CHAPTER 10

Air Cleaners for Indoor Air Pollution Control

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ABSTRACT

Indoor air pollutants include both particles and gases, and different technologies are required to control these pollutants. An experimental study was conducted to evaluate the performance characteristics of currently available control technologies. One aspect of the study was to evaluate the particle-size dependent collection efficiency of seven commercially available devices for control of particles: one common furnace filter, four industrial-grade filters, and two electronic air cleaners (EACs). The furnace filter had negligible effect on particles in the size range 0.1 to 1 mm (i.e., those that penetrate deep into the human lung). The industrial-grade filters, which had ASHRAE ratings of 95, 85, 65, and 40%, exhibited a minimum efficiency at approximately 0.1 mm, which was substantially lower than the ASHRAE efficiency. Of the two EACs, one was essentially a furnace filter with a high-voltage electrode while the other was similar to an industrial electrostatic precipitator (ESP). The furnace-filter type of EAC reached a maximum efficiency of 30% at low flowrates (7 m^3/min); however, it had Ra negligible effect at higher flowrates (14 and 20 m^3/min). The ESP-like EAC exhibited efficiencies from 80 to 90% over the entire size range at low to moderate flow rates. At the highest flowrate, a minimum efficiency of 60% was detected at 0.35 mm. Measured ozone emission rates for the EACs were used to estimate a worst-case ozone exposure in a typical residential environment. The worst-case scenario yielded a maximum concentration of 60 ppb. Actual concentrations would be much lower.

Another aspect of the study was to evaluate the suitability of commercially available carbon-based sorbents for removing low concentrations of volatile organic compounds (VOCs). A laboratory experiment was conducted to measure the capacity of three different carbons (wood-, coal-, and coconut-shell-based carbons) for three different VOCs (benzene, acetaldehyde, and 1,1,1-trichloroethane) at low concentrations (100–200 ppb). Measured capacities ranged from 10^{-8} to 10^{-6} g-mol/g carbon. Model calculations based on a challenge concentration of 150 ppb and a breakthrough concentration of 50 ppb indicated that commercially available 15 cm (6 in) thick in-duct carbon filters would have a bed life on the order of minutes.

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INTRODUCTION

The growing awareness of indoor air pollution has been accompanied by a growing interest in air cleaners to remove pollutants from the air. Although air cleaners have been on the market for many years, there is very little information available on how well these devices work. Within the past few years, the U.S. Environmental Protection Agency (EPA) has begun research programs to evaluate various aspects of indoor air pollution. One such program is being conducted at the Research Triangle Institute (RTI) to evaluate indoor air cleaner technologies.

Indoor air pollution can be divided into two categories: gases and particles. Gaseous pollutants include VOCs, combustion products, and other substances. The VOCs in indoor air are the result of emissions from clothing (e.g., chemicals used in dry cleaning), building materials (e.g., plywood), carpeting, and upholstery. Products of combustion result from cooking and gas heat and include carbon dioxide and carbon monoxide, among other gases. Any or all of these gases may be present in indoor air at one time. This study focused on removal of VOCs from indoor air. The novel aspect of this problem in the context of indoor air is the low concentrations that are encountered. Typical concentrations that may be found in an indoor environment are on the order of 100 ppb. Because no isotherm data have been published for sorbents at these concentrations, it is not clear how well air cleaners will work in an indoor environment.

Airborne particles are the result of cooking, smoking, infiltration of dust and pollen from outdoors, and everyday activities in the home or office. While all particles can be a nuisance, the particles of most concern are those with a diameter between 0.1 and 1 µm. These minute particles penetrate deep into the human lung and may be of concern from a health standpoint.

The purpose of this report is to describe the results of our research program to evaluate five air filters and two electronic air cleaners (EACs), and to evaluate three different carbon sorbents that are typical of those used for removal of vapors from indoor air. The experimental approach and the results obtained are described below.

PARTICLE AIR CLEANERS

There are two main types of indoor air cleaners: in-duct and room cleaners. In-duct cleaners are installed within heating, ventilating, and air-conditioning (HVAC) systems. Room air cleaners contain a filter and perhaps an absorber with a self-contained fan. The control approach used in both cases includes fibrous filtration, electrostatic precipitation (ESP), and/or electrostatically augmented filtration. Vapors are usually absorbed by activated carbon. A more complete description of the hardware may be found in the *ASHRAE Handbook*.[1] Recently, the Association of Home Appliance Manufacturers published a standard test procedure[2] for evaluating room air cleaners. However, only in-duct air cleaners were considered in this research.

Filter Test Results

The filter efficiency tests were conducted in the apparatus illustrated in Figure 1. The test section of the system has back-to-back stainless steel filter holders that can accommodate filters as large as 60 × 60 cm (2 × 2 ft). System ducting is 20 cm (8 in) diameter polyvinyl chloride (PVC) both upstream and downstream of the test section. Thus, for a given flow rate, the air velocity through the ductwork is much greater than that through the test section. The resulting turbulence enhances mixing of the particles in the gas stream and improves accuracy in velocity measurements and particle sampling.

The test section is maintained at 1 cm H_2O positive pressure to prevent inleakage of aerosol, which would bias the results. In addition, the test section is enclosed within a Class 100 clean room. Depending upon the test and the allowable background aerosol concentration, the test air may be drawn either from the clean room airflow or from the ambient laboratory air. Aerosol penetration ratios as small as 10^{-8} have been measured with this apparatus.

