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THE EFFECTIVENESS OF AIR CLEANERS USING AN ENVIRONMENTAL TOBACCO SMOKE MATERIAL BALANCE MODEL

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ABSTRACT

Using a contaminant material balance model, the effectiveness of six air cleaners has been evaluated for a typical restaurant, lounge, and office. The contaminant balance model takes into account particle removal by air cleaners, particle decay due to sedimentation and other mechanisms, and ventilation. The six air cleaners evaluated include an ionizing electrically stimulated filter (IESF), electrostatic precipitator (ESP), two 95% DOP "hospital"-type filters, a HEPA filter, and a 95% ASHRAE filter. The results show that air cleaner effectiveness in various applications can be directly related to the product of the 0.3 μm particle removal efficiency and the air cleaner flow rate (referred to as the effectiveness factor). The IESF device was the most effective air cleaner, followed by (in descending order) the 95% DOP hospital-type filters, the 95% ASHRAE filter, the ESP, and the HEPA filter.

INTRODUCTION

Current public interest in the indoor environment and the related health and annoyance aspects of environmental tobacco smoke (ETS) have led to increased use of indoor air cleaners in residential and commercial buildings. A variety of different types of air cleaner products are available to the end user. The cleaning efficiency of these devices is typically specified by at least one of two different test methods: ASHRAE 52-76 and the 0.3 μm DOP. The ASHRAE dust spot test efficiency is the removal efficiency of *local* atmospheric aerosol, while the DOP method focuses on 0.3 μm particle size removal efficiency. Further confusing the proper selection of air cleaners is the fact that air cleaner particle removal efficiency *alone* does not relate to effectiveness in a particular application.

The air cleaning effectiveness for a specific application depends not only on the particle removal efficiency of the device at various particle sizes, but also on the airflow rate of the device; the ventilation flow rate; the ETS generation rate; ETS particle removal via sedimentation, diffusion, and coagulation; and on the cleanliness of the ventilation air. Here it is assumed that the air distribution aspect is adequately addressed. The effect of all these factors can be determined by laboratory studies, but at high expense. Offermann et al. (1985) have conducted a laboratory study limited to portable air cleaners. However, they did not investigate all the above factors and their impact on air cleaner performance for the range of diverse applications such as lounges, restaurants, offices, and residential buildings.

This study attempts to fill this need by utilizing an ETS specific material balance (Appendix A), assuming uniform ETS concentration in the area of interest. The approach here is to use experimentally determined particle size efficiencies of six classes of air cleaners/filters and to use this as input for the ETS material balance in order to determine the effectiveness of air cleaners as a function of the previously discussed variables.

A previous study by Turk (1963) used a similar material balance model for odor vapors. However, Turk's work does not take into accouont particle decay due to sedimentation, diffusion, and coagulation since it is concerned with vapors. This model takes into account particle removal via sedimentation, diffusion, and coagulation (and other possible mechanisms) by using a particle decay rate constant (K) calculated from the chamber measurements of Offermann et al. (1985). It is important to note that these measurements were done for a low air exchange rate. Further, in rooms of different geometry, airflow patterns, and contents this decay rate constant could vary. However, for most applications the particle removal rate due to air cleaners should significantly exceed the natural decay rate. Hence, for the purpose of comparing air cleaners, this approach (using the value of K from Offermann et al. [1985]) is justified. A more rigorous model (published very recently, after this work was completed) by Nazaroff and Cass (1989) takes into account most mechanisms of particle deposition onto surfaces and also considers the effect of coagulation on the changing size distribution of ETS. It should be noted that Nazaroff and Cass also utilize the particle decay measurements of Offermann et al. (1985) for the evaluation of their model. Their results also support the fact that particle removal due to filtration and ventilation far exceeds the removal via natural decay mechanisms.

It should be noted that on-site experimental confirmation of this material balance model in lounges, restaurants, etc., is next to impossible due to the continuously changing number of smokers (ingression rate) and other factors. Further note that this study is limited to evaluating air cleaner devices in terms of ETS and other particulate matter (such as bacteria, moisture aerosols containing viruses, etc.) only, and does not address the issues related to gaseous contamination due to ETS.

EXPERIMENTAL DESCRIPTION

Experimental Setup

The object here was to measure the *single-pass* efficiency (at 0.3 μm) of the various air cleaners. This information was then used in the material balance model. A simple schematic drawing of the test setup is shown in Figure 1. All experiments were performed in a temperature- and humidity-controlled aerosol filtration laboratory capable of maintaining temperature at 70°F ± 2°F and relative humidity at 50% ± 5%. The laboratory has three separate test flow systems, with a combined flow range of 25 to 5000 m³/h. Each system is equipped with appropriate flow- and pressure-measuring instrumentation. Further, each test flow system has been eval-

