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"The Effect of Portable HEPA Filtered Air Cleaning Devices Upon Residential Indoor Particulate And Allergen Concentrations."

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ABSTRACT

People who suffer from airborne respiratory allergies often advised to obtain and rely upon portable HEPA filtered air devices for relief. While this advice may work for some individuals, many allergic people do not experience relief or a lessening of symptoms. For allergic individuals for whom this mitigation strategy is not successful, the manufacturers' claims seem over stated. It is important for the manufacturers, allergists, indoor air quality professionals and allergic individuals to understand when air cleaners would be successful and the parameters that determine their effectiveness.

The ability of these devices to benefit allergic residential occupants depends upon the generation rate and particulate characteristics of the allergen, as well as the room ventilation. This paper reviews, airborne allergenic sources and presents a theoretical model for determining the efficacy of HEPA filtered air cleaning devices of various flow rates upon the equilibrium allergen concentration. The model demonstrates the importance of infiltration, settling rate, room dimensions and flow rate upon removal of particulate allergens. The model will assist in determining if a HEPA filtered air cleaning device will be successful in reducing airborne concentrations of specific particulate allergens and in selection of an appropriate size device for varying residential or indoor environments.

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INTRODUCTION

Inhalation of particulate indoor air contaminants can result in irritation, sensitization and chronic respiratory diseases. Portable High Efficiency Particulate Air Filtration devices are currently marketed to respond to occupant concern. These HEPA filtered air cleaning devices typically have flow rates of 60-350 cubic feet per minute and range in price from $75-$750. As of 1982, in the United States, $150 million was spent on room air cleaning devices.(Nelson, 1988) There is a wide range of HEPA air filtration devices available and an even greater diversity of indoor spaces in which they must function. (Lajeikova, 1994). There is a need to be able to select an appropriately sized unit to significantly reduce the airborne contaminants of specific interest. This paper reviews major indoor particulate contaminants and provides a mathematical model to predict the efficacy of portable HEPA filtered air cleaning devices.

Nelson and associates have reviewed the residential air cleaning devices. In addition to those containing High Efficiency Particulate Filters, they evaluate the advantages and disadvantages of mechanical filtration, electrostatic filtration, negative ion generation, charged media, charcoal and chemical absorbents and air conditioning. (Nelson, 1988). They find that the reduction of pollen in indoor environments relates to the small amount of outside supply air. This conclusion is in agreement with studies conducted by Solomon, Burge and Boise (1980), Trasoff (1936) and Hirsch (1978) who found a statistically significant reduction of spore counts in air conditioned homes. The effectiveness of central filtration in reducing particle concentrations has long been recognized. (Cohen, 1927, Lefcoe, 1971). Lefcoe's study also is significant in that it notes the three hour transient 100 fold elevation in environmental tobacco smoke generated by cigar combustion in one residence. Criep and Green (1936) also cite early studies on air conditioning while they present an evaluation of electrostatic air cleaning device on 53 patients with pollen asthma. Decker and colleagues (1963) presented an introduction into the mechanisms of particle impact on filtration media of both HEPA and Ultra High Efficiency Particulate (ULPA) filters. McNall (1975) has provided an engineering evaluation of filter and electrostatic air cleaning devices to predict steady state indoor contaminant levels. Using tobacco smoke as a contaminant he has evaluated the model on a three bedroom house and concludes that "It is not often economically feasible to use filtration and dilution technology to control contaminant

levels much below 20%-25% of the levels that would occur in most interior spaces under usual installation of heating, air conditioning and ventilation systems."

Kranz (1963) presents a general treatment of air cleaning devices as they pertain to pollen allergens and stresses the importance of controlling infiltration. He provides nomograms for the quantity of flow in air cleaning devices as a function of particle size, the effects of outdoor pollen levels and house conditions. Whitby and colleagues have presented a dynamic method for evaluating room sized air purifiers that emphasize the importance of the product of the efficiency flow volume as a key index of performance. (Whitby, 1983).

Many studies on the effects of HEPA air cleaning devices have sought to ascertain their clinical effectiveness among atopic subjects by scoring subjective symptoms or the use of medications. Often these studies provide inadequate information regarding the room size, ventilation, air conditioning, air exchange rate or fenestration to allow the results to be extended to new applications. Crossover study designs conducted during the ragweed pollen season may not have equal outdoor concentrations between the first and second phase of the study.

Luczynska and co-workers suggest that to be effective in reducing Fel d I allergen, a portable HEPA filtered air cleaning device must have an air exchange rate in excess of 20 air changes per hour. Furthermore, the effectiveness depended upon cleaning the wall and floor surfaces that accumulated allergen.(Pope, 1993)

Scherr and Peck conducted a double-blind study of the effectiveness of HEPA filtered air cleaning devices installed at a children's asthma camp. Air cleaning devices with and without HEPA filters were alternated on a monthly basis for two summers. The test failed to generate statistically significant results although it was felt that there was a trend to fewer nighttime symptoms. (Sherr and Peck, 1977).

Kooistra and co-workers evaluated HEPA air cleaning devices with a 99% removal efficiency for all particles greater than 6 microns. He added these air cleaning devices to homes with central air conditioning in Madison, Wisconsin in an 8 week prospective double-blind cross-over study. His study population consisted of 20 adults allergic to ragweed, alternaria or both. These people were free to pursue their normal daytime activities and participated in the study during the evening and night. The efficacy of the HEPA air cleaning devices was evaluated by a physician who was able to discern the correct sequence of cleaner placement in 14 of 20 cases. While a statistically significant 14% reduction in self reported patient symptoms was found for night study periods, the overall daily symptoms

reduction was not statistically significant. The authors conclude that the addition of a HEPA air cleaning device to a central air conditioning system provided only a minimal improvement in hay fever symptoms. (Kooistra, 1978).

