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ABSTRACT

Eleven portable air cleaning devices have been evaluated for control of indoor concentrations of respirable particles using *in situ* chamber decay tests. Following injection of cigarette smoke in a room-size chamber, decay rates for particle concentrations were obtained for total number concentration and for number concentration by particle size with and without air cleaner operation. The size distribution of the tobacco smoke particles was log normal with a count median diameter of 0.15 μm and a geometric standard deviation of 2.0. Without air cleaner operation, the natural mass-averaged surface deposition rate of particles was observed to be 0.1 h^{-1}. Air cleaning rates for particles were found to be negligible for several small panel-filter devices, a residential-sized ion-generator, and a pair of mixing fans. Electrostatic precipitators and extended surface filters removed particles at substantial rates, and a HEPA-type filter was the most efficient air cleaner studied.

keywords: air cleaning, ion-generator, particle deposition, electrostatic filtration, indoor air quality, mechanical filtration, residential buildings, respirable particles, tobacco smoke.

INTRODUCTION

As residential ventilation rates are reduced through weatherization measures or new construction practices, indoor pollutant concentrations may increase. One strategy for controlling indoor air contaminants in residences that is receiving increased consideration, especially for particulate phase contaminants, is air cleaning. Air cleaners for control of particulate matter are available as both in-duct devices, which are designed to be integrated with a forced-air heating/cooling system, and as unducted devices which are portable and designed primarily for cleaning the air in one room. In the past few years a variety of portable residential air cleaners have appeared on the market. Aggressive national advertising along with an increased consumer awareness of indoor air pollution has resulted in the rapid formation of a $150 million/year market (ACHR, 1982) embracing approximately 50 manufacturers. Prices range from $10 to $450 with the majority of the sales going to manufacturers of the less expensive fan-filter units ($10-40). Because there is currently no standard evaluation procedure or test program for these air cleaners, little information regarding their performance is available to consumers beyond the general claims of the manufacturers. The results of the few published evaluations of these devices (Whitby et al., 1983; New Shelter, 1982) indicate a wide range in performance.

The indoor environment contains a wide variety of particles and particle sources. Combustion-generated particles arise from tobacco smoking, use of unvented combustion appliances (e.g. gas ranges and kerosene heaters), and wood stoves or fireplaces. Other sources include infiltration of outdoor particles, cooking, cleaning, human and pet dander, use of aerosol sprays, and the wear and sloughing of building materials.

Particles may be intrinsically toxic due to their chemical or physical characteristics (e.g. lead, asbestos) or they may act as a carrier of an adsorbed toxic substance (e.g. BaP, HCHO, radon progeny). Carbon particles, such as those created by combustion processes, are efficient absorbers of many organic compounds and are able to carry toxic gasses such as sulfur dioxide into the lungs. Tobacco smoke particles are spherical droplets of hundreds of condensed chemicals, some of which are known tumor initiators.

The health effects resulting from inhaling particles depend on both their chemical composition and the site at which they deposit within the respiratory system. The probability of a particle being deposited in a specific region of the lung is mainly a function of the aerodynamic diameter of the particle. Particles less than 3 μm in diameter have a high probability of being deposited in the pulmonary regions of the lung, while larger particles are deposited in the protected upper portion of the respiratory system (Task Group on Lung Dynamics, 1966). Adverse health effects are typically associated with particle deposition deep in the unciliated tracheobronchial or alveolar regions of the lung where particles have long residence times.

While control of gaseous indoor contaminants such as carbon monoxide, formaldehyde, and odorous substances in general, are best controlled by ventilation or source removal, control of particulate contaminants may be achieved with high efficiency mechanical or electrostatic air cleaners. The removal of particles from air by mechanical filtration is accomplished by passing the air through a fibrous medium. The deposition mechanisms of impaction, interception, and diffusion predom-

inate for different conditions of particle size and air velocity. The relationship between filter efficiency and particle size is shown in Figure 1 for a typical fibrous filter. For particles less than 0.1 μm in diameter, diffusion is the dominant removal mechanism while interception and inertial impaction account for the removal of particles larger than 1.0 μm. Because these two mechanisms dominate in different size ranges, all filters have a particle size that gives a minimum efficiency. Depending on the fiber size, fiber density, and air flow rate, the particle diameter at which the minimum efficiency occurs can range from 0.05 to 0.5 μm. The collection efficiency of an electrostatic air cleaner is a function of air flow rate, collection surface area, and particle migration velocity (i.e., mobility). Particle collection efficiency will vary with particle migration velocity which is a function of particle size. As with mechanical filters, a minimum collection efficiency occurs for particles in the size range of 0.05 to 0.5 μm. Particles greater than 1.0 μm have higher mobilities because particle charging increases as a function of particle size while particles smaller than 0.1 μm have higher mobilities because aerodynamic drag decreases as a function of particle size.

In this paper we discuss an *in situ* measurement technique for evaluating the performance of portable air cleaners, and report the results from the evaluation of ten different models of air cleaners. The behavior and control of radon progeny, studied in conjunction with the experiments described here, are discussed in another paper (Sextro *et al.*, 1984).