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TABLE 1

Efficiencies and Effectiveness Factors of Air Cleaners

Type	Rated Efficiency %	Flow Rate (scfm) Q	Measured Eff. % (at 0.3 Um DOP) (N × 100)	Pressure Drop "WC	Effectiveness Factor N × Q (scfm)
1) ESP	99% ASHRAE	800 1200	70.7% 50.1%	0.08" 0.16"	566 601
2)* 6" DEEP AL SEPARATORS	Approx. 95% DOP	850	97%	0.5"	825
3)* 2" DEEP (SEPARATORLESS) MINI-PLEAT	Approx. 95% DOP	850	97.4%	0.56"	828
4)* 2-3/4" DEEP SEPARATORLESS MINI-PLEAT HEPA	99.99% DOP	350	99.97%	0.5"	Approx. 350
5)* 6" DEEP FIBER GLASS MAT	90–95% ASHRAE	800	81.2%	0.52"	650
6)* 1-3/4" DEEP IESF	99.9% DOP	1200	99.9%	0.45"	1199

*ALL FILTER ELEMENTS WITH approximately 4 $FT.^2$ CROSS SECTIONAL AREA.

uated for aerosol loss characteristics. This is accomplished by measuring particle counts at various sizes at the influent and effluent sections of the ducts at the lowest flow rate at which the system will be used. The laboratory has approximately 1000 ft² floor area with about a 10-ft-high false ceiling.

Efficiency Measurement

All the air cleaners were challenged using cold polydisperse DOP aerosol. The polydisperse aerosol was generated using an atomizer. A special aerosol dispersion "cross" feeder and a "cross" sampler were utilized to result in a well-mixed and average upstream sample. A sharp edge sampler was used downstream. This was adequate since the downstream aerosol was uniformly mixed. Both upstream and downstream particle counts were measured using a light-scattering optical particle counter with 0.3 μm particle size sensitivity. The optical particle counter was coupled with a suitable dilution system capable of a 350:1 dilution ratio. The output of the optical particle counter was interfaced with a realtime data acquisition computer system with software for automatic data analysis.

Six types of air cleaners/filters were used in this study:

(1) An electrostatic precipitator (ESP) rated at 99% ASHRAE dust spot efficiency. This is a single-collection-stage Penney-type ESP that has two collector cells in parallel. Each cell consists of 58 plates, 19 in by 4 in deep spaced 0.187 in apart. The measured ionizer and collector cell voltages are 9.4 kV and 4.2 kV, respectively.

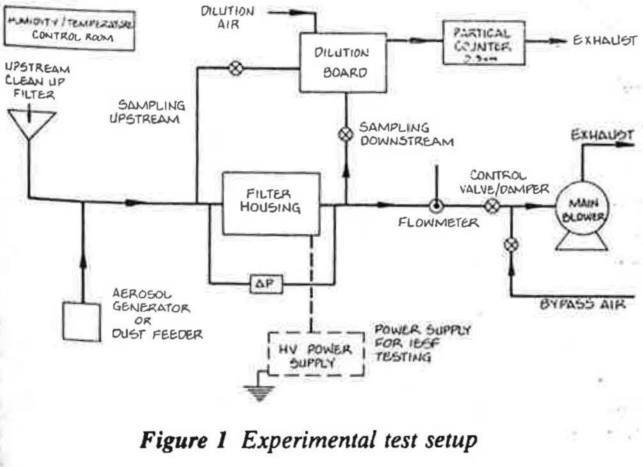

Figure 1 Experimental test setup

(2) A 6-in-deep aluminum separator-filter element, with 95% efficiency at 0.3 μm DOP. This is commonly referred to as a "hospital"-type filter.

(3) A 2-in-deep string separatorless mini-pleat filter element, with 95% efficiency at 0.3 μm DOP, also referred to as a "hospital"-type filter.

(4) A 2 3/4-in-deep mini-pleat separatorless HEPA filter element, with 99.99% efficiency at 0.3 μm DOP.

(5) A 6-in-deep fiberglass mat-type element rated at 90% to 95% ASHRAE 52-76 efficiency.

(6) An ionizing, electrically stimulated filter (IESF) rated at 99.9% at 0.3 μm DOP, with a 20.5 in by 28 in filter element.

Item 1—ESP—is the most commonly used device, while item 6 is a newly introduced device described by Jaisinghani and Bugli (1988a, b). Briefly, this device utilizes a highly permeable, low-mechanical-efficiency filter paper with electrical enhancements of its efficiency to high levels. The flow and contaminant-holding properties of the IESF far exceed those of equivalent efficiency mechanical filters.

It should be noted that air cleaners 1 (ESP) and 6 (IESF) were tested as complete units with integral blowers. Both units fit into a 2 ft by 4 ft ceiling panel. These units were also evaluated for single-pass efficiency in the test ducts by disconnecting the blowers (i.e., testing the ESP ionizer and cells, and IESF at rated voltage without using the blowers) and by using the test duct blower to maintain the rated flows. Both methods resulted in almost identical values of efficiency. The other mechanical filter units—2, 3, 4, and 5—were evaluated in a well-sealed generalized filter housing. This eliminated the need to purchase individual units without sacrificing the accuracy of the efficiency measurements. All the filter units (2-4) were of approximately the same size, 2 ft by 2 ft cross section. The IESF filter also had approximately the same cross-sectional area. Items 2-4 were evaluated at flow rates such that the pressure drop across the clean filter elements was approximately 0.5 in w.c. This is typical since most indoor air pollution control devices use low-pressure blowers due to cost, size, weight, and especially noise considerations. The pressure drops for units 1-6 are shown in Table 1.

