Practical Methods of Reducing Airborne Contaminants in Interior Spaces

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• Prediction of airborne concentrations of environmentally important contaminants is supported by field test data on tobacco smoke. The analysis discussed herein is completely general in nature, and the contaminants can be gases, vapors, liquid droplets, and solid particulates, including microorganisms and pollens. Several engineering controls can be applied to practical environmental systems to reduce and control undesirable contaminants in normally occupied structures. The use of the method is an important research tool to more accurately quantify airborne contaminant levels in environmental medicine experiments with animals or human subjects. It is difficult and expensive to control inside environmental contaminant levels at values less than 20% to 25% of those occurring outside. The same is true for internally generated contaminants.

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The engineering aspects of contamination control will be treated in this article in the hope that the methods suggested can be an aid to better quantification of contaminant levels in the course of necessary research on living organisms to establish biologic effects. At the same time, the methods make possible a better "feel" for contaminant levels that can be practically attainable in residential, industrial, and commercial applications. As an engineer, I profess no knowledge of the effects on health that may result from reduction of airborne contaminants. Those relationships can be quantified only by medical research.

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The General Nature of the Problem

Air contaminants, for the purpose of this study, include all gases, vapors, liquid droplets, and solids, including microorganisms of small size, that can be dispersed in air and that are unwanted.

Contamination of air in interior spaces can be introduced by a process within the space or it can be present in the surrounding air and thus enter a space with the inevitable and necessary ventilation and leakage.

Contaminants can leave the air by several means. In all cases, dilution with less contaminated air is important. Dilutional air may be from outside the space or it may be reprocessed, recirculated air that has been filtered by one or more of a wide variety of filters and then perhaps heated or cooled. (Filters and the ventilation system comprise the most important and useful practical technology for inside contaminant control.) In addition, particulates can settle out on floors and other surfaces or be electrostatically deposited on the interior surfaces in some cases. Particles, (solid or liquid) can agglomerate and subsequently deposit. Gases and vapors may react with other materials in air or in space, such as drapery fabrics, and either be removed or changed in this way.

Predicted Levels

Figure 1 shows a diagram of a typical space with a practical ventilation system. All important parameters relating to the contaminant concentration are shown. Using the physical parameters of this figure, one can derive a general steady state equation (equation 1)[1]:

$$C_S = \frac{V_O C_O + V_V C_O \ (100 - E) + N_P}{\frac{V_r E}{100} + V_e + K},$$

where C_S represents the steady state inside contaminant concentration; C_O, the outside contaminant concentration; V_O, the infiltration of outside air through cracks and so on (cubic meters per second); V_V, the outside air for ventilation, which passes through the filter (cubic meters per second); E, the filter efficiency (percent in unit time), equal to $100\times$ contaminant trapped in filter/contaminant entering filter; N_P, the rate of contaminant production in the space; V_r, the ventilation system recirculation rate (cubic meters per second); V_e, the rate of air exhausted from the space (cubic meters per second) or $V_O + V_V$; N_S, the particle removal rate, due to settling, chemical reaction, absorption on walls, and so on; K, N_S/C_S, "settling" constant (cubic meters per second). If K is due primarily to particle settling, then K also equals Av, where A is the floor area of the space (square meters) and v is the average particle settling velocity (meters per second).

Note that the units for C_S, C_O, N_P, and N_S can be in any consistent units, depending on the contaminant. For example, C_S and C_O may be in micrograms per cubic meter. Then N_P and N_S would be in micrograms per second. The efficiency, E, would then be a weight efficiency, as measured for the particular contaminant of interest. Examination of equation 1 reveals the following conclusions if C_S is to be minimized:

1. Outside concentration (C_O) should be minimized. Usually this cannot be accomplished. Therefore, the infiltration (V_O) should be minimized (by sealing cracks or by pressurizing the space with more ventilation air [V_V]).
2. The filter efficiency (E) should be

