from a combination of particle transport, air exchange, and air cleaner removal occurs three times in succession (once for each air cleaner trial).

The 0.1-0.2 µm size range in Figure 1 had a sudden drop in concentration in the middle of the natural decay portion of the curve followed by an increase in concentration. This anomaly probably resulted from a momentary disturbance of the optical particle counter. Enough good data were recorded before the optical particle counter was disturbed that CADRs could be calculated in the smallest size range. Also, in the 0.2-0.3 µm range the Lasair recorded small negative concentrations until concentrations dropped below about 8,000/cm^3 at which point it began giving normal concentration readings. Again, enough good data points were reported for reasonable results to be obtained for the 0.2-0.3 µm particles.

The next step in interpreting the results was to obtain γ using Equation 8. This was accomplished by plotting the negative natural logarithm of normalized concentration as a function of time. The slope of the resulting best-fit line is γ, which was used in Equation 9 to calculate CADR. In order to eliminate end disturbances, data points in the middle of each linear decay curve were used with the first data point in the series serving as C(0).

Finally, CADRs for each air cleaner in each size range were tabulated and an average CADR for each particle size rage was calculated. Results are presented in Table 1.

Table 1: CADRs for each air cleaner

Particle Diameter	**Air Cleaner CADR (m^3/hr)**			
(μm)	**AC1**	**AC2**	**AC3**	**Average**
0.1 - 0.2	306	286	221	271
0.2 - 0.3	341	321	258	307
0.3 - 0.4	347	331	261	313
0.4 - 0.5	354	336	264	318
0.5 - 0.7	358	349	267	325
0.7 - 1.0	361	365	271	332
1.0 - 2.0	363	361	272	332

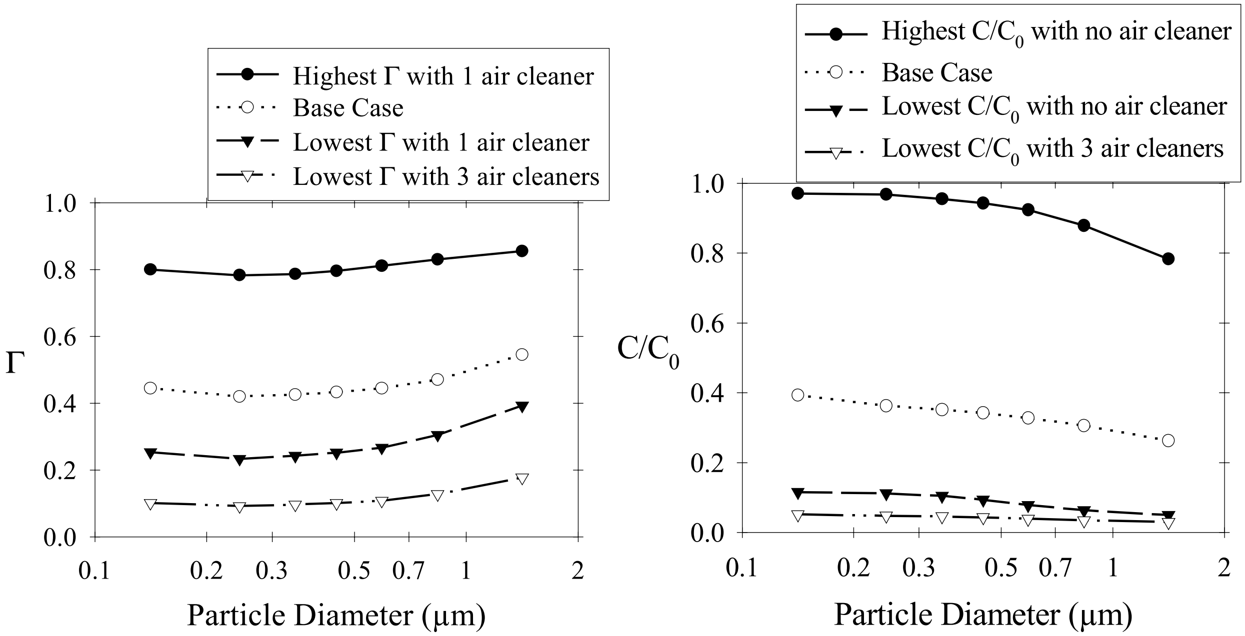
CADRs varied between 221 and 306 m^3/h for the smallest particle size range up to between 272 and 363 m^3/h for the largest particle size range. The average CADRs were used in our screening model.