RESULTS AND DISCUSSION

Efficiency of Various Air Cleaners

Table 1 shows the measured efficiency and flow rates of the six air cleaner units. The measured efficiency is in terms of 0.3 μm DOP particle size. This particle size is relevant for ETS removal applications. Hinds (1978) reported that the median size of ETS ranges from 0.1 to 0.5 μm, with the mass median diameter typically being 0.37–0.52 μm. Based on the more recent work by Chang et al. (1985) and Ueno and Peters (1986), the number and mass median diameters for sidestream smoke are 0.1 μm and 0.16 μm, respectively. The mainstream smoke is bimodal, the lower mode having a number average of 0.24 μm and a mass average of about 0.26 μm. Hence, it is advantageous to utilize the 0.3 μm DOP efficiency, especially due to its common use in the filtration industry.

Based on the material balance model (Appendix A), the effectiveness of an air cleaner can be approximately expressed as the product of its efficiency, N, and the flow rate, Q. Sutton et al. (1964) have also shown this to be of primary importance in an essentially closed system with good mixing. Table 1 also shows the effectiveness factor, NQ, which is the product of the flow rate times the fractional 0.3 μm efficiency of the various air cleaners. As is clear from Appendix A, this is *approximately* the equivalent of the *additional* ventilation rate required to achieve the same particulate concentration in the room without use of the air cleaner. The higher the value of NQ, the higher the effectiveness of the air cleaner. In this case, the IESF exhibited the highest NQ (1199 scfm), with the 95% DOP filters (hospital types) being second highest (NQ is approximately 825 scfm). Within this range of flows, the mechanical filters had little change in efficiency with respect to flow rate (since the change in capture by interception is compensated by the change in efficiency due to the diffusion mechanism). However, the ESP's efficiency, as expected, was reduced at higher flow rates. Consequently, there was little change in the NQ value for the ESP (566 to 601 for a flow rate change of 800 to 1200 scfm). On the other hand, the efficiency of the IESF is only marginally affected by the flow rate in this range (600-1200 scfm) of operation. At 600 scfm the IESF has a measured efficiency (at 0.3 μm DOP) of 99.95%, while at 1200 scfm the 0.3 μm DOP efficiency is 99.9%. Note that the IESF has approximately the same filter cross-sectional area as the other mechanical filters.

Generalized Effectiveness of Air Cleaners

Particle Decay Rate and Particle Generation. The ETS particle material balance model is developed in Appendix A. A similar material balance model has been used by Whitby et al. (1983). It is important to note that the concentration level, C, is an average concentration since the model assumes that no spatial concentration distribution exists. In order to use this model for evaluating the air cleaner effectiveness for ETS, values for the particle decay rate constant K and particle generation rate need to be determined.

The decay or loss rate constant K should depend on room size, particle type and size distribution, airflow patterns, and ventilation, among other factors. In the experimental work of Offerman et al. (1985), the ETS concentration change with respect to time, in a chamber, was used to determine the value of K (0.1 h^{-1}). It should be noted that Offermann et al. used 0.1 ach ventilation. In this study, although the model is applied to higher ventilation rates, the value of $K = 0.1$ h^{-1} has been taken as a constant. When air cleaners with high recirculation rates (i.e., V/Q is low, Equation 2, Appendix A), or when Qv, the ventilation flow rate, is significantly greater than N_eQ, the solution to the material balance equation (Equation 4, Appendix A) becomes relatively insensitive to the actual value of K, since O (Equation 4, Appendix A) is not significantly affected. This is especially true for high-efficiency (N is approximately 0.95) air cleaners. For example, consider an air cleaner with efficiency N of approximately 0.95 operating at a recirculation rate of 5 per hour. Here, $N_e = 0.97$ for $K = 0.1\ h^{-1}$ while $N_e = 0.99$ for $K = 0.2\ h^{-1}$.

The amount of particulate matter generated per cigarette varies in the reported literature. In this study, a value of 12 mg/cigarette has been chosen based on our own internal experience. This is in close agreement with the work of Chang et al. (1984), who obtained 11.2 mg/cigarette. The average rate of cigarettes smoked is taken to be two cigarettes per hour per smoker throughout this study. This is based on the work of Cain et al. (1983), among others. Further, it is assumed that besides incoming particulate matter from the ventilation airflow, all particulate matter generated is due to ETS. The incoming ventilation particulate concentration is taken to be 154 μg/m³, which is the value commonly used for urban areas with populations of about 10^6 (Hinds 1982). With these values for particle generation and decay rate constants, we are now in a position to apply the material balance model.

Generalized Results. Noting that the equilibrium concentration (Equation 6, Appendix A) is independent of the room/area size and volume and is only dependent on the net ingression rate, I, and equivalent ventilation rate, O, the model results can be expressed in generalized terms. Note that the room volume only affects the time to reach equilibrium concentration.