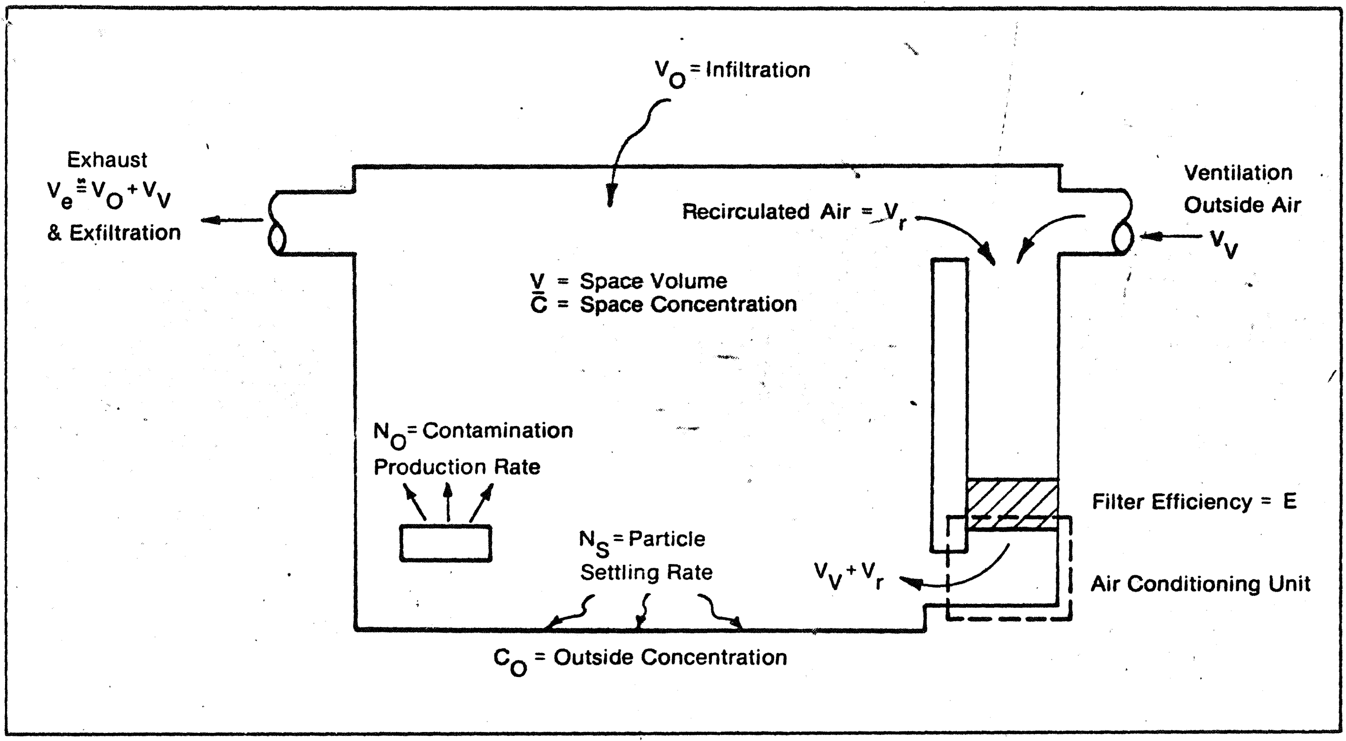