Antonicelli and co-workers (1991) evaluated the efficacy of HEPA filtration air cleaning devices on dust mite allergens and found no statistically significant change in respiratory function or rhinitis symptoms of nine subjects after two months. He notes that the most important phase of dust mite allergen exposure is during sleeping when there is close contact with contaminated pillow and mattress where air cleaning devices are insufficient.

Reismann and associates (1990) conducted a double blind study on thirty two subjects suffering from perennial rhinitis and/ or asthma who had a positive skin test for house dust mite extract. A HEPA filtered air cleaning device was installed in the bedrooms of the subjects for 4 weeks during an eight week study. During the other 4 weeks a blank filter was used as a control. A 70% reduction in particulate matter greater than 0.3 microns was determined. No information is provided regarding the outdoor particulate concentrations or the infiltration rate. The study failed to statistically demonstrate a reduction in symptoms or medication use in the study group. This result was confirmed for both HEPA and electrostatic air cleaning devices during a two week study conducted by Bowler and co-workers. (1985).

Table 1 presents a list of major indoor airborne contaminants and their particle size ranges. This paper presents a mathematical model for the prediction of the efficacy of portable High Efficiency Particulate Air Filters for particulate contaminants and aeroallergens of from cats and rats. If generation rates for other aeroallergens are known, the model can be used to test the efficacy of HEPA filtration.

ALLERGENS

More than 150 types of aeroallergens are currently recognized. (Hamilton, 1992). Aeroallergens are produced within an indoor environment or may enter the indoor environment by infiltration or ventilation. Tree, grass and weed pollen, molds, organic dusts and animal allergens arise from the outdoor environment while house dust mites, fur bearing pets, insects and microorganisms are produced in indoor spaces. (Reed, 1985). Environmental tobacco smoke produces both particulate and gaseous chemicals such as aldehydes that are allergenic irritants.

Aeroallergens can result in allergic rhinitis, asthma, extrinsic alveolar alveolitis, hay fever, reactive airway disease, hypersensitivity pneumonitis and dermatitis in both atopic and non-atopic individuals. (Swanson, 1985, Hamilton, 1982, Nelson, 1988). These reactions arise from Aeroallergens interaction mechanism involving immunoglobulin E, cellular or complement mediated biochemical pathways. (Edwards, 1992, do Poco, 1986)

Sundell, (1994) has reviewed a number of studies that suggest an increase in the incidence and prevalence of asthma in industrial countries. It is currently estimated that 15% of Americans are asthmatics. In industrialized regions of the Czech Republic, thirty percent of the children have allergies associated with polluted air. (Lajeikova, 1994) This trend arises partly from efforts to shift to more energy conservative insulation and ventilation and may be effected by environmental factors such as air pollutants, ETS, and increases in relative humidity associated with water incursions or condensation. (Flannigan, 1991). Nevertheless, it is clear that airborne allergens must be present in the air in sufficient amounts to sensitize occupants. Once sensitization has occurred, even exposure to minute quantities of allergens can elicit reactions. Many allergens are finely divided organic dust of respirable diameter others are proteins that are adsorbed on or incorporated into finely divided environmental particles with mean aerodynamic diameters less than 10 microns.(Reed, 1985). Large molecular weight allergens may also exist as aerosols in an unbound form. (Willeke, 1993).

CAT

Approximately, two percent of the population of the United States are allergic to cats. Cat allergens, Fel d I and serum albumin, are recognized as risk factors for asthma in the general population and has been associated with an increasing number of urban emergency room visits. (de Blay, 1991b, Pope, 1993). The antigen is produced by the sub-lingual salivary glands and hair root sebaceous glands of the domestic cat (felis domesticus). Swanson has estimated that a cat sheds 5×10^{-4} units of Fel d I allergen per minute.(Swanson, 1989). De Blay and colleagues measured shedding rates ranging from 60-90 nanograms of Fel d I per minute from a two year old male cat. (de Blay, 1991b.) Antigens from differing species of cat appear to be closely related in structure. (Hamilton, 1992) Fel d I antigen binds strongly to carpet and upholstered furniture as well as airborne dusts ranging from 2 to 10 microns. De Blay has measured 22% of cat Fel d

I antigen associated with airborne dust particles having a mean aerodynamic diameter less than 2.5 microns, 26% associated with a particle >6 microns, 34% with particles between 2-15 microns and 18% associated with particles between 1 and 5 microns. (de Blay, 1991a).

The Fel d I antigen is heat stable and thus steam cleaning and regular vacuuming do little to reduce indoor antigen levels. Even after the removal of the pet, indoor antigen levels may take as long as 5 months or more to decline to tolerable concentrations. (Hamilton, 1992). Carpets have been found to be a sink for Fel d I allergen and may have concentrations about 100 fold greater than those measured on polished floor. (de Blay, 1991b). Airborne resuspension of Fel d I deposited upon carpet depends upon fiber type, pile length, ventilation and degree of mechanical disturbance. De Blay estimated Fel d I resuspended from a synthetic carpet with a 2 centimeter pile at 0.0001%/hr.