Figure 2 is a three-dimensional plot of the equilibrium concentration, C_{eq}, plotted against N_eQ and number of smokers. Since this is a generalized pictoral view, a hypothetical ventilation flow rate, $Qv = 5$ scfm/person, assuming 35% smokers, has been used here. As expected, C_{eq} increases with an increase in the number of smokers, but this increase is limited as the N_eQ value of the air cleaner increases. Noting that N_eQ approximately = NQ (the effectiveness factor), the effectiveness of three hypothetical air cleaners with identical flow rates (but having different efficiencies of 50%, 90%, and 99.95%) is shown in Figure 2. Clearly, for a high number of smokers, air cleaners with high NQ values are required for effective air cleaning.

In Figure 3, the equilibrium concentration, C_{eq}, is plotted against the "effective" ventilation rate, O, for various constant net ingression rates, I, using Equation 6, Appendix A. Figure 3 shows that as O increases, the equilibrium concentration asymptotically approaches a limiting value. Practically, there is a minimum attainable concentration, which is higher for higher net ingression rates. This limiting concentration is also dependent upon the value of ventilation air particle concentration, C_a.

The time to clean a previously contaminated area to a given level is given by Equation 5, Appendix A. This is illustrated in Figure 4 for a 425 m³ room contaminated to an initial concentration of 1200 μg/m³, using a ventilation flow rate of 425 m³/h. The time-based concentration curves are

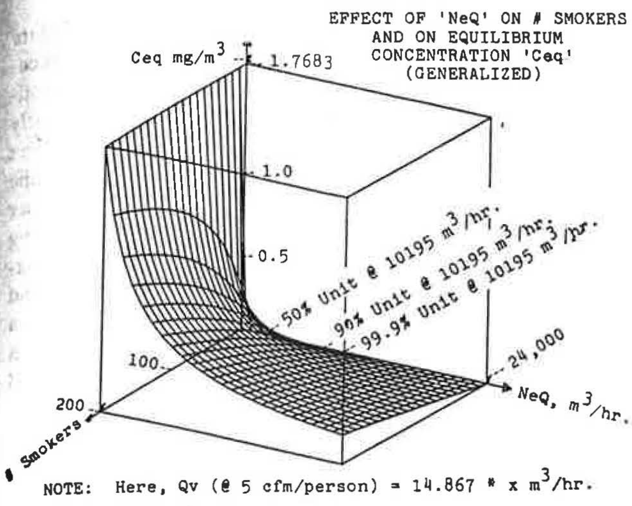

Figure 2 *Three-dimensional plot illustrating the effect of number of smokers (generation rate) and N_eQ (approximate effectiveness factor, NQ) on equilibrium concentration. Q_v = number of smokers x 14.867 m^3/h*

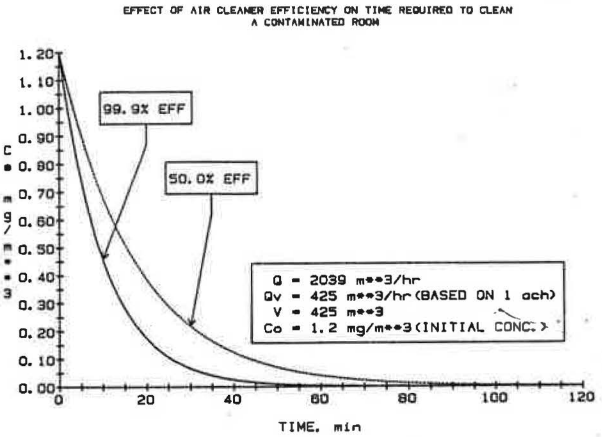

Figure 4 *Effect of air cleaner efficiency on time required to clean a contaminated room*

shown for 50% and 99.9% efficient (at 0.3 μm DOP) air cleaners, both operating at the same flow rates (2039 m³/h). Clearly, time for cleaning a room to a desired concentration is shorter for the 99.9% efficient unit. This cleaning speed should be qualitatively related to the effectiveness of devices in terms of quickly eliminating the irritation aspects of high-concentration sidestream cigarette smoke.

Specific Applications

The ETS material balance model has been used to evaluate the air cleaners described in Table 1 in three specific situations. The three situations are close approximations of actual field installations of the IESF. These situations, described in detail in Table 2, are (a) a medium-sized restaurant, (b) a typical lounge, and (c) a large office. The medium-sized restaurant is analyzed in detail using ventilation rates from 5 to 30 scfm/person (based on maximum occupancy). Due to brevity requirements, the other three situations are analyzed only at the 5 scfm/person ventilation rate.