The aerosol sample taps are located just upstream of the test section and also sufficiently far downstream of the test filter to allow for the complete mixing of any penetrating aerosol with the entire airstream. Running the downstream ducting back under the filter holders locates the challenge and penetrating aerosol taps near each other, thereby allowing short sample lines and reducing particle losses. The losses in the ductwork were found to be insignificant for the particle sizes of interest.

Aerosol instruments used for the tests included a PMS, Inc. Laser Aerosol Spectrometer (LAS-X), a Climet 226/8040 Optical Particle Counter (OPC), and a TSI Differential Mobility Particle Sizer (DMPS). The laser counter was used to measure the particles from 0.009 to 3 µm, the OPC from 0.3 to 3 µm, and the DMPS from 0.011 to 0.457 µm.

Airflow was monitored with a digital thermal anemometer probe placed at the center of the duct. Duct traverses and pitot probe measurements were used to determine the flowrate. The pressure drop of the air cleaner was measured with an included manometer.

An aerosol generated by nebulizing aqueous solutions of potassium chloride (KCl) was used as the particle challenge. The mean diameter of the dry residue of KCl was controlled by the strength of the solution and was varied during the test to cover the range from 0.01 to 3 µm.

Five filters were tested at three flowrates: 7, 14, and 28 m^3/min. One filter was a common household furnace filter and the other four were industrial grade filters with ASHRAE ratings of 40, 65, 85, and 95% efficiency.

An example of the results obtained for a furnace filter is shown in Figure 2. Even at the lowest flowrate (7 m^3/min), the filter had a negligible efficiency for

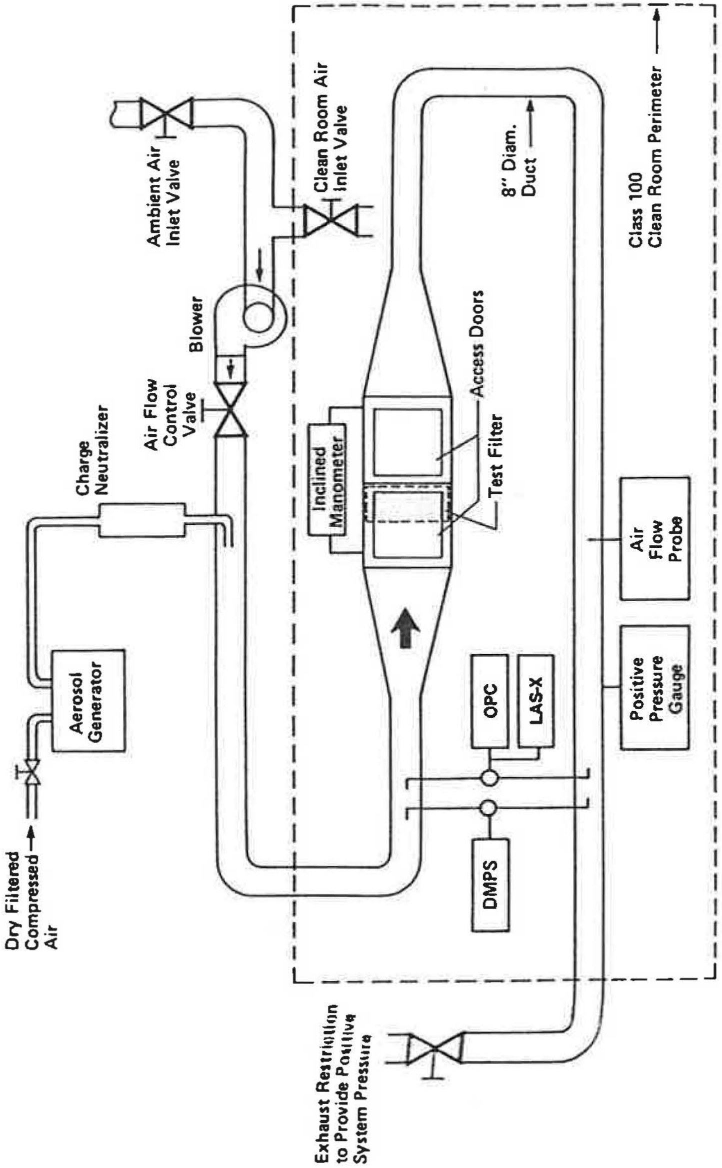

Figure 1. Schematic diagram of ultra-high efficiency filter testing facility.