RESULTS AND DISCUSSION

Every combination of the two HVAC filter efficiencies, three HVAC flow rates, and three air exchange rates was modeled for cases in which zero, one, two, and three air cleaners were activated. Relative air cleaner effectiveness (Γ) and relative indoor concentration (C/C_o) were plotted as functions of particle diameter for each case (variable combination). Fifteen cases of particular interest were selected for presentation and are shown in Figures 2 through 5. Each graph presents a group of related cases for comparison. The Base Case has been included in each graph to serve as a reference. Values of Γ and C/C_o should be interpreted as in the following examples: $\Gamma = 0.3$ means that the steady state indoor concentration is 30% of what it would be if no air cleaner was activated; and $C/C_o = 0.4$ means that the steady state indoor concentration is 40% of the outdoor concentration.

Figure 2a shows the boundary envelope for Γ. The curve labeled 'Lowest Γ with 3 air cleaners' represents the case where the air cleaner contribution to particle removal relative to other removal mechanisms is maximized. This case occurs when the air exchange rate is low and the HVAC system is not running. The upper limit of Γ corresponds to the case where no air cleaner is operating, the air exchange rate is high, and the HVAC system runs continuously with an electret filter. Since the upper limit of Γ equals unity, which is not useful information, we have substituted the curve labeled 'Highest Γ with 1 air cleaner' to represent the upper meaningful bound of Γ. To summarize Figure 2a, the lowest concentration possible with 3 air cleaners activated is about 10% of what it would be with no air cleaners, and the concentration with one air cleaner activated varies between about 25% and 80% of what it would be with no air cleaner. Also of note in Figure 2a is the decreasing relative air cleaner effectiveness (increasing Γ) as particle diameter increases. This trend indicates that air cleaner contribution to particle removal drops off for larger particles for which interior surface deposition and removal by filtration in the HVAC system each increase.

Figure 2b shows the relative indoor concentration envelope. The upper bound curve represents the worst-case scenario for a terrorist attack in which the HVAC system is switched off in a house with a high air exchange rate and no air cleaner. In this case the indoor concentration is almost the same as the outdoor concentration. The lower bound represents the best case where The HVAC system runs continuously with an electret filter in a house with a low air exchange rate and three portable air cleaners in operation. Under these circumstances the indoor concentration can be kept below around10% of the outdoor concentration. Of note in Figure 2b is that when the particle removal contribution of all parameters is maximized, there appears little difference between the cases where one and three air cleaners are activated. This indicates diminishing returns as the relative indoor concentration approaches zero. However, the small difference in the lower curves in Figure 2b still represents a 50% decrease in relative indoor particle number concentration.