It is important to note here that, based on the work of Weber (1984), we can assume that in most situations and for

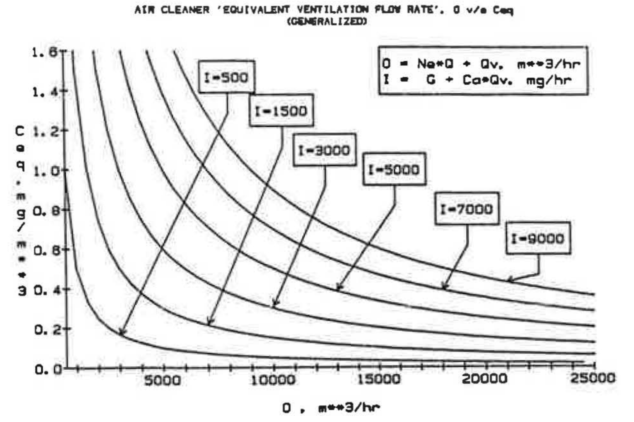

Figure 3 *Effect of air cleaner "equivalent ventilation rate," O, on equilibrium concentration*

TABLE 2

Description of Specific Applications of Material Balance Model

Variables (Input Data)	APPLICATION: Med. Size Restaurant	Typical Lounge	Large Office
a) Area (sq. ft.)	1500	2670	4000
b) Room Volume (cu. ft.)	15,000	21,360	36,000
c) Design Occupancy (# of people)	120	220	50
d) % Smokers	30%	50%	30%
d) # of Smokers	36	110	15
f) Actual Ventilation Flow (cfm)	600 1800 3600	1100	250
g) Equivalent ach	2.4 7.2 14.4	3.09	0.42
h) Equivalent cfm/person	5.00 15.00 30.00	5.00	5.00

most people eye and membrane irritation *starts* developing at ETS concentration levels above approximately 200 μg/m³. This level, therefore, has been chosen as an irritation threshold limit and air cleaner performance is evaluated on this basis.

Detailed Analysis for a Medium-Sized Restaurant. The performance characteristics of the various devices (Table 1) are illustrated in Figures 5 and 6. Figure 5 shows the equilibrium concentrations obtained as a function of the number of units* of the devices (Table 1) at maximum occupancy with an existing ventilation rate of 5 scfm/person. Based on the previously discussed irritation onset level (200 μg/m³), the corresponding required number of units can be determined by reading the abscissa values (in Figure 5) at C_{eq} = 200 μg/m³. For example, four ESP units are required, as opposed to

*Note that each of the devices in Table 1 has a corresponding airflow rate shown in Table 1. Hence, the number of units can be related to the total flow rate for each type of device.

two IESF units, to achieve this threshold concentration limit. Note that both these ESP and IESF devices have the same airflow rate (1200 scfm).

Figure 6 is the plot for C_{eq} vs. the number of smokers in the restaurant with a 5 scfm/person ventilation rate (using maximum occupancy). For all air-cleaning devices two units have been used in this situation (i.e., the total flow rate for each device is twice that of the corresponding value in Table 1). Once again based on the 200 μg/m³ threshold limit, the IESF is clearly the most efficient device, able to handle the maximum number (36) of smokers while maintaining the ETS concentration level below 200 μg/m³. The ESP and the 95% ASHRAE filter can maintain this level only up to half the maximum number of smokers. The hospital-type (95% DOP) filter on the other performs to this level up to about 25 smokers and hence is the second most effective device. The HEPA filter can achieve this threshold limit to only about 11 smokers due to its low flow rate (i.e., low NQ value). Also shown, in Figure 6, is the "no air cleaner, 5 scfm/person ventilation only" situation. In this case, with approximately 3 smokers, the concentration limit can exceed the 200 μg/m³ threshold limit; at maximum occupancy, a highly irritating situation exists with an ETS equilibrium concentration of 1001 μg/m³.

The effect of ventilation rate on C_{eq} is shown in Figure 7. Using 5, 15, and 30 scfm/person (using maximum occupancy), the effectiveness of the different devices and ventilation rate alone is illustrated at maximum occupancy. Clearly the performance differences between the air cleaner devices diminishes as the ventilation flow rate increases, with the IESF still having a slight edge over the other devices. Another way to view these data (Figure 7) is to note that devices having higher NQ values require less ventilation for satisfactory performance. This would result in a net savings in heating and air-conditioning costs. For example, the IESF can maintain lower ETS levels with a 5 scfm/person ventilation rate than all the other devices operating with a ventilation rate based on 30 scfm/person. Of course, ventilation rates must also be based on gaseous contaminants and not on particulate matter only.

Typical Lounge. Our field experience with existing (not new construction) lounges shows that, at best, ventilation rates of 5 scfm/person, based on maximum occupancy, are utilized. Hence, the application of the material balance model for the evaluation of the air cleaner devices in lounges uses this ventilation rate. The lounge occupancy, size, and other constants and assumptions are shown in Table 2.