In a study of 97 Baltimore residences, Fel d I allergens were found in 100% of the homes at concentrations ranging from 2 to 130,000 nanograms/gram of dust. (Hamilton, 1992) Hamilton considers that 8000 nanograms/gram of dust is a demarcation between low and significant airborne allergen concentrations. The airborne concentration or dose of Fel d I necessary to elicit an allergic response has not been reported.

RAT

Rat urinary allergens become airborne on particles with mean aerodynamic diameters of approximately 7 microns. Platts-Mills and associates have measured concentrations ranging 0.9 to 24 nanograms of rat allergen per cubic meter in undisturbed animal rooms. Male rats can release 20 nanograms per minute of airborne urinary allergens. Concentrations as high as 310 nanogram per cubic meter have been reported in typical animal rooms but greater airborne concentrations can be measured during cage cleaning. (Pope, 1993). They estimate that in rat cages up to 4 grams per cage of rat urinary allergens can be measured but only a small portion become airborne. Rat n I allergen is an alpha -2-euglobulin found in mature male rats whereas the other major rat allergen is a prealbumin. Factors that effect the airborne generation rate are the number of animals, cage design, type of cage litter and its water content. (Platts-Mills, 1986). Rat and mice urinary allergens have been found in inner-city indoor environments. Approximately 12 percent of laboratory animal care workers exhibit allergies to rats and may have to change occupation after sensitization.(Pope, 1993)

TABLE 1
INDOOR AIR CONTAMINANTS PARTICLE SIZE RANGES

CONTAMINANT	SIZE RANGE MICRONS
AMBIENT PARTICULATES	0.1-30
POLLEN	1-100
RAGWEED	19-32
RAGWEED INFLORESCENCE	0.3-3
DUST MITES	> 10
CAT FEL D I	< 0.25
GUINEA PIG URINE	< 0.8
GUINEA PIG PELT	< 0.8 OR > 4.9
RAT URINE	<0.8
PARTICLE BOUND RAT URINE	5-10
FUNGAL SPORES	1-200
TOBACCO SMOKE	0.01-1
RICKETTSIA	0.06-0.7
VIRUSES	0.004-0.05
AMOEBAE (NYGLERIA)	8-20
AMOEBAE CYSTS	9-12
BACTERIA	0.3-50

*(ASHRAE, 1989, ETKIN, 1994, WILLEKE, 1996, WHITBY, 1955, 1957.)

TERMS

C=Concentration of Particulate $\left[\frac{\mu g}{ft^3}\right]$
C_o=Concentration of Particulate outdoors $\left[\frac{\mu g}{ft^3}\right]$
C_i =Initial partilce concentration
R=Volume of Room $[ft^3]$
G=Generation rate of Particulates $\left[\frac{\mu g}{\text{min}}\right]$
q=Infiltration flow rate=Leakage rate $\left[\frac{ft^3}{\text{min}}\right]$
H= Room height ft.
F_g =Gravitational force $[N]$
m=Mass of particle $[g]$
ρ_g =Density of air; at normal temperature and pressure= $0.001192\left[\frac{g}{cm^3}\right]$
ρ_p =Density of particle
V= Velocity $\left[\frac{ft}{\text{min}}\right]$
d=Distance $[cm]$
d_p =Particle diameter
υ_p =Volume of particle
g = Gravity acceleration
η =Dynamic gas viscosity=$1.833\text{x}10^{-4}$ $\left[\frac{dyne-sec}{cm^2}\right]$
Q=Air cleaner flow rate $[cfm]$
ϵ = Filter efficiency
Z= Fraction of settled contaminant that is resuspended in the air

PARTICLE SETTLING

Aeroallergen particles will settle out of the room air as a result of gravitational forces. Particle settling is mechanism that will result in a loss of airborne allergens and a decrease in allergen concentration. Consider a small particle in air acted on only by gravitational forces.

$$F_g = m_p g = \rho_p \upsilon_p g \tag{0.1}$$

for a spherical particle, the volume is:

$$\upsilon_p = \frac{4}{3}\pi \left(\frac{d_p}{2}\right)^3 = \frac{\pi d_p^3}{6} \tag{0.2}$$

then substituting

$$F_g = \frac{\rho_p \pi d_p^3 g}{6} \tag{0.3}$$

When a particle flows through a gas, the motion of the particle and the flow pattern of the gas are determined by the forces involved. For a falling particle in still air, the gravitational force is countered by the buoyant force of the viscous gas. The flow pattern is governed by the ratio of the inertial force of the gas to the frictional force of the gas moving over the particle. This ratio is designated as the Reynolds number which can be expressed as follows:

$$Re_p = \frac{\rho_g V d_p}{\eta} \tag{0.4}$$

The particle drag force is

$$F_{drag} = \frac{\pi d_p^2}{8} C_{drag} \rho_g V^2 \tag{0.5}$$

When the inertial force pushing the gas aside, due to the difference in velocity between the particle and the gas, is much smaller than the viscous resistance force, the drag coefficient C_{drag} is expressed in terms of the gas flow parameters

$$C_{drag} = \frac{24}{Re_p} = \frac{24\eta}{\rho_g V d_p} \tag{0.6}$$

When $Re_p < 0.1$
Combining equation 4 and 6 with 5 yields Stokes law

$$F_{drag} = 3\pi\eta V d_p \tag{0.7}$$

Equating the drag force with the gravitational force provided in equation 3 and solving for the gravitational settling velocity ,V yields

$$V = \frac{\rho_p d_p^2 g}{18\eta} = 0.003\rho_p d_p^2 \tag{0.8}$$

In the case where a small particulate, with diameter=d_p, is uniformly distributed in the volume of an unventilated room with still air whose height is H, the particle concentration at any time=t will be determined by the settling velocity in the following manner

$$R\frac{dC}{dt} = -C\left(\frac{V}{H}\right) \tag{0.9}$$

$$C(t) = e^{-\frac{V}{RH}t}C\,|_{t=0}^{t=\infty} = C - Ce^{-\frac{V}{RH}t} + \text{ constant} = C\left(1 - e^{-\frac{V}{RH}t}\right) + C_0 \tag{0.10}$$