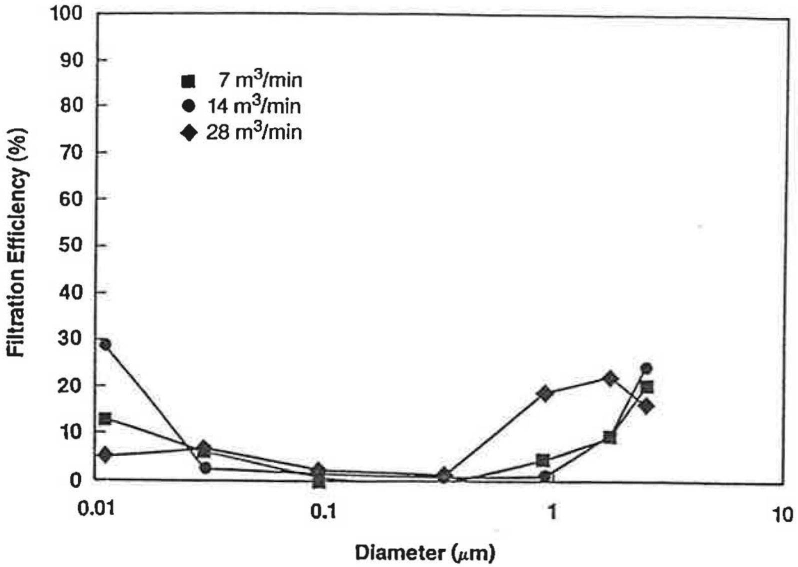

Figure 2. Filtration efficiency vs. particle diameter for the furnace filter.

removal of small particles (i.e., those smaller than 1 μm). The particles between 0.1 and 1.0 μm deposit deep within the human lung. At higher flowrates (14 and 28 m^3/min) the collection efficiency decreased. These results reflect the fact that furnace filters are designed to prevent dust balls from clogging the heat transfer surfaces of furnaces and air conditioners and are not intended to protect human health.

Particles between 0.1 and 1.0 μm also affect equipment, especially electronic equipment.[3] Particles in this size range deposit on vertical as well as horizontal surfaces. A large fraction of submicron particles consist of water-soluble salts. When the relative humidity rises above the deliquescence point of these salts, they can cause current leakage, shorts, and corrosion. Resulting failures cost U.S. companies millions of dollars per year and are of concern wherever highly integrated electronic equipment operates.

Industrial-grade filters are somewhat more effective at collecting small particles. Figure 3 represents the size-dependent efficiency for four filters at their rated flowrate (14 m^3/min). All of the curves show a sharp dip in the efficiency curve, with a minimum near 0.1 μm. The general shape of these curves is typical of filters. For particles larger than 1 μm, the dominant collection mechanisms are interception and impaction. For particles smaller than 0.1 μm, diffusion is the dominant collection mechanism. Filter efficiencies are always worst for particle sizes between 0.1 and 1.0 μm. An important observation about the data is the

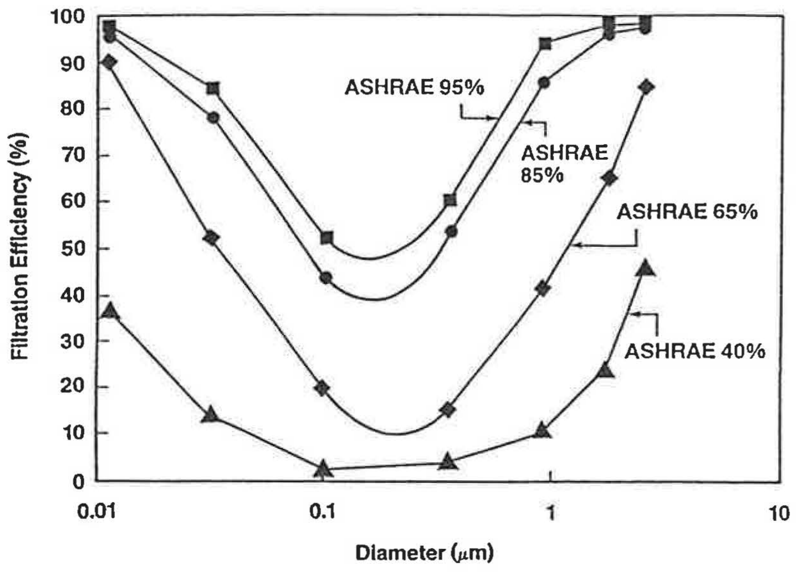

Figure 3. Filtration efficiency vs. particle diameter for the four ASHRAE-rated filters at a nominal flow rate of 14 m³/min.

discrepancy between the size-dependent efficiencies and the ASHRAE efficiencies. As mentioned above, the ASHRAE test procedure is biased toward large particles. While a filter may collect 95% of particles larger than 1 μm, as many as 50% of particles with a diameter of 0.1 μm penetrate the filter. This points out the weakness of relying on a single number for designation of efficiency. Nevertheless, the industrial filters (with the possible exception of the ASHRAE 40% filter) would serve as good collectors of pollen and other natural aerosols, which tend to have large diameters (5 μm and larger).

EACs

Another way to remove particles from an airstream, either as an adjunct to or in place of filtration, is electrostatics. Several devices have been developed to incorporate electric fields into filters, and some devices combine an ionizing section as well to charge incoming particles. On the other end of the spectrum is the conventional wire-plate ESP in which there is no filtration medium and particles are removed entirely by the charging and electrostatic collection of aerosol particles.