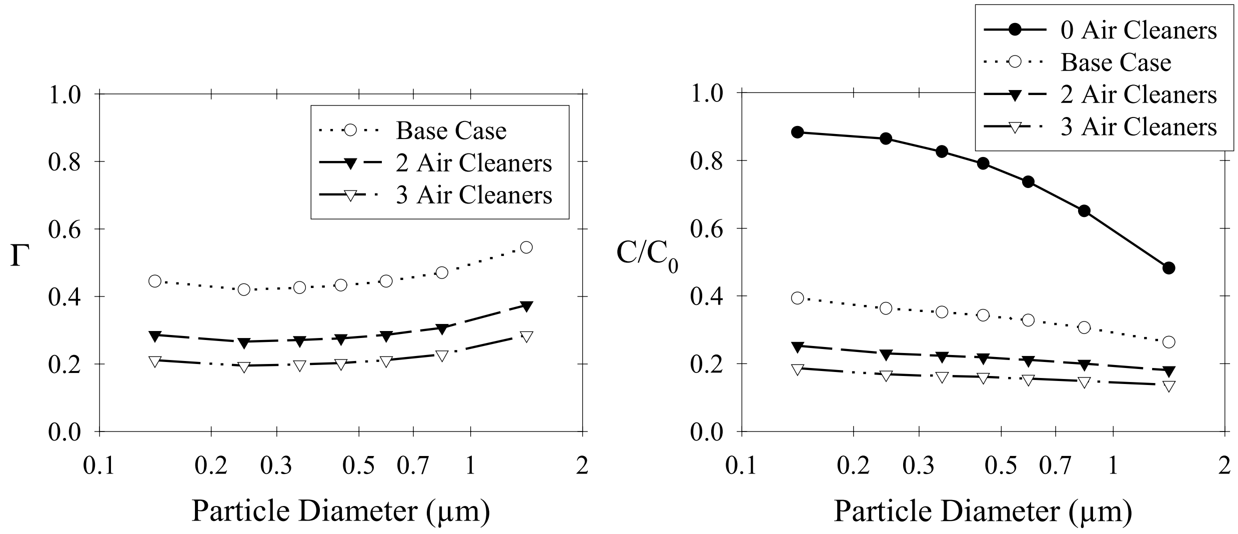


(a) **(b)**

Figure 2: Upper and lower bounds on Γ (a) and C/C_0 (b) for different numbers of air cleaners.

Each curve in Figures 3 through 5 differs from the Base Case as indicated by its legend label. This method of presentation visually isolates the effect of individual variables. Figures 3a and 3b show the Base Case modified by changing the number of air cleaners, Figures 4a and 4b show the Base Case modified by varying the air exchange rate, and Figures 5a and 5b show the Base Case modified by varying the HVAC parameters.

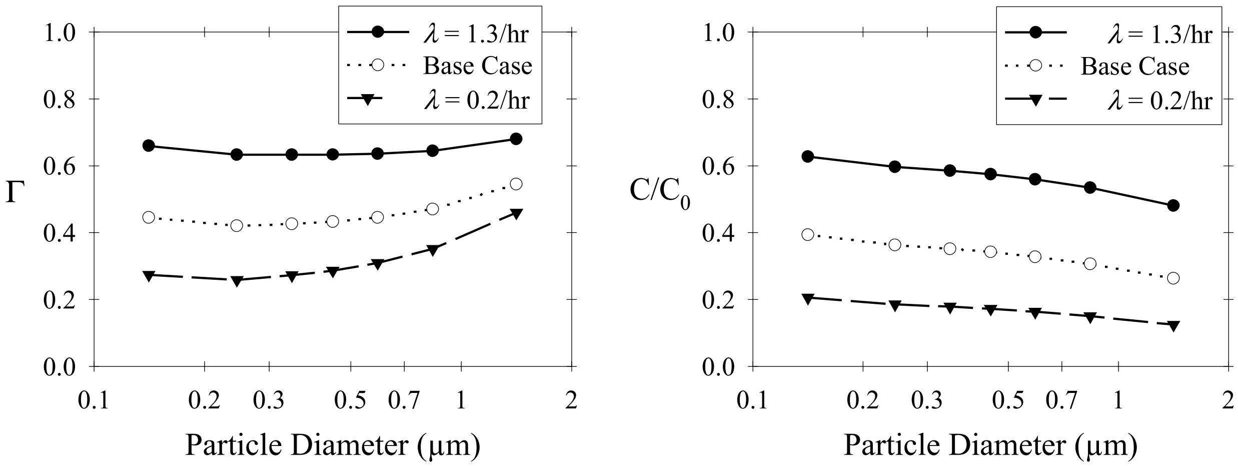
Figures 3a and 3b indicate a moderate effect from increasing the number of air cleaners from one to three. However, the effect of increasing the number of air cleaners from zero to one is substantial, especially for smaller particles. Figure 3b shows the diminishing returns of adding more air cleaners.



(a) **(b)**

Figure 3: Γ (a) and *C/C₀* (b) for different numbers of air cleaners.