The solution of equation 10 is based upon the premise that the initial concentration is equal to the outdoor concentration. The particle concentration in the room will be determined by the rate of particle generation plus the rate of infiltration from external or extra compartmental sources minus the removal rates for gravitational settling, electrical plating out of particles on surfaces and agglomeration etc. For purposes of this model, all these removal rates will be assumed to be zero except gravitational settling. In this case the mass balance equation for room particle concentrations can be expressed as the following differential equation::

$$R\frac{dC}{dt} = G + C_o q - Cq - C\left(\frac{V}{H}\right)(1 - Z) \tag{0.11}$$

Rearranging equation 12 yields:

$$R\frac{dC}{dt} + \left(q + \frac{V}{H}(1 - Z)\right)C = G + C_o q \tag{0.12}$$

The exact solution is :

$$C(t) = \frac{-GH - C_o qH - Ce^{t\frac{-qH-V+VZ}{RH}} qH - Ce^{t\frac{-qH-V+VZ}{RH}} V + Ce^{t\frac{-qH-V+VZ}{RH}} VZ}{-qH - V + VZ} \tag{0.13}$$

If the fraction of settled particles that are resuspended into the air (Z) is assumed to be zero. The solution of Equation 13 is:

$$C(t) = \left[\frac{\mu g}{ft^3}\right] = \left[\frac{GH + C_o qH + Ce^{-t\frac{qH+V}{RH}} qH + Ce^{-t\frac{qH+V}{RH}} V}{qH + V}\right] \Big|_{t=0}^{t=\infty} \tag{0.14}$$

It will be assumed that the internal air concentration is equal to the outdoor air concentration at time t=0. Furthermore, all parameters are assumed to be fixed and constant. In other words, the generation rate, the particle characteristics, the infiltration rate and the outdoor concentration do not vary over the duration of interest. Equation 15 can be rearranged to yield

$$C(t) = \left[\frac{\mu g}{ft^3}\right] = \left[\frac{G + C_o q}{q + \frac{V}{H}}\right]\left[1 - e^{\frac{-\left(q+\frac{V}{H}\right)}{R}t}\right] + C_o\left[e^{\frac{-\left(q+\frac{V}{H}\right)}{R}t}\right] \tag{0.15}$$

INTRODUCTION OF A PORTABLE HEPA FILTERED AIR CLEANER

Consider the use of a small portable HEPA filtered air cleaning device introduced into room.

Typical devices are available at modest cost and have filters rated at 99.97% efficiency at 0.3 microns. One manufacturer makes them available in two sizes; 150 CFM and 85 CFM. Another manufacturer has configured a 500 CFM HEPA air filter for tuberculosis isolation patient care rooms. Equation 12 becomes

$$R\frac{dC}{dt} = G + C_o q - Cq - C\left(\frac{V}{H}\right) - QC\epsilon \tag{0.16}$$

This additional removal rate changes equation 16
to yield

$$C(t) = \left[\frac{\mu g}{ft^3}\right] = \left[\frac{G + C_o q}{q + \frac{V}{H} + Q\epsilon}\right]\left[1 - e^{\frac{-\left(q+\frac{V}{H}+Q\epsilon\right)}{R}t}\right] + C_o\left[e^{\frac{-\left(q+\frac{V}{H}+Q\epsilon\right)}{R}t}\right] \tag{0.17}$$

Once again, the resuspended fraction is assumed to be zero. In addition, the filter efficiency, generation rate, outdoor air concentration and flow rate are also assumed to be constant over the duration of interest.

When the resuspension rate is not assumed to be equal to zero, the following relationship holds:

$$C(t) = \frac{GH + C_o qH + C\exp(a)\,qH + C\exp(a)\,V - C\exp(a)\,ZV + C\exp(a)\,Q\epsilon H}{qH + V - ZV + Q\epsilon H} \tag{0.18}$$

Where

$$a = \left(-t\frac{qH + V - ZV + Q\epsilon H}{RH}\right) \tag{0.19}$$

TIME TO REACH 99% OF EQUILIBRIUM CONCENTRATION

As time$\rightarrow \infty$, equilibrium is asymptotically approached. To aid in understanding how a HEPA filtered air device would work in a particular room, the time that it would take to reach 99 percent of the final equilibrium concentration, ($t_{0.99}$),can be calculated as follows when the resuspended fraction is assumed to be zero:

$$0.99 \times C(t_{\rightarrow\infty}) = 0.99 \times \left[\frac{G + C_o q}{q + \frac{V}{H} + Q\epsilon}\right] \tag{0.20}$$