One design of EAC is illustrated in exploded view in Figure 4a. This design, hereafter referred to as the "furnace filter design", consists of high-voltage wires sandwiched between a lightweight, open foam collection medium. Metal grilles on

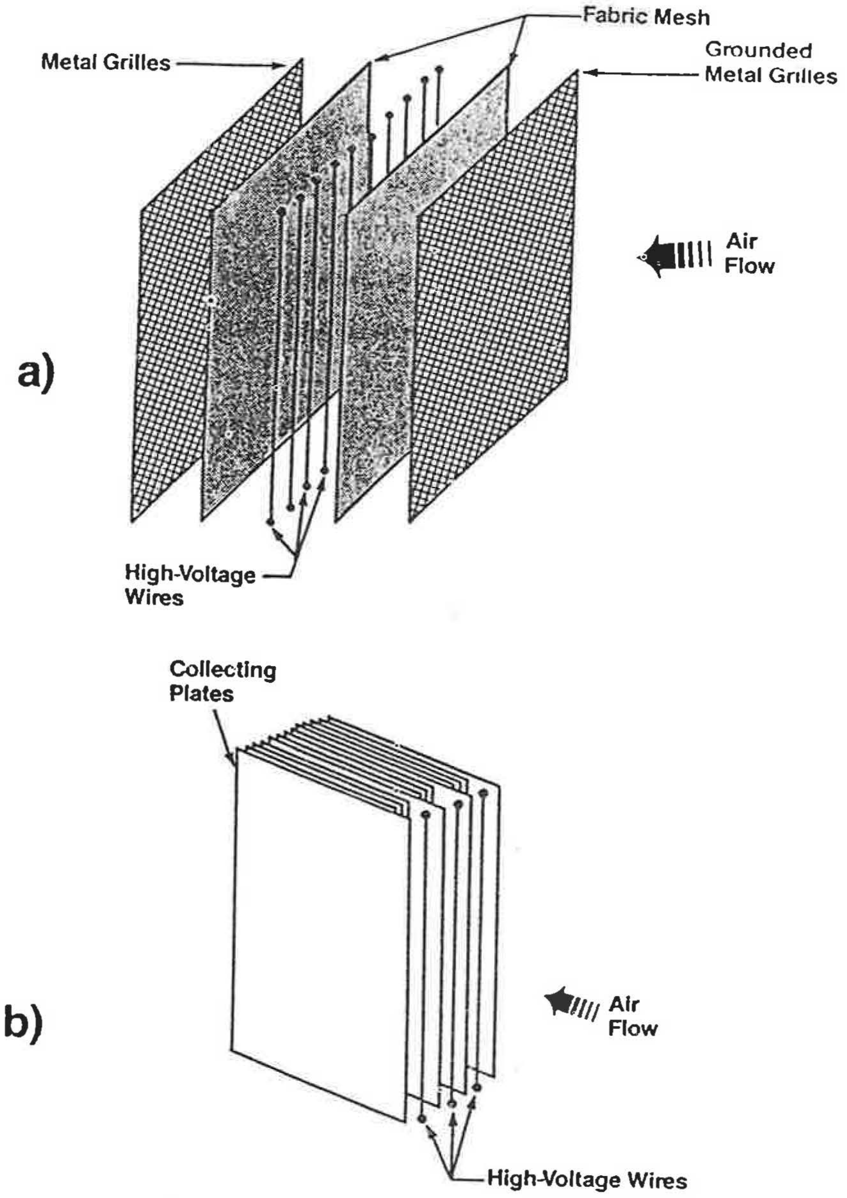

Figure 4. (a) The "furnace filter" design for electronic air cleaners; (b) the wire plate design.

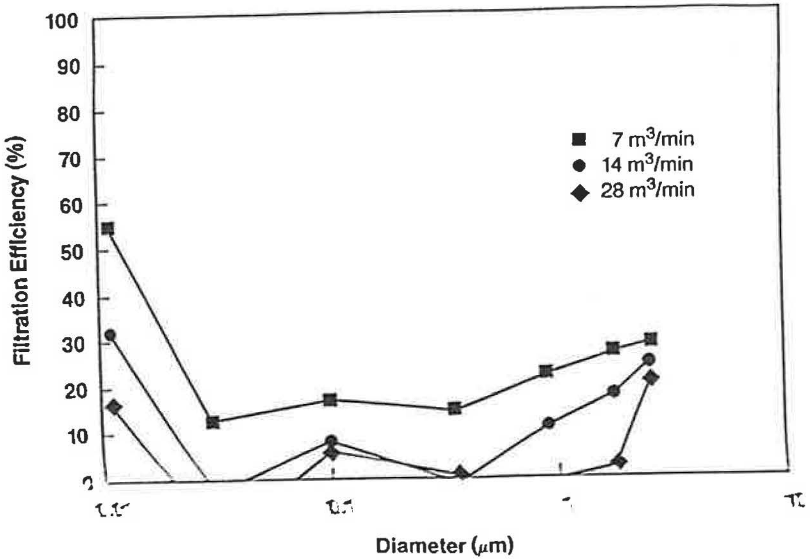

Figure 5. Filtration efficiency vs. particle diameter for Electronic Air Cleaner No. 1.

the outside of the foam serve as ground planes for the electric field. Nonconductive spacers maintain a separation of approximately 12.5 mm between the high-voltage wires and the metal grilles, for a total grille-to-grille width of 25 mm. The unit is designed to replace a conventional furnace filter and thus is easy to install. For safety, the power control unit for the device includes a flow-sensor switch so that the high-voltage current is only on while air is flowing through the device.