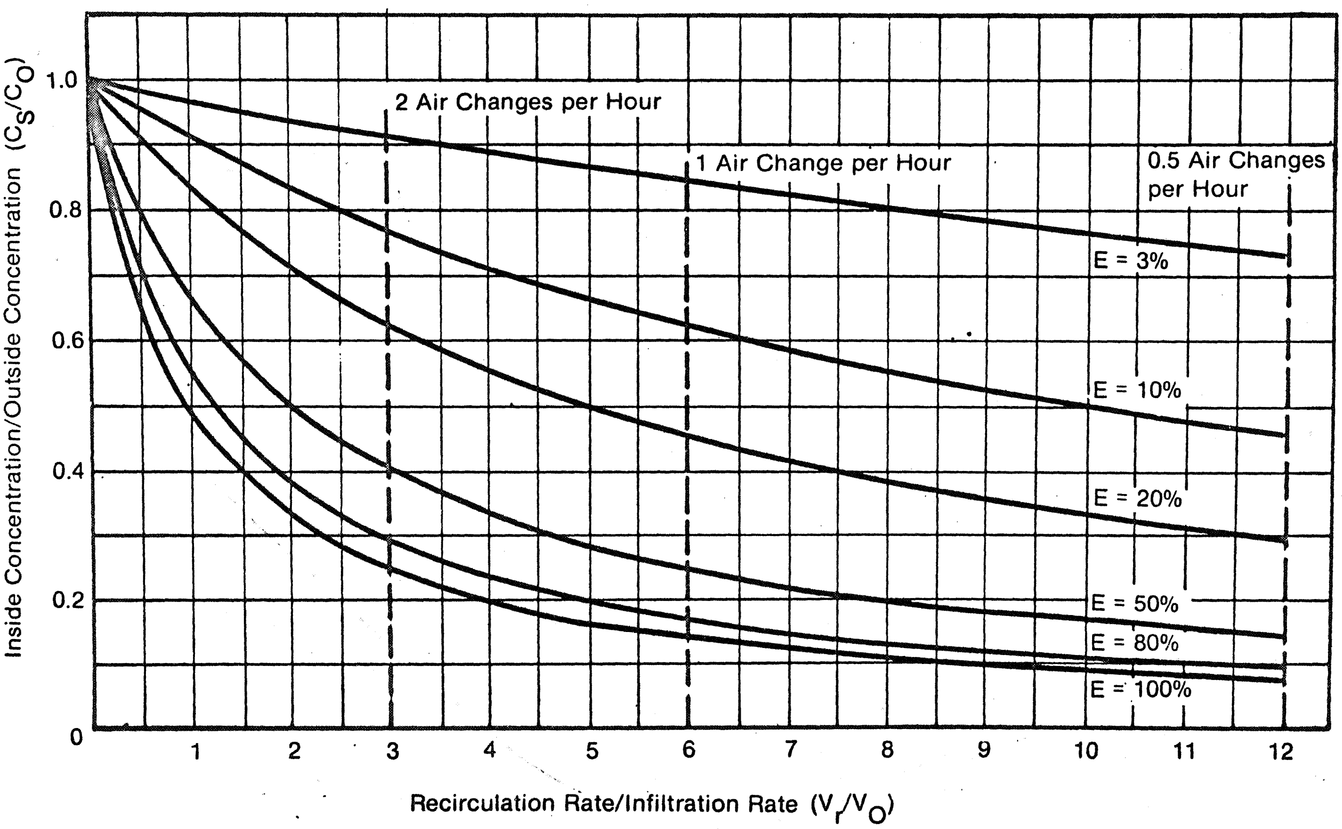