$$0.99\left[\frac{G + C_o q}{q + \frac{V}{H} + Q\epsilon}\right] = \left[\frac{G + C_o q}{q + \frac{V}{H} + Q\epsilon}\right]\left[1 - e^{\frac{-\left(q+\frac{V}{H}+Q\epsilon\right)}{\mathrm{R}}t_{0.99}}\right] + C_o\left[e^{\frac{-\left(q+\frac{V}{H}+Q\epsilon\right)}{\mathrm{R}}t_{0.99}}\right] \tag{0.21}$$

$$0 = (0.01) \times \left[\frac{G + C_o q}{q + \frac{V}{H} + Q\epsilon}\right] - e^{\frac{-\left(q+\frac{V}{H}+Q\epsilon\right)}{\mathrm{R}}t_{0.99}}\left\{\left[\frac{G + C_o q}{q + \frac{V}{H} + Q\epsilon}\right] - C_0\right\} \tag{0.22}$$

$$e^{\frac{-\left(q+\frac{V}{H}+Q\epsilon\right)}{\mathrm{R}}t_{0.99}}\left\{\left[\frac{G + C_o q}{q + \frac{V}{H} + Q\epsilon}\right] - C_0\right\} = (0.01) \times \left[\frac{G + C_o q}{q + \frac{V}{H} + Q\epsilon}\right] \tag{0.23}$$

$$e^{\frac{-\left(q+\frac{V}{H}+Q\epsilon\right)}{\mathrm{R}}t_{0.99}} = \frac{(0.01) \times \left[\frac{G+C_o q}{q+\frac{V}{H}+Q\epsilon}\right]}{\left\{\left[\frac{G+C_o q}{q+\frac{V}{H}+Q\epsilon}\right] - C_0\right\}} \tag{0.24}$$

$$\frac{-\left(q + \frac{V}{H} + Q\epsilon\right)}{\mathrm{R}}t_{0.99} = \ln\left[\frac{(0.01) \times \left[\frac{G+C_o q}{q+\frac{V}{H}+Q\epsilon}\right]}{\left\{\left[\frac{G+C_o q}{q+\frac{V}{H}+Q\epsilon}\right] - C_0\right\}}\right] \tag{0.25}$$

$$t_{0.99} = \left[\frac{1}{\frac{-\left(q+\frac{V}{H}+Q\epsilon\right)}{\mathrm{R}}}\right] \times \left[\ln\left[\frac{(0.01) \times \left[\frac{G+C_o q}{q+\frac{V}{H}+Q\epsilon}\right]}{\left\{\left[\frac{G+C_o q}{q+\frac{V}{H}+Q\epsilon}\right] - C_0\right\}}\right]\right] \tag{0.26}$$

$$t_{0.99} = \left[\frac{R}{-\left(q + \frac{V}{H} + Q\epsilon\right)}\right] \times \left[\ln\left[\frac{(0.01) \times \left[\frac{G+C_o q}{q+\frac{V}{H}+Q\epsilon}\right]}{\left\{\left[\frac{G+C_o q}{q+\frac{V}{H}+Q\epsilon}\right] - C_0\right\}}\right]\right] \tag{0.27}$$

$$= \left[\frac{R}{-\left(q + \frac{V}{H} + Q\epsilon\right)}\right] \left[\ln(0.01) + \ln\left(\frac{G + C_o q}{q + \frac{V}{H} + Q\epsilon}\right) - \ln\left\{\left[\frac{G + C_o q}{q + \frac{V}{H} + Q\epsilon}\right] - C_0\right\}\right] \tag{0.28}$$

Please note that the numerator of the first term in the above equation is the room volume (R). Thus if a portable HEPA filtered air cleaning unit of a fixed capacity is introduced into a room whose volume is R, the equation will directly determine the time it will take to reach 99 percent of the equilibrium particulate concentration. Now consider the effect of placing the same portable HEPA filtered air cleaner in a room with similar conditions but twice the volume ($R_2 = 2R$). It should be apparent that the time it will take to reach 99% of the equilibrium concentration will now be doubled. The equilibrium concentration reached in both rooms will be the same concentration. Thus the time it would take to reach equilibrium will be directly proportional to the room's volume.

EVALUATION OF THE MODEL FOR THE CASE OF CAT FEL D-1

Consider a particle of 0.25 microns with a specific gravity of 1.1 containing cat Fel D I allergen in an indoor environment. The settling velocity then can be calculated as described in equation 8 where d_p is in microns:

$$V = 0.003\rho_p d_p^2 = 0.003(1.1)(.25)^2 = 2.0625 \times 10^{-4} \left[\frac{cm}{\text{sec}}\right] \tag{0.29}$$

To convert this to units of $\left[\frac{ft}{\text{min}}\right]$

$$V = 2.0625 \times 10^{-4} \left[\frac{cm}{\text{sec}}\right] (\frac{60\,\text{sec}}{\text{min}})(\frac{1inch}{2.54cm})(\frac{ft}{12\ inches}) = 4.06 \times 10^{-4} \left[\frac{ft}{\text{min}}\right] \tag{0.30}$$

Assume the following values
H=10 feet
V=800 ft^3
G=0.090 $\left[\frac{\mu g}{\text{min}}\right]$
Q=150 CFM
$\epsilon = 99.97\%$
Z=0
$C_O = 0$

INFILTRATION RATE CLASSES

Let us assume that room particles are uniformly distributed and instantaneously mixed. Consider four infiltration conditions:

CASE 1: Sealed room : 0 air changes per hour q= 0 $[cfm]$
CASE 2: Tight room : 0.1 air changes per hour q = $80.0 \div 60 = 1.3333$ $[cfm]$
CASE 3: Medium tight : 0.5 air changes per hour q= $400 \div 60 = 6.6667$ $[cfm]$
CASE 4: Ventilated room :1.0 air change per hour q= 13.333 $[cfm]$

CASE 1 CONDITION 1: SEALED ROOM

A: Absence of Air Cleaner:

$$C(t) = \left[\frac{G + C_o q}{q + \frac{V}{H}}\right]\left[1 - e^{\frac{-\left(\frac{V}{H}\right)}{R}t}\right] + C_o\left[e^{\frac{-\left(q+\frac{V}{H}\right)}{R}t}\right]$$

$$C(t) = \left[\frac{GH}{V}\right]\left[1 - e^{-\left(\frac{V}{HR}\right)t}\right]$$

$$C(t) = \left[\frac{(0.090) \times (10)}{4.06 \times 10^{-4}}\right]\left[1 - e^{-\left(\frac{4.06\times10^{-4}}{10\times800}\right)t}\right]$$

$$C(t) = \left[2216.7 - 2216.7 \exp\left(-5.075 \times 10^{-8} t\right)\right]$$

B: With HEPA Air Cleaner

$$C(t) = \left[\frac{G + C_o q}{q + \frac{V}{H} + 149.955}\right]\left[1 - e^{\frac{-\left(q+\frac{V}{H}+149.955\right)}{R}t}\right] + C_o\left[e^{\frac{-\left(q+\frac{V}{H}+Qe\right)}{R}t}\right]$$

$$C(t) = \left[\frac{0.090}{\frac{4.06\times10^{-4}}{10} + 149.955}\right]\left[1 - e^{\frac{-\left(\frac{4.06\times10^{-4}}{10}+149.955\right)}{800}t}\right]$$

$$C(t) = 0.00060018 - 0.00060018 \exp\left(-.18744t\right)$$

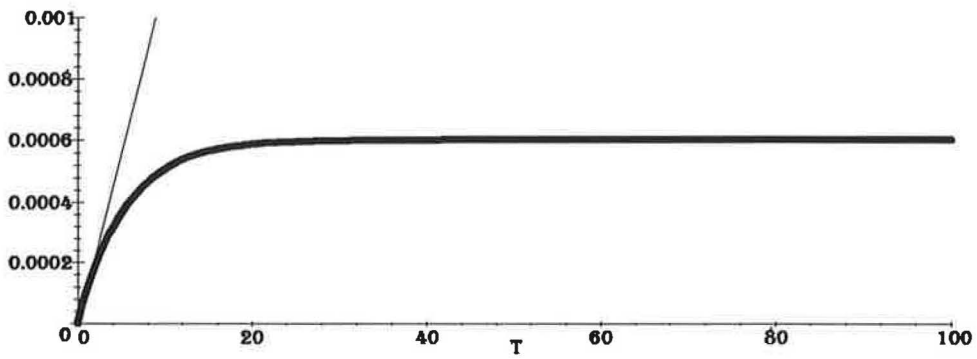

FIGURE 1: SEALED ROOM CAT FEL D I VS TIME :——HEPA = THICK LINE

CASE 2 CONDITION 1: TIGHT ROOM

q=1.33 $[cfm]$
$C_0 = 0 \left[\frac{\mu g}{ft^3}\right]$

A: Absence of Air Cleaner:

$$C(t) = \left[\frac{G + C_o q}{q + \frac{V}{H}}\right]\left[1 - e^{\frac{-\left(q+\frac{V}{H}\right)}{R}t}\right] + C_o e^{\frac{-\left(q+\frac{V}{H}\right)}{R}t}$$

$$C(t) = \left[\frac{GH}{qH + V}\right]\left[1 - e^{-\left(\frac{qH=V}{HR}\right)t}\right]$$

$$C(t) = \left[\frac{(0.090)(10)}{(1.33 \times 10) + 4.06 \times 10^{-4}}\right]\left[1 - e^{-\left(\frac{(1.33\times 10)+4.06\times 10^{-4}}{10\times 800}\right)t}\right]$$

$$= 0.067667 - 0.067667 \exp\left(-1.6626 \times 10^{-3} t\right)$$

B. With HEPA Air Cleaner

$$C(t) = \left[\frac{G + C_o q}{q + \frac{V}{H} + 149.955}\right]\left[1 - e^{\frac{-\left(q+\frac{V}{H}+149.955\right)}{R}t}\right] + C_o e^{\frac{-\left(q+\frac{V}{H}+149.955\right)}{R}t}$$

$$C(t) = \left[\frac{0.090}{1.33 + \frac{4.06\times 10^{-4}}{10} + 149.955}\right]\left[1 - e^{\frac{-\left(1.33+\frac{4.06\times 10^{-4}}{10}+149.955\right)}{800}t}\right]$$