The size-dependent collection efficiency of this air cleaner is shown in Figure 5 for three different airflow rates. Except for the smallest particle size at the lowest flowrate, the collection efficiency was consistently below 30%. At moderate to high flowrates (14 and 28 m^3/min) the collection efficiency was even worse. By comparison with the results obtained for a conventional furnace filter (Figure 2), it appears that, for all practical purposes, the use of electrostatics does not improve the efficiency of the filter. As with a conventional furnace filter, this device may be appropriate for removal of large dust balls and thereby provide some protection to the heat-transfer surfaces of a furnace/air conditioner; however, it does not appear to be useful in removing particles that are most likely to affect human health.

A more rigorous design for an electronic air cleaner is shown in Figure 4b. This wire-plate design is very similar to that of ESPs used in industrial plants to control dust emissions. It consists of a parallel array of electrically grounded plates spaced approximately 0.5 cm apart. Airborne particles entering the device acquire a charge from the ions generated by the high-voltage electrode. The charged particles then travel through the channels bounded by the grounded plates, which are 12 cm long. The length of the channel provides sufficient residence time to attract and collect the charged particles onto the plates.

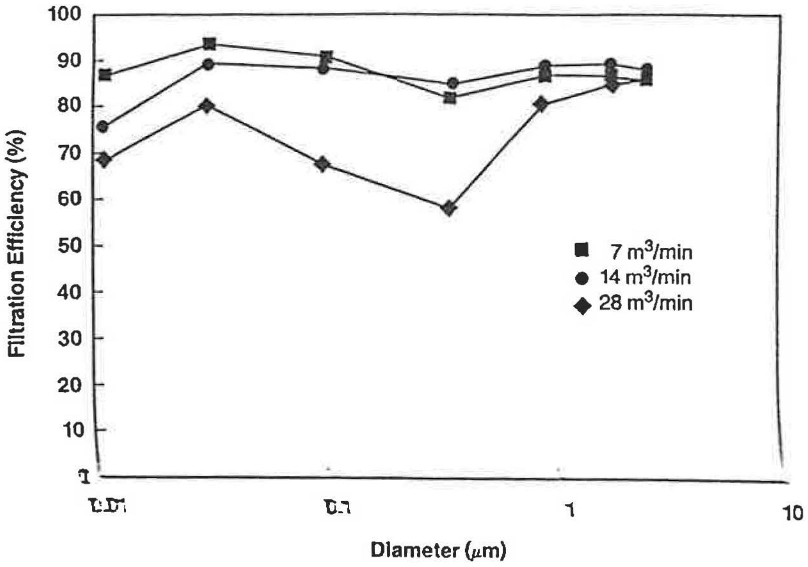

Figure 6. Filtration efficiency vs. particle diameter for Electronic Air Cleaner No. 2.

The filtration efficiency of this device is shown in Figure 6 for three flowrates (7, 14, and 28 m^3/min). At low and moderate flowrates (7 and 14 m^3/min), the efficiency ranged from 75 to over 90% over the entire size range. At the highest flow rate there is a dip in the efficiency curve at 0.35 μm. The decrease in efficiency with increasing flowrate was a result of the reduced residence time in the collection section of the air cleaner. Overall, however, this EAC performs quite well when compared with the industrial filters.

In comparing the performance of EACs and industrial filters, it should be noted that, up to a point, the efficiencies of filters improve as they "load dust". The converse is true for EACs. As their plates load, they become less efficient. Routine inspection and maintenance is even more important with EACs than with filters. (With filters, the pressure drop provides an easily monitored indicator of loading.)

Ozone Emissions from EACs

High electron energies, such as those found in ESPs, induce a number of chemical reactions in gas molecules surrounding electrodes. These gaseous reactions are fundamental steps inherent in electrical breakdowns rather than incidental side effects. Ozone is one of the products that result from electronic excitation of oxygen.

The hazardous nature of ozone has prompted several studies of ozone generation by electrostatic discharges over the last 50 years. Castle et al.[4] conducted one of the more rigorous studies by quantifying ozone generation in a cylindrical ESP using positive corona. Their results confirmed the work of White and Cole,[5] which showed that the ozone production rate is proportional to the power input to the electrode. Based on these results, Castle outlined a set of design criteria for electronic air cleaners to minimize the production of ozone, the most important of which was to use a positive polarity for the discharge (corona) electrode. Virtually all electronic air cleaners designed for indoor air applications use positive corona and are otherwise designed to minimize ozone generation while maximizing collection efficiency. Nevertheless, a small amount of ozone is still generated. The objective of this task was to quantify the ozone generation rate and to estimate the effect on indoor air quality.

The ozone generation rate was measured for both the "furnace filter" EAC and the wire-plate model. The apparatus used to measure ozone emissions is shown schematically in Figure 7. An ultrasonic humidifier was used to inject a water aerosol into room air. The water droplets were evaporated in a mixing chamber, after which the air was introduced into the ozone generation section where the air cleaner was placed. Ozonated air exiting from the air cleaner was funneled into a 10 cm diameter glass pipe through a Teflon®-lined transition section. The glass pipe was 2.4 m long to provide adequate mixing of the ozone in the turbulent air stream. Ozone concentration, air velocity, and dewpoint were measured at the exit of the glass pipe. Given flat profiles for both concentration and air velocity, the total ozone generation rate (in micrograms per second) was calculated from the measured values.