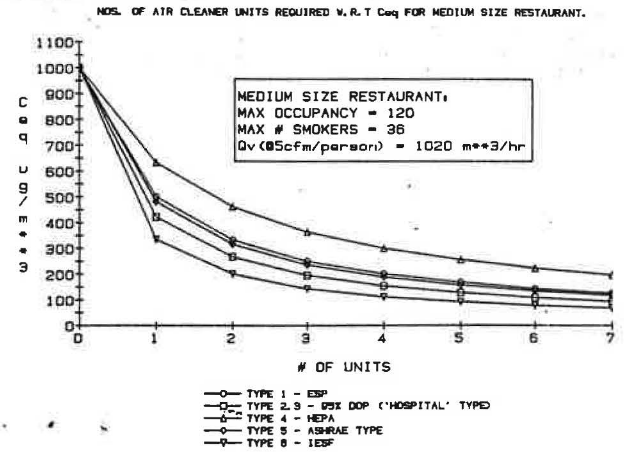

Figure 5 Effect of number of air cleaner units on equilibrium concentration for medium-sized restaurant

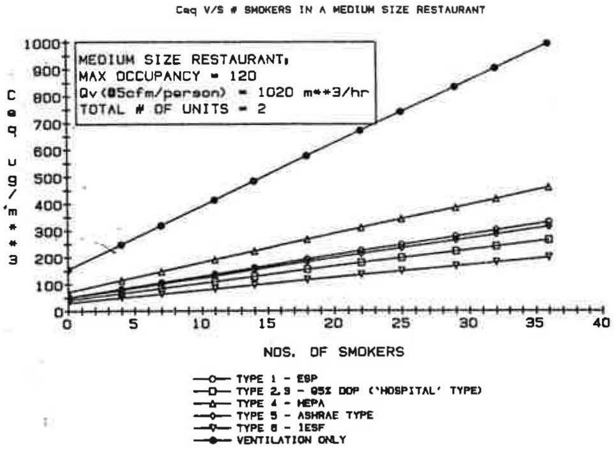

Figure 6 Equilibrium concentration as a function of number of smokers in restaurant

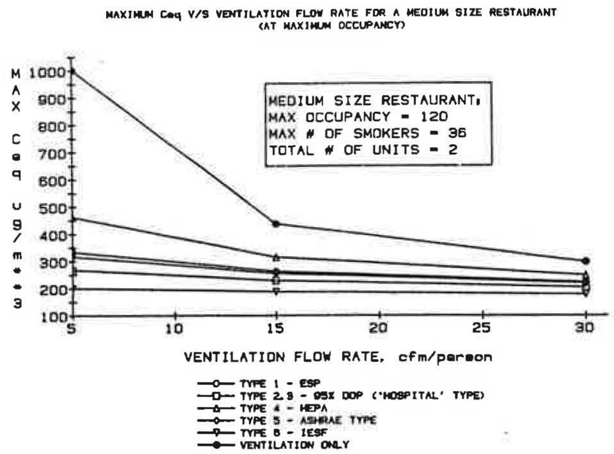

Figure 7 Equilibrium concentration at maximum restaurant occupancy at various ventilation flow rates

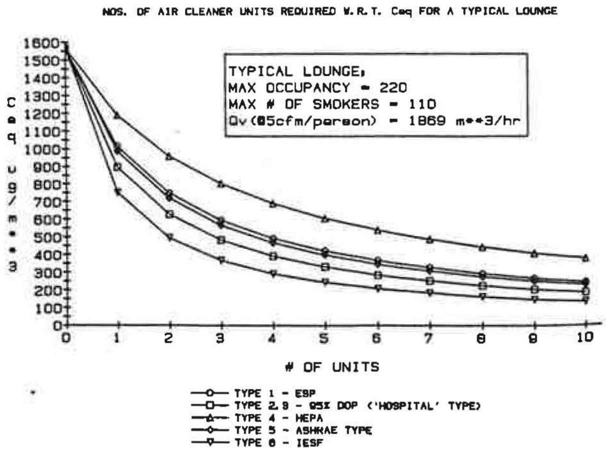

Figure 8 Effect of number of air cleaner units on equilibrium concentration in lounge

Figure 8 for the lounge corresponds to Figure 5 for the restaurant case. In this high occupancy density application, about six IESF units would be required to approach the threshold concentration limit *at maximum occupancy.* The next best unit (hospital-type 95% DOP filter) would require nine installed units. This is not practical or economical since this means that about every 300 ft² of floor space would require one air cleaner. This situation is significantly worse for the other air cleaner devices (Figure 8). Practically, there is room for a maximum of five to six units in this application.

Choosing six units of each type of air cleaner with the existing fixed 5 scfm/person ventilation rate (based on maximum occupancy), the effect of the number of smokers on the air cleaner performance is shown in Figure 9. Only the IESF unit can maintain the ETS concentration at or below the 200 μg/m³ threshold limit at maximum occupancy (110 smokers). The 95% DOP filter (hospital-type) can maintain this limit to about 77 smokers, while the ESP can handle up to 55 smokers at this level. The 95% ASHRAE filter can operate at this threshold level for a maximum of approximately 60 smokers and the HEPA filter, due to its low flow characteristics, would exceed the threshold limit beyond 33 smokers in the lounge. Note, in Figure 9, the excessive ETS concentration with the 5 scfm/person ventilation rate only (i.e., no air cleaner used). By increasing the ventilation rate to 30 scfm/person (based on maximum occupancy), the threshold limit can only be maintained up to about 22 smokers in the lounge.