$$= 5.949 \times 10^{-4} - 5.949 \times 10^{-4} \exp\left(-.18911 t\right)$$

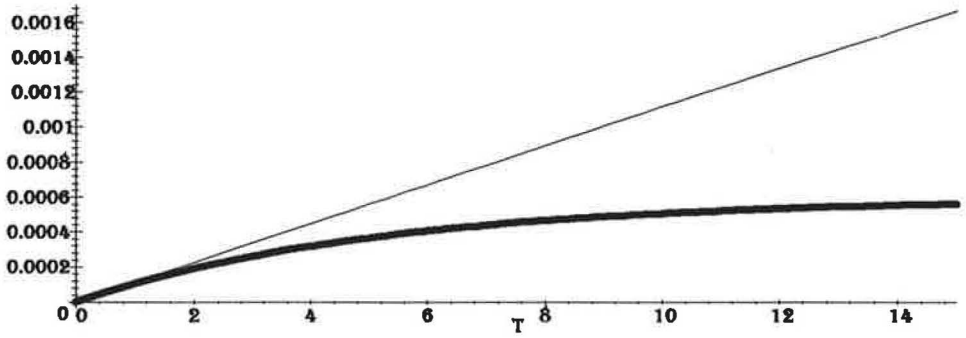

FIGURE 2: TIGHT ROOM CAT Fel D I VS. TIME :–HEPA=THICK LINE

CASE 3 CONDITION 1: MODERATELY VENTILATED ROOM
NO OUTDOOR PARTICLES

q=6.6667 $[cfm]$

$C_0 = 0 \left[\frac{\mu g}{ft^3}\right]$

A: Absence of Air Cleaner:

$$C(t) = \left[\frac{G + C_o q}{q + \frac{V}{H}}\right]\left[1 - e^{\frac{-\left(q+\frac{V}{H}\right)}{R}t}\right] + C_o e^{\frac{-\left(q+\frac{V}{H}\right)}{R}t}$$

$$C(t) = \left[\frac{(0.09)(10)}{(6.6667 \times 10) + 4.06 \times 10^{-4}}\right]\left[1 - e^{\frac{-\left(6.6667+\frac{4.06\times10^{-4}}{10}\right)}{800}t}\right]$$

$$= .0135 - .0135 \exp\left(-8.3334 \times 10^{-3} t\right)$$

B. With HEPA Air Cleaner

$$C(t) = \left[\frac{G + C_o q}{q + \frac{V}{H} + 149.955}\right]\left[1 - e^{\frac{-\left(q+\frac{V}{H}+149.955\right)}{R}t}\right] + C_o e^{\frac{-\left(q+\frac{V}{H}+149.955\right)}{R}t}$$

$$C(t) = \left[\frac{0.090}{6.6667 + \frac{4.06\times10^{-4}}{10} + 149.955}\right]\left[1 - e^{\frac{-\left(6.6667+\frac{4.06\times10^{-4}}{10}+149.955\right)}{800}t}\right]$$

$$= 5.7463 \times 10^{-4} - 5.7463 \times 10^{-4} \exp\left(-.19578t\right)$$

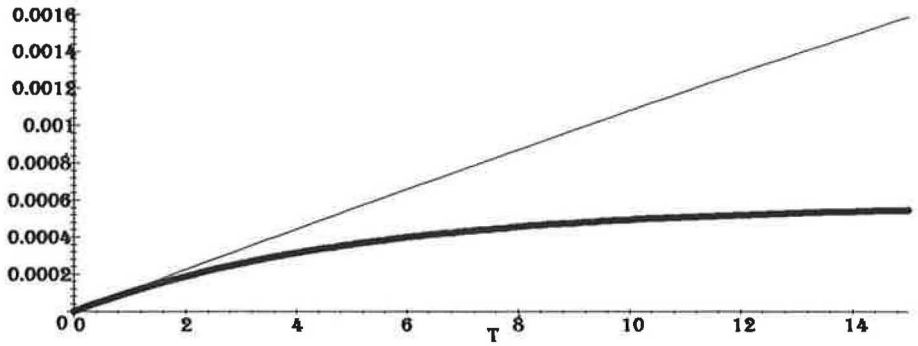

FIGURE 3: MODERATELY TIGHT CAT Fel D I VS. TIME:HEPA=THICK LINE

CASE 4 CONDITION 1: WELL VENTILATED ROOM
NO OUTDOOR PARTICLES

q=13.333 $[cfm]$
$C_0 = 0 \left[\frac{\mu g}{ft^3}\right]$

A: Absence of Air Cleaner:

$$C(t) = \left[\frac{G + C_o q}{q + \frac{V}{H}}\right]\left[1 - e^{\frac{-\left(q+\frac{V}{H}\right)}{R}t}\right] + C_o e^{\frac{-\left(q+\frac{V}{H}\right)}{R}t}$$

$$C(t) = \left[\frac{(0.090)(10)}{(13.333 \times 10) + 4.06 \times 10^{-4}}\right]\left[1 - e^{\frac{-\left(13.333+\frac{4.06\times10^{-4}}{10}\right)}{800}t}\right]$$

$$= 6.7501 \times 10^{-3} - 6.7501 \times 10^{-3} \exp\left(-1.6666 \times 10^{-2} t\right)$$