The results obtained from these measurements are summarized in Figure 8, which presents ozone generation rate as a function of humidity at the measured current (i.e., 1.3 mA) for both air cleaners. It appears that the effect of humidity on ozone generation is negligible below 50% relative humidity (R.H.); however, there is a 25% decrease in generation rate as the R.H. increases from 50 to 80%. Interestingly, ozone generation from the furnace-filter EAC was substantially lower than that from the wire-plate EAC. However, given the poor performance of the furnace-filter EAC for removing respirable particles, we shall focus on the wire-plate EAC.

A worst-case estimate of potential ozone exposure can be obtained by considering the use of the wire-plate air cleaner in a typical residential application. A simple dilution model can be used to estimate the steady-state concentration of ozone:

$$C = \frac{q\,C_{\text{outside}} + S / V}{q + k} \qquad (1)$$

where

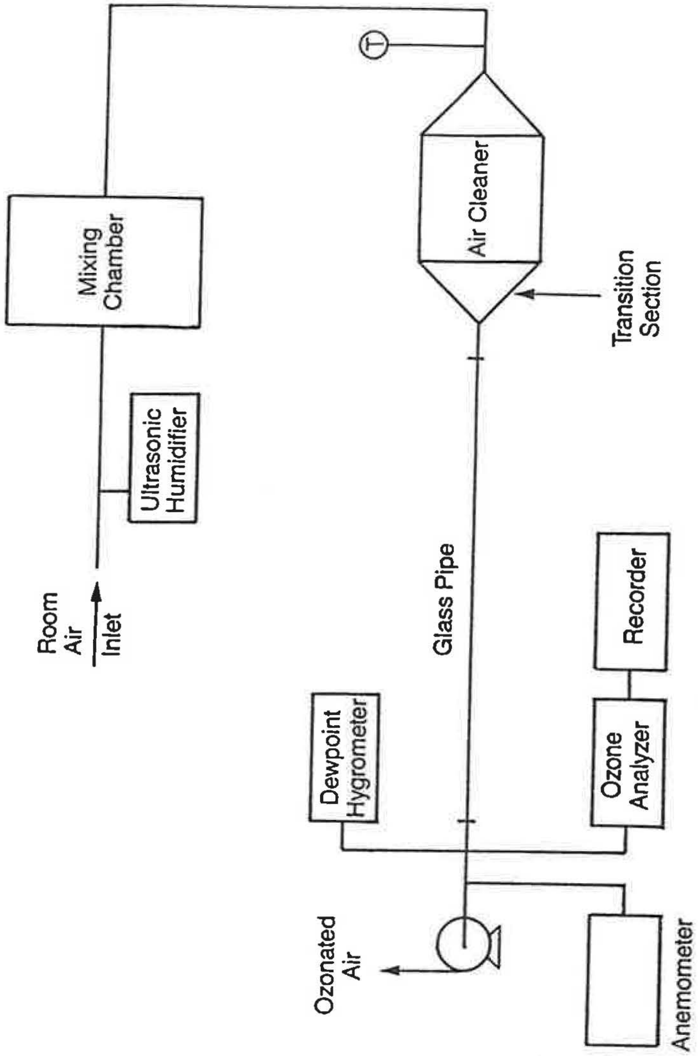

Figure 7. The ozone generation test apparatus.

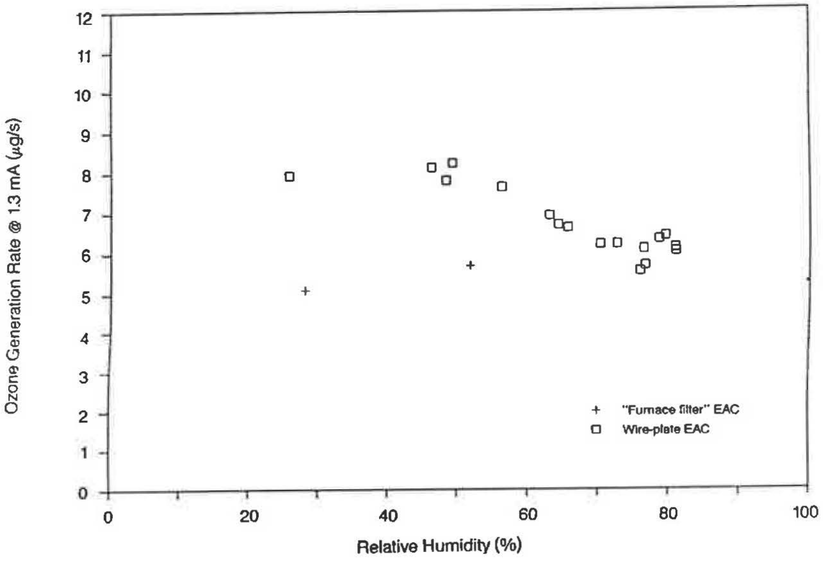

Figure 8. Measured ozone generation rates from commercial air cleaners.