Large Office Area. The material balance has been applied to a large office area (see Table 2) with a 5 scfm/person ventilation flow rate (using maximum occupancy). The required number of units of each type of air cleaner for this application (with maximum occupancy) is obtained from Figure 10. In this case, one IESF unit has approximately the same performance level (C_{eq} = 173 μg/m³) as two of the ESPs. By comparison, one of the 95% DOP (hospital-type) filters results in an equilibrium concentration of 233 μg/m³. Although higher than the IESF, it is still an effective solution in this particular application.

Figure 11 illustrates the effect of the number of smokers on the ETS equilibrium concentration for one unit of each type of device. Also, the effects of the existing (5 scfm/person) and 30 scfm/person ventilation rates only (i.e., no air cleaner used) are shown in Figure 11. At maximum occupancy, the IESF results in a concentration level of 173 μg/m³, well below the 200 μg/m³ threshold limit, while the 95% DOP (hospital-type) filter is also effective, maintaining the ETS concentration at 233 μg/m³. The ESP is effective, in this sense, only to about 10 smokers in the office. The existing ventilation rate (5 scfm/person) is entirely ineffective without air cleaners, while the higher (30 scfm/person) ventilation rate is effective, without air cleaners, to about six smokers in the office.

SUMMARY

In most applications, properly sized air cleaners can be used at existing ventilation rates (5 scfm/person, based on maximum occupancy) in order to control the irritating aspects of the particulate phase of ETS. Gaseous phase considerations may require higher ventilation rates. Of the devices evaluated here, the ionizing electrically stimulated filter (IESF) air cleaner resulted in the best performance or room cleanliness level when an equal number of units was considered. The 95% DOP (hospital-type) filter was next in terms of effectiveness, followed by the 95% ASHRAE filter and ESP. The HEPA filter was ineffective due to its low flow characteristics. In the three applications considered (lounge, restaurant, and office), in order to match the performance level of the IESF, more units of the other types were required.

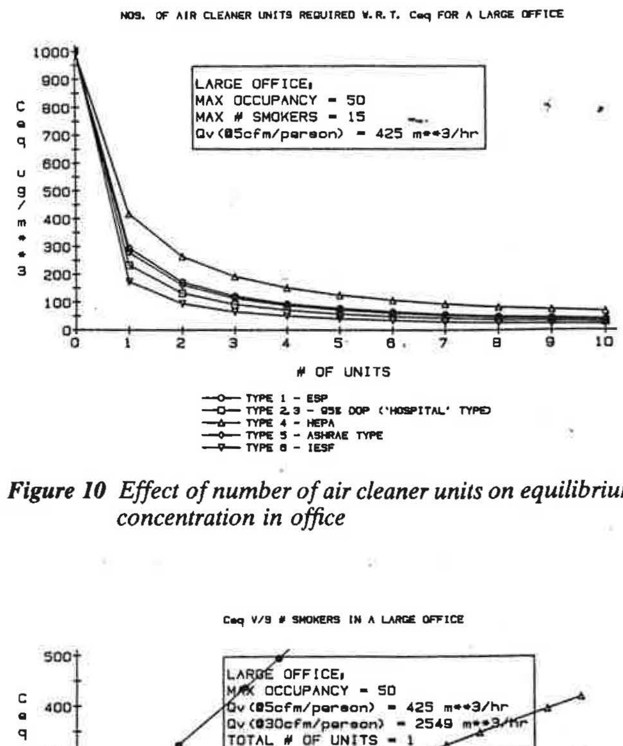

Figure 10 *Effect of number of air cleaner units on equilibrium concentration in office*

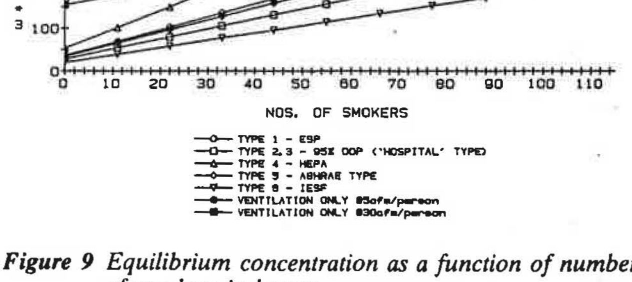

Figure 9 *Equilibrium concentration as a function of number of smokers in lounge*

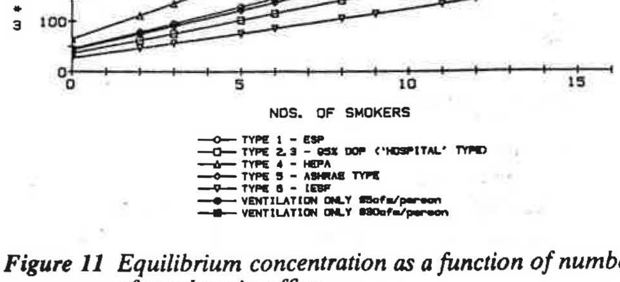

Figure 11 *Equilibrium concentration as a function of number of smokers in office*

A good measure of the effectiveness of a single unit of a particular type of air cleaner is the product of its 0.3 μm DOP efficiency and its flow rating. This product, referred to as the effectiveness factor, has also been utilized by Sutton et al. (1964). The higher this value, the more effective the air cleaner.