B: With HEPA Air Cleaner

$$C(t) = \left[\frac{G + C_o q}{q + \frac{V}{H} + 149.955}\right]\left[1 - e^{\frac{-\left(q+\frac{V}{H}+149.955\right)}{R}t}\right] + C_o e^{\frac{-\left(q+\frac{V}{H}+149.955\right)}{R}t}$$

$$C(t) = \left[\frac{0.090}{13.333 + \frac{4.06\times10^{-4}}{10} + 149.955}\right]\left[1 - e^{\frac{-\left(13.333+\frac{4.06\times10^{-4}}{10}+149.955\right)}{800}t}\right]$$

$$= 5.5117 \times 10^{-4} - 5.5117 \times 10^{-4} \exp\left(-.20411t\right)$$

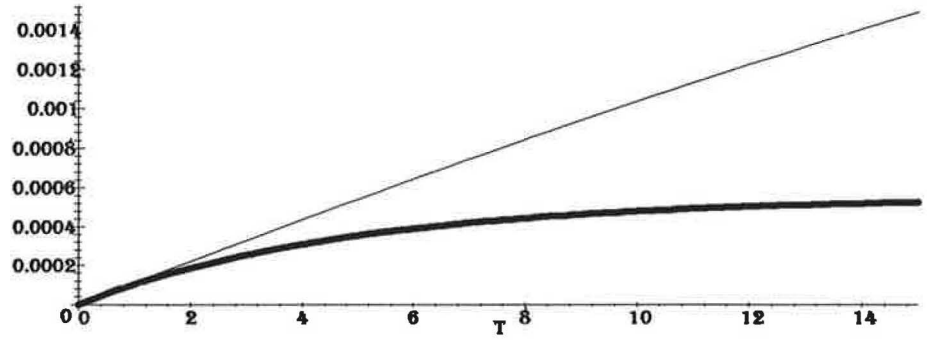

FIGURE 4: WELL VENTILATED ROOM CAT Fel D I VS. TIME :HEPA=THICK LINE

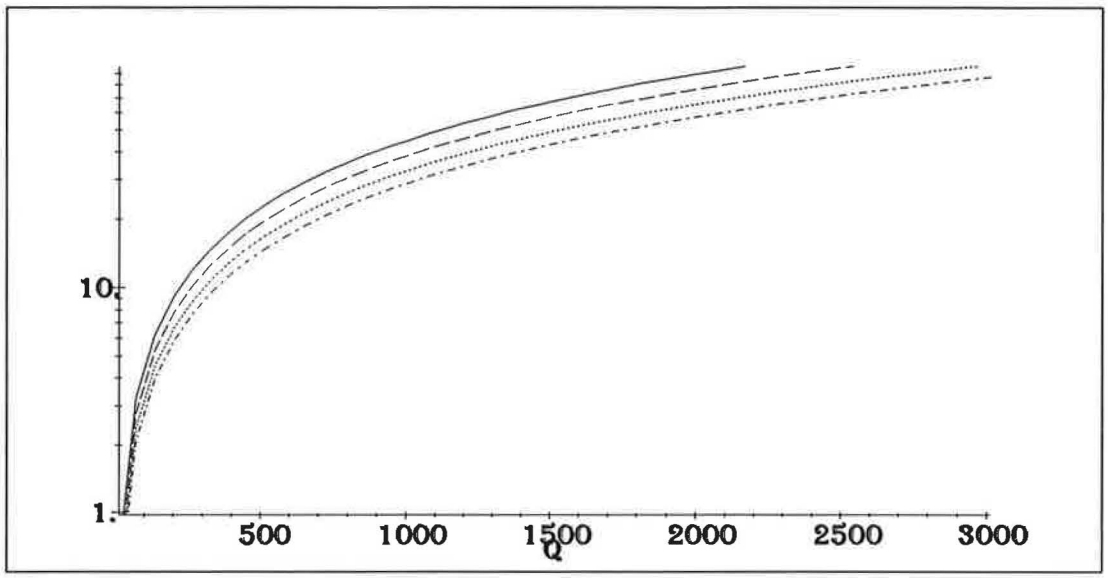

FIGURE 5: % REDUCTION CAT ALLERGENS VS AIR CHANGES PER HOUR

CONCLUSION

Concerns regarding the potential adverse health effects of microscopic particles of respirable size range, airborne microorganisms and airborne allergens have led to the manufacture of portable filtered air cleaning devices. Some of these air cleaning devices contain High Efficiency Particulate Air (HEPA) filters that will remove 99.97 percent of all particles greater than or equal to 0.3 microns. Commercially available units are currently marketed with flow rates of 85, 150, and 500 cubic feet per minute.

The efficacy of these units depends upon the particulate concentration of the outdoor air, the particle aerodynamic diameter, the particle density, the room dimensions and ventilation characteristics. This technical document establishes a mathematical model for evaluating the performance of a portable HEPA filtered air cleaning device in a residential setting.

The ability of these devices to benefit allergic residential occupants depends upon the particulate characteristics of the allergen, as well as the room ventilation and allergen generation rate. Allergen generation rates are reported in the literature for both cat and rat allergens. This paper reviews, airborne allergenic

sources and presents a theoretical model for determining the efficacy of HEPA filtered air cleaning devices of various flow rates upon the equilibrium allergen concentration. The model demonstrates the importance of infiltration, settling rate, room dimensions and flow rate upon removal of particulate allergens. The model demonstrates that if the room size is doubled, it will take twice as long to reach equilibrium concentrations for any size air cleaning device. The model demonstrated that for both cat and rat allergens, the percent reduction decrease as the air exchange rates increase. To obtain a 95% reduction in airborne allergens for these units in a room 8 x 10 x 10 with one cat or one rat, would require a HEPA filtered unit of at least 2000 cfm. Based upon this model it would seem that most of the portable HEPA filtered air cleaning devices will not significantly improve the indoor environment. The model will assist in determining if a HEPA filtered air cleaning device will be successful in reducing airborne concentrations of specific particulate allergens and in selection of an appropriate size device for varying residential or indoor environments.

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