Fig 1.—Typical interior space, including ventilating system and contaminant production.

Fig 2.—Theoretical contaminant concentrations in interior space, including ventilation system with no internal contaminant production.



as high as possible, to minimize (100−E).

3. Internal contamination production (N_p) should be minimized. Often this is not possible.

4. In the denominator, the term V_rE occurs as a product, so *both* ventilation rate (V_r) and efficiency (E) should be large. They are of equal importance in this term. This explains why small portable filters with very low flow rates are not very effective, even if the filters are of high efficiency.

5. The exhaust rate (V_e) should be high, but this is controlled by $V_v + V_o$ and can be costly due to the heating or cooling necessary to control temperature in the space.

6. The "settling" constant (K) cannot usually be controlled, but its effect is to reduce the contaminant level (C_s). So if it is ignored in the predictions, the actual concentration will be lower than the predicted concentration, which is conservative.

Equation 1 can be solved for various practical values of the variables. In this way the effects of filter efficiencies, flow rates, and so forth can be easily demonstrated. Figure 2 shows a solution in a case of an interior space in which there is no production of contaminant inside ($N_p = 0$). Also, the ventilation rate is assumed to be zero, which means that outside air leaks into the space without passing through a filter. In this case, the outside air is the only source of contamination.

The settling rate for particles less than 10μ in size is usually negligible, and atmospheric dust is usually comprised of smaller particles, so K = 0 for this example. Then, equation 1 reduces to equation 2:

$$C_s = \frac{V_oC_o}{V_rE + V_o}$$

It is plotted in Fig 2 for various efficiencies and rates of ventilation. This case approximates an ordinary residence, heated by a warm air furnace. A practical value of $V_r = 6V_o$ is usual. In other words, the ordinary uncontrolled infiltration (V_o) is about one sixth of the flow rate (V_r) through the furnace system. This is indicated by a dashed line on Fig 2, and also represents an infiltration rate of one complete air change in the residence per hour. A less well-constructed house could have two air changes per hour, and this level ($V_r/V_o = 3$) is also indicated, as is an extremely well-constructed residence, where only one half air change per hour occurs.