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NOMENCLATURE

C = concentration at time, t (mg/m³)
C_a = ventilation air particulate concentration (mg/m³)
C_{eq} = equilibrium concentration reached (mg/m³)
C_o = initial room air particulate concentration (mg/m³)
G = particulate generation rates (mg/h) (depends on number of smokers)
I = total ingression rate of contaminant = $(G + Q_vC_a)$ (mg/h)
K = particulate decay rate constant (h⁻¹)
N = air cleaner efficiency
N_e = effective air cleaner efficiency
N_eQ = product of effective air cleaner efficiency x volumetric flow rate of the air cleaner; effective air-cleaning rate (m³/h)
NQ = effectiveness factor (m³/h)
O = equivalent ventilation flow rate such that the room is maintained at the same equivalent concentration without an air-cleaning device = $(N_eQ + Q_v)$ (m³/h)
Q = total rated flow of air cleaner (m³/h)
Q_v = total ventilation flow rate (m³/h)
t = time (h)
V = volume of indoor space/room (m³)

APPENDIX A
Material Balance Development

Ignoring spatial concentration variation, a material balance equation is set up as follows:

$$V\frac{dC}{dt} = -N\,Q\,C + G - Q_v(C - C_a) - V\,K\,C \quad (1)$$

The first term on the right-hand side of Equation 1 is the particle removal rate by the air cleaner, the second is the generation rate, the third is the net removal rate by ventilation and the fourth term is the particle decay rate, expressed in terms of the decay rate constant K as per Offermann et al. (1985).

Equation 1 can be expressed as:

$$\frac{dC}{dt} + \frac{(N_eQ + Q_v)}{V}C = (G + Q_vC_a)/V$$

where

$$N_e = N + \frac{KV}{Q} \quad (2)$$

Note that V/Q is the inverse of air turnover rate.

The solution to this differential equation is:

$$e^{\frac{(N_eQ + Q_v)t}{V}}C = \frac{(G + Q_vC_a)\,e[(N_eQ + Q_v)t]/V}{N_eQ + Q_v} + K'' \quad (3)$$

Applying boundary conditions $C = C_o$ at $t = 0$

$$K'' = C_o - \frac{(G + Q_vC_a)}{(N_eQ + Q_v)}$$

therefore,

$$C = \frac{I}{O}[1 - e^{\frac{-(Ot)}{V}}] + C_o e^{\frac{-(Ot)}{V}} \quad (4)$$

where:

$$I = (G + Q_vC_a)$$
$$O = (N_eQ + Q_v)$$

Note that I is the net ingression rate, while O is the equivalent ventilation flow rate that would be required to achieve the same room concentration.

The second term on the right-hand side of Equation 4 is the exponential decay if there was no continuous ingression, i.e., the decay of particle concentration in a room that is previously contaminated and the contamination source is eliminated. The time to achieve a certain concentration, C, is then

$$t = \frac{V}{O} \ln [(C_o - I/O)/(C - I/O)] \qquad (5)$$

Note that the numerator of the logarithmic term is the initial net removal rate, while the denominator is the similar net removal rate at the desired or specific concentration.

The equilibrium concentration can be calculated from Equation 4 by applying boundary conditions at $t = \infty$, $C = C_{eq}$

$$C_{eq} = \frac{I}{O} \qquad (6)$$

Note that this is simply the ratio of the total contaminant ingression rate to the "equivalent ventilation" rate. Further, note that for low particle decay rates (or large air cleaner turnover rates), the equivalent concentration does not depend on the room volume.

DISCUSSION

Carl N. Lawson, LRW Engineers Inc., Tampa, FL: If you had tested using 10 or 15 cfm instead of the 5 cfm do you feel the filters could have been smaller?

R.A. Jaisinghani, American Filtrona Corp., Richmond, VA: By increasing the ventilation rate, the size of the filters could be reduced while maintaining the same effectiveness or performance. The reduction in filter size can be calculated by keeping O = (NeQ + Qv) = constant.

Ole Fanger, Technical University of Denmark, Lyngby, Denmark: Our studies in Denmark show that removal of the particles from environmental tobacco smoke did not change the odor, irritation, or acceptability of the air. But particles on walls in the space or on filters can be a substantial source of gaseous emission. Have you any practical solution to this problem?

Jaisinghani: Regarding the comment on the effect of the ETS particulate phase on irritational aspects, I must point out that Weber's results contradict this statement. The ETS particulate phase consists of many irritation-causing components. It is important to use a significantly higher efficiency filtration device to be sure that the particulate phase is removed for such studies aimed at evaluating the irrational aspects of ETS. This is important due to the extremely small size of ETS.

No, as yet there is no practical solution (besides ventilation) for the removal of the vapor phase of ETS. It is important to note that while a filter can accumulate part of the gas phase that may emit from the ETS particles, this in no way contributes to the time average concentration of such emissions. Our experience has not shown this to be a problem in various air cleaner applications.