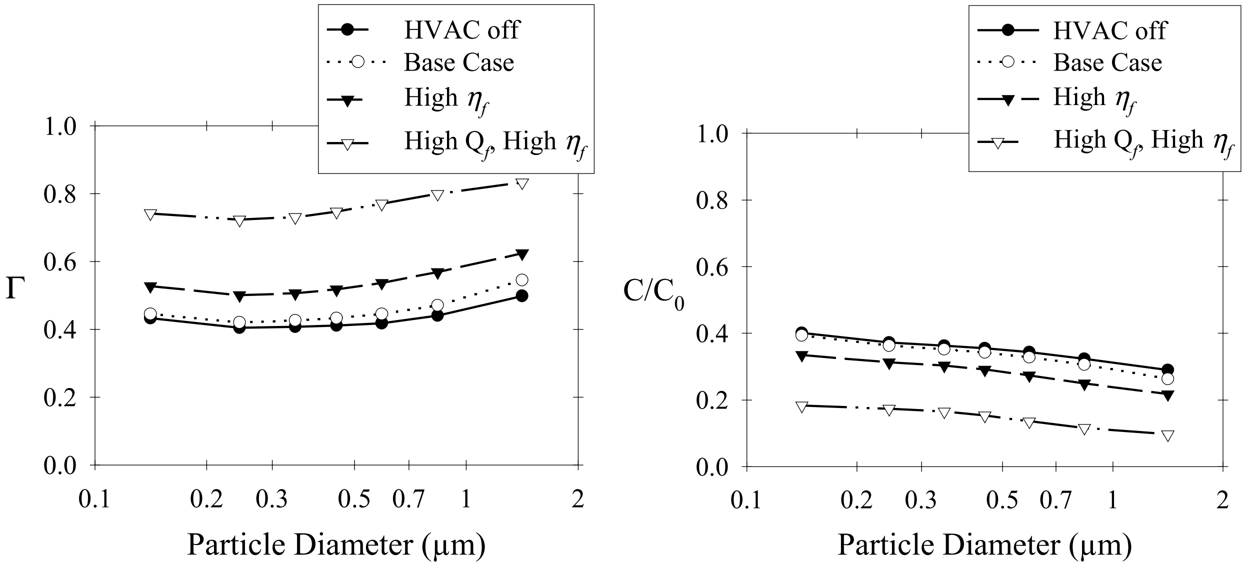
The curves in Figure 4a indicate a significant relative air cleaner effectiveness when the air exchange rate is low and a diminished but still substantial relative effectiveness when the air exchange rate is high. The results presented in Figure 4 demonstrate the tendency of outside air exchange to overwhelm the contribution to particle removal of air cleaners. The difference in Γ between low and high λ is very much dependent on particle size, but the difference in C/C_o between low and high λ is not. This observation can be explained by the fact that air cleaners have their greatest effect relative to other factors on particles around 0.25 μm and decrease in relative effectiveness as particle size increases. That trend doesn't appear in Figure 4b because C/C_o doesn't indicate the effectiveness of air cleaners relative to other variables.



(a) **(b)**

Figure 4: Γ (a) and C/C_0 (b) for different air exchange rates.

Figure 5 shows curves representing maximum and minimum HVAC contributions to particle removal. Electret filtration and continuous flow are combined to yield the maximum HVAC removal curves. Curves showing the Base Case with a high efficiency filter are included to show the relative contribution of filter efficiency to HVAC removal. Both graphs indicate the importance of HVAC filter efficiency. The similarity between the cases when the HVAC system is on and off can be explained by the fact that the Base Case HVAC filter efficiency is quite low (typical of residential furnace filters), which allows little HVAC removal even for continuous flow. It is important to keep in mind that this model considers only the contribution of the HVAC filter. A more rigorous treatment of the HVAC system would include parameters for deposition on other HVAC components.



(a) **(b)**

Figure 5: Γ (a) and C/C_0 (b) for different HVAC flow rates (Q_f) and HVAC filter efficiencies (η_f)

CONCLUSIONS

The following conclusions can be drawn from this screening study:

1. Portable air cleaners with HEPA filters can be effective for reducing levels of particles in the size range of 0.1 to 2 μm, and therefore may serve as important shelter-in-place tools for U.S. residences. Reductions of approximately 50% with a single air cleaner and more than 90% for three or more air cleaners are possible in typical U.S. residences.