EXPERIMENTAL PROTOCOL

Air Cleaning Performance Parameters

Currently there are no standard methods for testing or rating portable air cleaners. The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) have a standard testing procedure (ASHRAE, 1976) for evaluating ducted air cleaning devices but in its present form it is not applicable to the evaluation of unducted devices. Furthermore the ASHRAE tests for arrestance and dust-spot efficiency do not give specific information regarding the efficiency of removing respirable-size particles. In order to evaluate the effect of ion-generators on particle removal it is necessary to conduct an *in situ* test without the aid of mixing fans since these devices normally rely on natural air movement to transport charged particles to surfaces in the room. Several researchers have used *in situ* measurement techniques which are appropriate for evaluating the performance of portable air cleaning devices (Offermann *et al.*, 1983; Whitby *et al.*, 1983). The test procedure normally involves filling a room-size chamber with a contaminant, mixing the air to obtain a uniform initial concentration, and measuring the contaminant decay rate with and without the air cleaner operating. The increase in the contaminant decay rate observed with the device operating is used to calculate the air cleaning rate of the device. If the flow rate of air through the device is known, a system efficiency may be calculated.

If an air cleaner is operating in a chamber of volume V, there is no significant internal source of particles, and the rate at which outdoor particles infiltrate into the chamber is negligible, then the following

differential mass balance equation describes the decay rate of the average particle concentration, $\overline{C}$, within the chamber:

$$\frac{d\overline{C}}{dt} = -\frac{Q_v C_{ex}}{V} - K\overline{C} - \frac{Q_d(C_{in} - C_{out})}{V}, \quad (1)$$

where

Q_v = the flow rate of ventilation air (infiltration and mechanical ventilation),

C_{ex} = the concentration of particles in the outgoing ventilation air,

K = a constant that accounts for removal of particles by mechanisms other than ventilation (e.g. surface deposition),

Q_d = the flow rate of air through the air cleaning device,

C_{in} = the concentration of particles in the air entering the air cleaner, and

C_{out} = the concentration of particles in the air leaving the air cleaner.

To characterize the "device efficiency", (i.e. the efficiency of the air cleaner in removing particles), we use the expression

$$\eta = \frac{(C_{in} - C_{out})}{C_{in}} . \tag{2}$$

To relate the concentration of particles in the air entering the air cleaner to the average indoor concentration, we define a short-circuiting factor (E_d),

$$E_d = \frac{C_{in}}{\overline{C}} . \tag{3}$$

Because of the close proximity of the inlet and outlet of a portable air cleaner, short-circuiting of air may occur from the outlet to the inlet, thus, we expect that E_d will typically be less than unity. Similarly we can relate the concentration of particles in the outgoing ventilation air to the average indoor concentration by a nominal ventilation efficiency (E_v),

$$E_v = \frac{C_{ex}}{\overline{C}} . \tag{4}$$

Substituting the expressions contained in equations (2-4) into (1) yields

$$\frac{d\bar{C}}{dt} = -\left[\frac{E_V Q_V}{V} + K + \frac{\eta E_d Q_d}{V}\right]\bar{C} \ . \qquad (5)$$

This equation describes the decay rate of the average particle concentration in a chamber. The decay is exponential and proceeds at a rate determined by the decay constant which is represented by the bracketed terms in equation (5); $E_V Q_V/V$ describes the rate of particle removal by ventilation, K describes the rate of removal by deposition on surfaces (coagulation and chemical reactions are negligible mechanisms in these experiments), and $\eta E_d Q_d/V$ describes the rate of removal by an air cleaning device. The decay constant may be determined by fitting the experimental data of concentration and time to an exponential curve. If two tests are made, one with and one without an air cleaner operating, and if we assume that the removal by ventilation and deposition are the same for both tests, then the difference between the calculated decay constants represents the rate of removal by the air cleaner, $\eta E_d Q_d/V$. If the ventilation rate is measured separately during the experiment as from a tracer gas decay measurement, only the surface deposition rate need be assumed to remain constant.

Two parameters that we calculate from our data are the effective cleaning rate (ECR), and the system efficiency. The ECR is the difference in the observed particle decay rates with and without the air cleaner operating multiplied by the chamber volume. This calculation yields an air flow rate that represents the effective amount of particle free air produced by the air cleaner. The ECR is particularly useful when estimating the effects of the device in various size rooms or in comparing air cleaning to ventilation as an indoor air quality control

technique. The system efficiency is the ECR divided by the actual air flow rate through the air cleaner.

The previous expressions relate the performance of the air cleaner to the decay rate of the average indoor particle concentration. One difficulty with this approach is that it requires an accurate measure of the average concentration within the enclosure. A common means of monitoring the average concentration is to vigorously mix the chamber air with fans during the test. A problem with this technique is that it can improve the performance of devices such as ion-generators which rely on natural air movement to transport particles. Mixing also obscures air cleaner inefficiencies resulting from short-circuiting. Another technique which may be employed is to use an elaborate multi-point sampling manifold, however, the complexity of such a probe makes this an unattractive and cumbersome option. We note, however, that it is not necessary to measure the average concentration to determine the decay rate of the average concentration. Sandberg (1981), Malstrom (1982), and others have shown mathematically and experimentally that with imperfect mixing of indoor air and an initially uniform pollutant concentration, the decay rate initially varies from location to location depending on the distribution pattern of clean air, but eventually the decay rate at all locations become equal. Thus, this equilibrium decay rate measured at any location will equal the decay rate in average concentration and can be used to characterize the performance of an air cleaner. From our experience with chamber decays without mixing fans the equilibrium decay rate is established quite quickly.