C = ozone concentration (mg/m^3)
q = air exchange rate (h^{-1})
$C_{outside}$ = ozone concentration in the outdoor air (mg/m^3)
S = rate at which the pollutant is generated (mg/h)
V = volume of the house/room (m^3)
k = rate of removal due to processes other than ventilation (h^{-1})

For this worst-case scenario, dilution is the only mechanism for reducing the ozone concentration, so that $k = 0$ (in actual settings, k is nonzero). In addition, we wish to consider only the contribution from the air cleaner, so we will ignore the concentration of ozone in the outside air ($C_{outside} = 0$). Finally, we will consider a fairly "tight" house with a typical volume (456 m^3, equivalent to a 187-m^2 house with 2.44-m ceilings), so that the air exchange rate is fairly low (i.e., $q = 0.4$ h^{-1}). The ozone generation rate for the wire-plate EAC is approximately 6 mg/s or 21.6 mg/h. Given these parameters, Equation 1 yields a steady-state ozone concentration of 0.118 mg/m^3 (approximately 60 ppb). For comparison, the OSHA Permissible Exposure Limit for an 8-h period is 0.196 mg/m^3. Note that the calculated value (0.118 mg/m^3) is based on continuous ozone emissions; however, air cleaners only operate intermittently. In addition, we have neglected any destruction mechanisms that would further reduce the concentration. Thus, it appears that in actual applications the ozone emissions from electronic air cleaners would have a negligible effect on indoor air quality.

Control of VOCs

There is a wide variety of sources of VOCs in indoor air. These sources vary tremendously depending on the nature of the facility, but often include contributions from outdoor air that enters the building through leaks and through the HVAC system. Other typical sources include combustion, smoking, building materials, and office machines. Various studies of indoor air quality have identified more than 250 organics at levels greater than 1 ppb[6] with total VOC concentration expected in the few hundred parts per billion range and not exceeding a few parts per million.[7,8]

A variety of methods have been proposed for control of VOCs. The most obvious methods are source removal and ventilation. These methods have received the most attention as control strategies. However, source removal is not always practical, and increasing the ventilation rate can result in prohibitively high HVAC costs. Other possible control strategies include adsorption, absorption, incineration, and catalytic conversion. All have demonstrated applicability in conventional pollution control applications and could be incorporated into an HVAC system with minimal retrofit. However, adsorption onto carbon seems to be the most popular technique currently in use for indoor applications.

The majority of adsorption systems currently marketed for indoor air pollution applications deal with odor control. These systems consist primarily of in-duct carbon filters. Quantifiable performance data are not available for any of the systems surveyed. The carbon in each unit is assumed to be spent when occupant complaints increase. Obviously, this method of bed lifetime estimation has drawbacks, particularly for potentially toxic compounds that have relatively high odor thresholds. Adsorption isotherm data in the low concentration regime (<10 ppm) are not publicly available for even simple compounds on any carbons. This led to our effort to obtain adsorption isotherms in the parts per billion range in order to determine the applicability of activated carbon adsorption for indoor air pollution control.

Experimental Design

Three types of activated carbon were tested: a coal-based carbon, a wood-based carbon, and a coconut-shell-based carbon. The activation method for all of these carbons was by steam, and surface areas ranged from 1050 to 1150 m^2/g. The pollutants chosen were relatively simple, low-molecular-weight compounds representative of three different classes of organic compounds: benzene (aromatic hydrocarbon), acetaldehyde (oxygenated hydro-carbon), and 1,1,1-trichloroethane (halogenated hydrocarbon).

The experimental setup is shown in Figure 9. It consisted of two mass flow controllers with flow ranges of 0 to 1000 and 0 to 100 cm^3/min, a microbalance, a thermostated water bath for the permeation tubes, and a balance jacket.

The microbalance used for the adsorption studies is capable of weighing up to 100 g with an accuracy of ±0.5 μg. This device may be operated under low-temperature, high-vacuum conditions for the determination of BET surface area

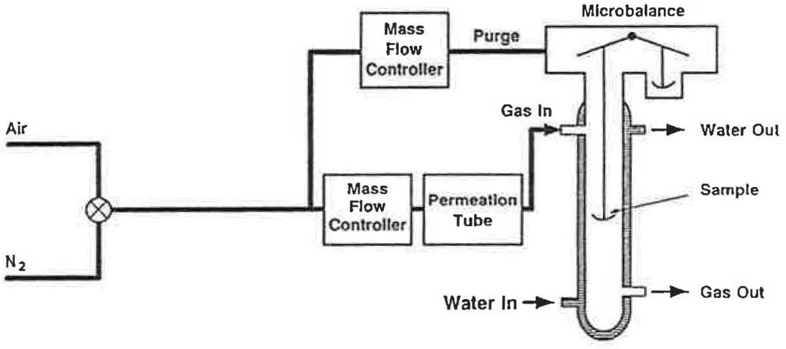

Figure 9. Schematic of the carbon adsorption experimental setup.

and is ideally suited to make adsorption isotherm measurements under different conditions of pressure and temperature.

Isotherms were measured in the dynamic (flow) mode at atmospheric pressure to reduce experimental time and to measure adsorption under conditions representative of real-work situations. The carbon sample (150 to 200 mg) was degassed under flowing nitrogen while being heated with an infrared lamp. Degassing was assumed to be complete when the weight remained constant for 10 to 15 min. The sample was then allowed to cool in nitrogen. Next, the nitrogen was switched off and an airstream was introduced through the permeation tube. The challenge concentrations were generated with clean, dry airstreams flowing over permeation tubes with certified permeation rates. Flow rates were adjusted to give the desired concentrations. All gases had purities greater than 99.999%.