2. The relative effectiveness of portable air cleaners with respect to reducing indoor particle counts is a function of particle diameter, and decreases as diameter increases above 0.25 μm.

3. High air exchange rates diminish the effectiveness of portable air cleaners for reducing fine particle concentrations.

4. High HVAC contributions to fine particle removal reduce the relative effectiveness of portable air cleaners.

The authors acknowledge that the results described herein are of a screening nature, and that additional work is needed to present a more realistic representation of certain model parameters and particle release scenarios. Specifically, the screening model presented in this paper does not include particle removal due to deposition on HVAC components other than the furnace filter. Furthermore, it would be useful to consider other outdoor release scenarios than steady-state, e.g., a bell-shaped concentration profile that might be more representative of a short-term release of a biological warfare agent.

Finally, the authors hope that the work presented in this paper will facilitate future studies related to the important topic of shelter-in-place strategies.

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REFERENCES

1. Antonicelli, L.; Bilo, M.B.; Pucci, S.; Schou, C.; Bonifazi, F. *Allergy*. **1991**, 46(8), 594-600.

2. Cheng, Y.S.; Lu, J.C.; Chen, T.R. *Aerosol Science and Technology*. **1998**, 29(2), 92-101.

3. Emmerich, S.J.; Nabinger, S.J. *HVAC&R Research*. **2001**, 7(3), 223-244.

4. Green, R.; Simpson, A; Custovic, A; Faragher, B.; Chapman, M.; Woodcock, A. *Allergy*. **1999**, 54(5), 484-488.

5. Huang, S.W. *Pediatric Asthma Allergy & Immunology*. **1993**, 7(2), 111-117.

6. Wood, R.A.; Flanagan, E.; VanNatta, M.; Chen, P.H.; Eggleston, P.A. *Journal of Allergy and Clinical Immunology*. **1997**, 99(1), 1584-1584.

7. Foarde, K.K.; Hanley, J.T.; Ensor, D.S.; Roessler, P. *Aerosol Science and Technology*. **1999**, 30(2), 223-234.

8. Foarde, K.K.; Myers, E.A.; Hanley, J.T.; Ensor, D.S.; Roessler, P.F. *Aerosol Science and Technology*. **1999**, 30(2), 235-245.

9. Shaughnessy, R.J.; Levetin, E.; Blocker, J.; Sublette, K.L. *Indoor Air*. **1994**, 4(3), 179-188.

10. *American Housing Survey 2001*, Washington, D.C.: U.S. Census Bureau, http://www.census.gov/hhes/www/ahs.html.

11. Liu, D.L.; Nazaroff, W.W. *Atmospheric Environment*. **2001**, 35(26), 4451-4462.

12. Murray, D.M.; Burmaster, D.E. *Risk Analysis*. **1995**, 15(4), 459-465.

13. Riley, W. J.; McKone, T. E.; Lai, A. C. K.; Nazaroff, W. W. *Environmental Science and Technology*. **2002**, 36, 200-207.

14. Hanley, J. T.; Ensor, D. S.; Smith, D. D.; Sparks, L. E. *Indoor Air*. **1994***,* 4(3), 169-178.

15. Hanley, J.T.; Ensor, D.S.; Foarde, K.K.; Sparks, L.E. *Proceedings of the 8th International Conference on Indoor Air Quality and Climate*. **1999**, Edinburgh, August 8 - 13, 4, 73-78.

16. Offermann, F.J.; Loiselle, S.A.; Sextro, R.G. *ASHRAE Journal*. **1992**, 34(7), 51-57.

17. Niu, J.; Tung, T.C.W.; and Chui, V.W.Y. *ASHRAE Transactions*. **1998**, 104(2), 1289-1296.

18. Offermann, F.J.; Sextro, R.G.; Fisk, W.J.; Grimsrud, D.T.; Nazaroff, W.W.; Nero, A.V.; Revzan, K.L.; and Yater, J.; *Atmospheric Environment*. **1985**, 19(11), 1761-1771.

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