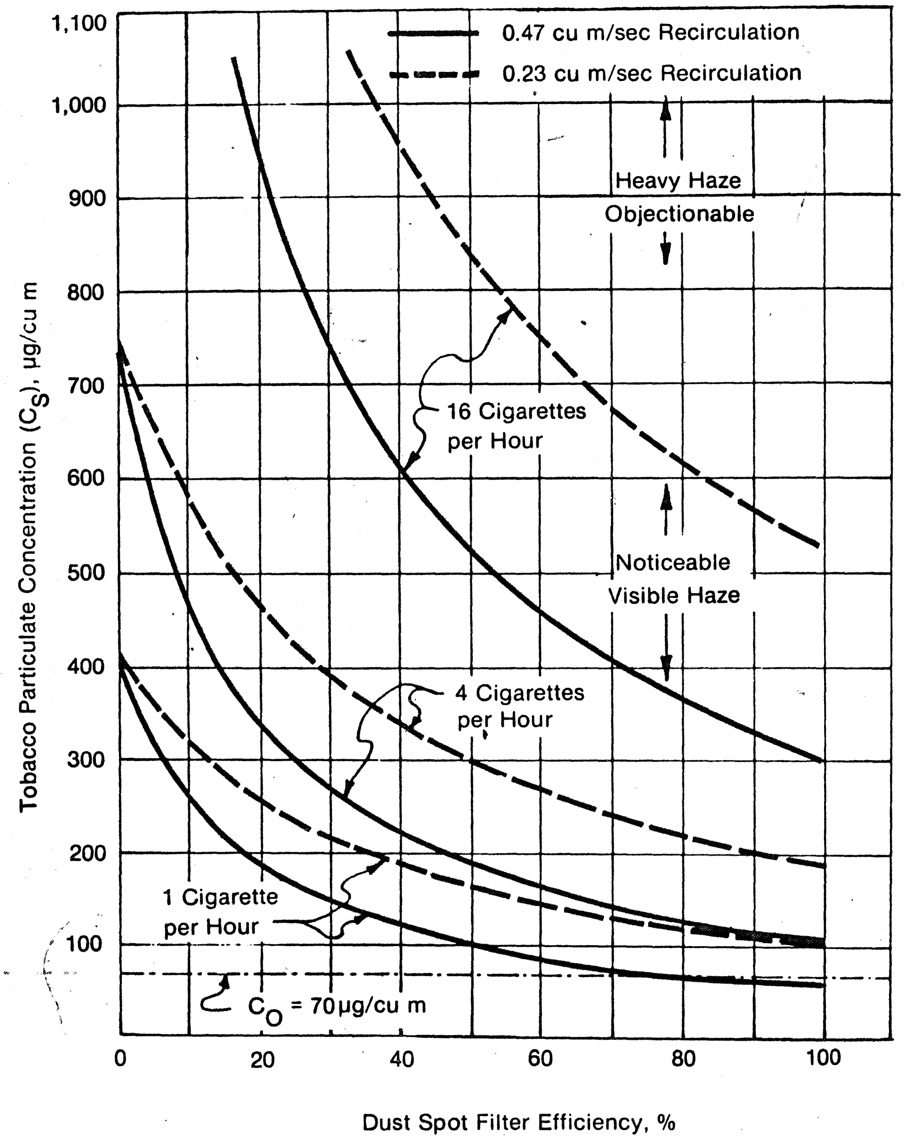


Fig 3.—Theoretical contaminant concentrations in interior space, including ventilation system and cigarette smoking.

Conclusions to be drawn from Fig 2 are as follows:

1. For any V_r/V_o, a diminishing return is clearly noted as the efficiency of the filter increases. Hardly any practical improvement is evident as the efficiency increases beyond 80%.

2. Another diminishing return is evident as the recirculation rate (V_r) increases. This recirculation rate is the air flow capacity of the heating (and sometimes) cooling system installed. To increase air flow larger fans, ducts, and so on must be employed, at increased first cost and operating cost. An economic limit clearly exists.

3. It also appears totally impractical to obtain inside air concentrations less than 10% the outside concentration. However, with an 80% efficient filter and practical air flows, inside concentrations of less than 25% of the outside are possible.

One important exception might be mentioned, and that is pollen. Most pollens are about 20μ in diameter and settle rapidly. For pollen, indoor con-

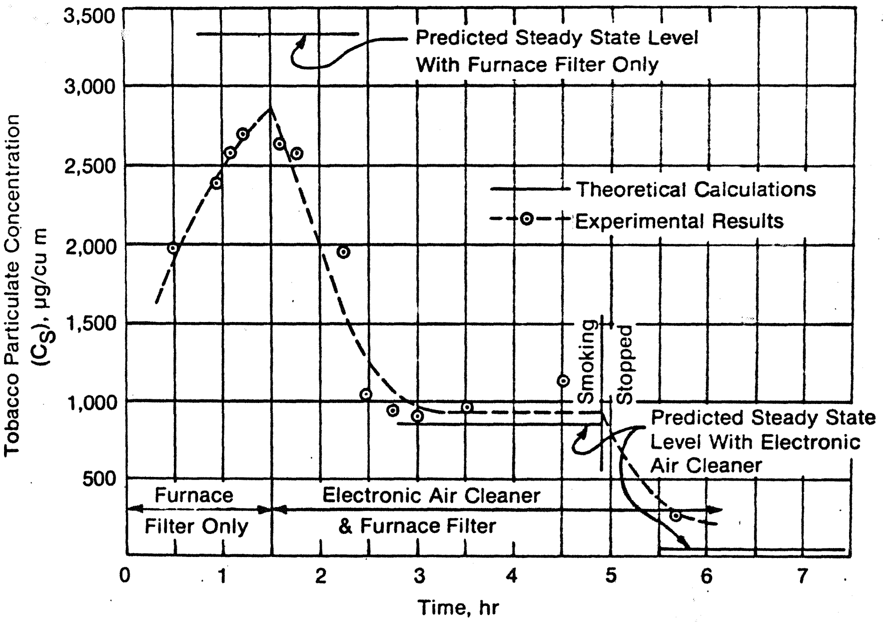


Fig 4.—Measured contaminant concentrations in residence showing effect of high-performance electronic air cleaner when cigarettes were smoked in machine (35 per hour).