Equilibrium was assumed when the weight gain (on the 100-µg scale) leveled off.

Results

The results for the uptakes of organic pollutants on the various carbons are summarized in Table 1. It is apparent that the capacities (g-mol/g carbon) do not vary much with either compound or carbon in the concentration range studied. Capacities ranged from 10^{-8} to 10^{-6} g-mol/g. Acetaldehyde uptake was about two to three times higher than for the other compounds studied.

While isotherm data are useful for carbon screening, they do not provide direct practical information on the applicability of the technique. For this reason, the weight of carbon required was estimated using a method based on carbon capacity recommended by the manufacturer of two of the carbons[9] and a fixed bed breakthrough model developed at RTI. These methods were used to substantiate the results. The superficial velocity of gas across the filter was assumed to be 12.7 cm/s, corresponding to a flow of 2.8 m³/min (100 cfm) across a 60 × 60 cm (2 × 2 ft) filter. An exit concentration of 50 pbb was set as the level corresponding to useful bed life.

Table 1. Summary of Adsorption Results

Compound	Concentration (ppb)	Uptake[a] (× 10^7)		
		Wood-base	Coal-base	Coconut shell-base
Acetaldehyde				
mol CH_3CHO/g C	119	3.39	3.52	10.0
	153	4.17	10.00	10.0
Benzene				
mol C_6H_6/g C	101	2.42	1.24	4.30
	119	4.30	6.47	5.60
	176	10.00	7.27	6.33
1,1,1-Trichloroethane				
mol CH_3CCl_3/g C	115	0.749	1.15	2.04
	183	1.33	2.80	1.19

[a] Each number represents an average of 3 to 4 data points.

Table 2. Calculated Carbon Bed Lifetime (15 cm)

Gas	Concentration (ppb)	Lifetime (min)		
		Wood	Coal	Coconut shell
Benzene	100	1.02	0.52	1.82
	120	1.54	2.29	2.01
	176	0.24	1.76	1.54
Acetaldehyde	119	1.22	1.26	7.14
	153	1.16	2.79	2.79
1,1,1-Trichloroethane	115	2.78	0.43	0.76
	183	0.31	0.55	0.45

The first method was applied to the data for all three compounds with challenge concentrations varying from 115 to 183 ppb. The lifetime for 15 cm (6 in.) thick filters (such as those typically marketed for odor control applications) was determined. The results in Table 2 show that breakthrough occurs rather quickly, bringing into question the applicability of a once-through filter even in the absence of other pollutants or humidity effects, both of which would cause performance to deteriorate further.

The second method, the RTI program, was applied only to the benzene data. MA regression analysis was performed to obtain a linear equation for benzene adsorption on the coconut-shell-based carbon. The challenge concentration was assumed to be 150 ppb, and the other variables were set as before. The results of the simulation are listed in Table 3. Again, breakthrough is shown to occur

Table 3. Variation of Exit Concentration with Bed Depth[a]

T = 4320 h (6 mo)		T = 30 h	
L (m)	C exit (ppb)	L (m)	C exit (ppb)
334.57	115	2.48	55.6
338.01	99.5	2.53	35.1
346.64	67.2	2.56	20
354.51	40.6		

[a] 150 ppb benzene challenge, 12.7 cm/s superficial velocity, 3.0-mm particle size, coconut-shell-base carbon.

quickly. Conversely, the bed length required to obtain any reasonable lifetime is prohibitively large.

This result reinforces the conclusions from the first method calculations that filter life would be extremely short, making these filters of negligible value as in-duct indoor air filters. However, it is important to note that the level at which acceptable breakthrough is set is critical to bed lifetime. In the absence of toxicological data, this level may have to be set rather arbitrarily, erring on the side of caution.

The results of this study are also supported by or verify the results reported by Daisey and Hodgson.[10] Both studies show that the small quantities of carbon used in panel and duct filters appear to have limited usefulness in controlling indoor air VOCs. Carbon devices using more complex flow schemes, involving parallel beds with regeneration, may work, but they may be uneconomical except in very large-scale applications. Carbon adsorption may be viable for major surges in concentration such as spills or releases, which push the ambient concentrations into regimes where the shape of the isotherm is more favorable and sufficient driving force exists for a reasonable uptake.

CONCLUSIONS

Air filters designed to remove particulate pollution from indoor air exhibit a minimum efficiency in the size range of importance to human health. Furnace filters provide virtually no protection from airborne particles, while industrial (ASHRAE-rate) filters do provide some protection. Nevertheless, the ASHRAE method for evaluating filter efficiency is biased toward large particles and is therefore an inadequate indicator of the protection that may be expected.

A properly designed EAC (i.e., the ESP design) can remove particles over the entire size range 0.01 to larger than 3 mm; however, the furnace filter EAC offers no advantage over the standard furnace filter in this size range. Ozone emissions from an EAC should not be of concern in a typical residential application.

Based on the measurements reported here, it appears that carbon-based sorbents at ambient conditions are not well suited for removing low levels of VOCs. Model predictions based on measured carbon capacities indicate that commercially available carbon-based duct filters are of limited utility for removing low concentrations of VOCs from indoor air.

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