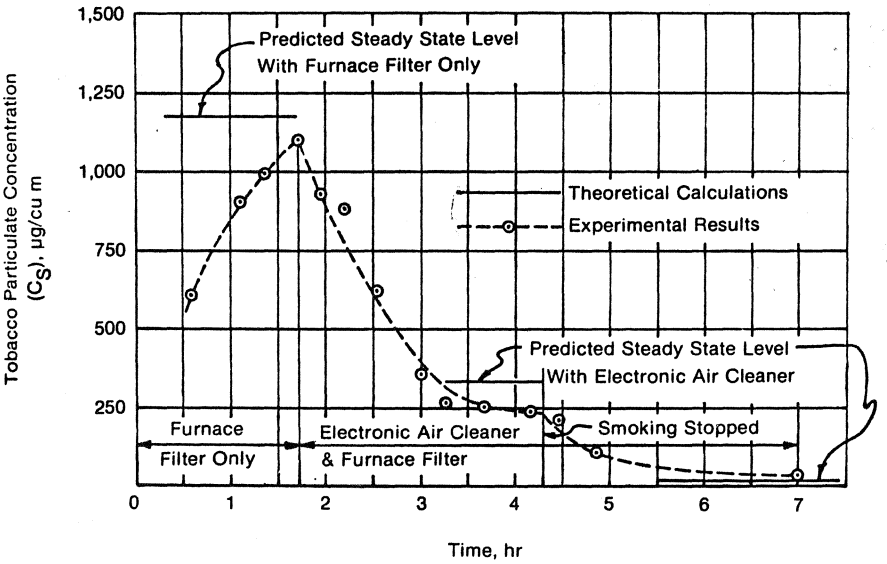


Fig 5.—Measured contaminant concentrations in residence showing effect of high-performance electronic air cleaner when cigarettes were smoked in machine (12 per hour).

centrations of less than 10% of the outside are easily possible with good filters in practical systems.

Figure 3 shows a somewhat different case when cigarette smoking occurs within a typical residence. In this case, equation 1 reduces to equation 3:

$$C_S = \frac{V_O C_O + N_P}{V_r E + V_O}$$

where C_O equals $70\mu g$/cu m (a relatively clean outside contamination level); V_r equals $6V_O$ (typical residence); and N_P equals the production of contamination due to cigarette smoking, or $40{,}000\mu g$ per each cigarette smoked.

Examination of Fig 3 shows that the cigarette smoking at the rates assumes is far more important than the outside concentration, and only with good filters and low smoking rates is it possible to obtain as low a concentration inside as outside. The diminishing return of improvement with filter efficiency is also evident.

Field Validation Experiments

In order to validate the theoretical equations, several field tests[1] using tobacco smoke as the contaminant were conducted. Tobacco smoke was used because it is a common, reproducible, and well-known contaminant. In addition, it is small in size (0.1μ to 3μ) and has a negligible settling rate. Its production rate (N_P) is fairly well known, and it is certainly one of the most important contaminants from the point of view of health and annoyance. For the following tests, cigarettes were smoked in a smoking machine, which "puffed" them for a few seconds each minute to a butt length of about 18 mm.

A three-bedroom residence was selected, and its warm-air heating system was calibrated for air flow and equipped with an ordinary furnace filter (about 10% efficient on cigarette smoke). In addition, an electronic filter was also fitted, which was about 85% efficient on cigarette smoke. It could be energized or deenergized at will. Similar results have been demonstrated using high-efficiency media filters also, and the choice of filter types for comparable efficiencies is not important to performance. The smoking machine was in a basement amusement room, and the smoke concentrations were measured in the return air duct ahead of the filter and furnace, representative of the mixed location.

The characteristics of the experimental residence important to this study are as follows:

Total interior volume	425 cu m
Recirculation rate (V_r)	0.35 cu m/sec
Electronic air cleaner efficiency "dust spot" (E)	85%
Furnace filter efficiency "dust spot" (E)	10%
Infiltration (V_O)	0.06 cu m/sec
Outside air contaminant concentration (C_O)	$60\mu g$/cu m

Figure 4 shows the results of one test, where smoking was at the rate of 35 cigarettes per hour and Fig 5 shows a 12-cigarette per hour rate. In both cases, as shown, the electronic air cleaner was energized after the tests were under way.

Equation 3 was used to predict the solid lines shown in Fig 3 and 4, and the circled points show the measured values, connected by the dotted curves.

The measured results are in excellent agreement with the theoretically predicted results and support the practical use of the theory. Much noticeable and subjectively objectionable haze and odors existed in both cases until controlled by the electronic air cleaner.

In addition, several other field tests[2-5] also support these results.

Filter Efficiencies and Filter Types

As equation 1 shows, the engineering system controls are the efficiency of the filter and the air flows obtained. The measurement and design of air systems is commonly understood by practicing engineers. Filters, however, are not as well understood. Filters for particulate contaminants, to be used in general ventilation systems designed for human occupancy, such as residences, offices, and so on, are rated by their manufacturers by two methods.

The first is the weight method, in which an artificial dust is fed to a sample filter and the amount retained is weighed and divided by the amount fed to calculate the efficiency number. Filters rated by this method are designed primarily to protect heating and cooling equipment from fouling, and assign very great importance to large particles. Therefore, this rating is not usually useful for health-related contaminants that can be deposited in the lungs (approximately 1μ to 15μ).

The second method is the "dust spot" method, which is more useful for present purposes. It heavily weighs particles in the 0.1μ to 2μ range and is directly applicable to tobacco smoke. Since small particles are more difficult to filter, good filters with "dust spot" efficiency numbers of 70% to 95% are comparatively expensive. The American Society of Heating, Refrigerating, and Air Conditioning Engineers[6] publishes standards for air-cleaner evaluation.

The filter industry does not usually publish efficiency vs particle size information, since there are no standard methods and the experimental techniques are expensive. However, existing information[7] can be of help in selecting filters.

In general, particulate filters fall into two classes, media types and electrostatic types. Media filters are usually glass or other fibers, formed into mats of varying thickness and density. By using variable density, thickness, fiber diameter, and so forth, a wide range of efficiencies is possible with media filters. Pressure drop increases with efficiency of filtration, and so does cost. Service life is also reduced, so that, in general, the higher the efficiency, the shorter the life before discarding, and the higher the cost per unit time. Most media filters are disposable. Some metal mesh ones can be washed and reused, but these are low-efficiency types.

Electrostatic filters, on the other hand, are almost always washable and have useful lives similar to other ventilating equipment. Their initial cost is much higher than media filters, but the life cycle cost may be less. Electrostatic filters are almost always high efficiency, and also have relatively low pressure drops. They also produce ozone in small quantities, which in itself may be annoying to a small fraction of the population, but most good filters operate in practical spaces well below the current threshold limit of ozone concentration.

Only activated charcoal is currently recommended for removal of vaporous contaminants. Charcoal adsorbs these and has, of course, a finite capacity, after which, heavier molecules usually replace lighter ones, already adsorbed, and release the lighter ones into the downstream air. After saturation, charcoal can be reactivated by the supplier for reuse. The charcoal granule size, bed thickness, and air velocity are all variables in filter design that affect the efficiency, life, and pressure drop. Efficiency is usually rated using a single vapor, such as carbon tetrachloride, but most manufacturers have data on many other common contaminants.

For either particulate or vapor applications, the manufacturer of the filter should be consulted to be sure that the filter will perform as expected on the contaminant of interest. This is often a difficult problem due to the wide variety of contaminants.

Conclusion

A rational theory for predicting air contamination levels in laboratory experiments or in field situations has been verified with tobacco smoke as the contaminant. The use of this theory in conducting medical research and in establishing practical contaminant threshold limits may aid in furthering this important area of public health.

In practical indoor spaces, such as residences and offices, it is not often economically feasible to use filtration and dilution technology to control contaminant levels much below 20% to 25% of the levels that would occur in most interior spaces under usual installation of heating, air conditioning, and ventilating systems. However, reductions to these figures have been shown to have a significant subjective effect on annoyance of human subjects.[1-4]

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