Test Space Description

The experiments were carried out at the Indoor Air Quality Research House (IAQRH) located at the University of California, Richmond Field Station. The research house is a two-story, wood-frame structure containing a three-room test space that has been extensively weatherized to reduce the infiltration rate below 0.1 air changes per hour (ach). Tests of the unducted control devices were performed in one room within this test space; a floor plan of this room is shown in Figure 2. The interior of the room, measuring 3.4 m by 4.6 m by 2.4 m high, is constructed of plasterboard for three walls and the ceiling, and plywood for the fourth wall. All these interior surfaces are painted white. The floor is covered with sheet vinyl. The net air space volume, accounting for displacement by equipment, is 35.1 m^3. The surface-to-volume ratio of the room and equipment is estimated to be 2 m^{-1}.

The approximate locations of the particle sources, instrumentation, particle sampling points, and the control device under test are indicated in Figure 2. An aerosol mass monitor was located at position 2, relative humidity and temperature probes were located near the center of the room, and a cigarette smoking machine was located at position 5. The unducted control devices were either table-top models, which were placed on a small wooden table located at position 3, or larger, console-type devices which were usually placed directly on the floor at position 3. Some devices were also tested at an alternative location - position 4 - near the center of the room in order to minimize possible effects of nearby walls.

Instrumentation

The instrumentation installed at the IAQRH is part of two computer-based data acquisition, monitoring, and control systems. The first of these systems acquires real-time indoor environmental data and provides programmable control over the operation of the experiment. Data are stored by a cartridge magnetic tape recorder (Columbia Data Products, Model DC300D) and are simultaneously printed by a terminal (Teletype, Model TTY 43). The operation of the various systems under computer control can be pre-programmed or directly executed during the course of the experiment.

Particle Measurements: Control and data logging for particulate instrumentation is provided by a second dedicated micro-computer system. Instrumentation is located on the second floor of the IAQ Research House and is connected to the test space via a 6-m-long, 1-cm-diameter copper sampling line. The end of this sampling line is 1.8 m from the floor of the test room. Air is drawn continuously from the test space, through the instrumentation manifold at 5 l min^{-1}, and then exhausted back into the test space. Total aerosol concentration is measured with a condensation nucleus counter (CNC) (TSI, Model 3020). The CNC also samples the output concentration of the electrostatic classifier (EC) (TSI, Model 3071); this procedure provides particle size and concentration data for particles with diameters between 0.01 and 0.3 μm. The optical particle counter (OPC) (PMS, Model LAS-X) uses a He-Ne laser as a light source and has a dynamic range specially adapted to measure particle size and concentration in the size range 0.09 - 3 μm. The OPC was calibrated for size using both polystyrene latex (PSL) spheres and tobacco smoke parti-

cles. Transport efficiency of the sampling line and manifold was observed to be 90% or higher for 0.01 - 3 μm particles.

The particle measurement sequence is begun by simultaneously initiating data acquisition by the OPC and positioning the three-way valve on the input to the CNC for sampling directly from the manifold. After a preset time to allow for flow stability, the computer reads the CNC output, records the total particle number concentration on tape, and repositions the three-way valve to sample the output aerosol from the EC. The computer controls the voltage applied to the central rod of the EC (which, for a given set of flow parameters, determines the particle size in the EC output stream) and the number of voltage steps in the EC measurement sequence. The CNC reading for each pre-programmed classifier voltage step is accumulated by the computer. At the end of the measurement sequence the computer writes the accumulated OPC and CNC data to tape and simultaneously provides a hard copy printout. Air flow through these instruments are monitored using several flowmeters whose analog signals are periodically recorded by the computer.

Particle Generation: Experiments were conducted using tobacco smoke as a source of particles because 1) it is one of the most prevalent indoor particle sources, 2) it is easily generated, and 3) it provides a polydisperse aerosol with a repeatable size distribution spanning the size range of respirable particles. Tobacco smoke is also an indoor contaminant for which most manufacturers of portable air cleaners have made performance claims. A cigarette smoking machine (Arthur D. Litte, Model ADL II Smoking System), modified to include an automatic extinguishing feature, was used to smoke a popular brand filter cigarette (17

mg tar-FTC value). A smoking rate of two 35 ml puffs per minute was used and both main-stream and side-stream from the cigarette maching were emitted into the test space. The duration of cigarette combustion was controlled by a timer that initiated the cigarette extinguishing sequence after a preset interval (usually six minutes).

Air Cleaner Air Flow Rate and Power Consumption Measurements

Air flow rate and power consumption measurements were made at each speed setting of each air cleaning device. The air flow rate measurements were made using an orifice plate flowmeter constructed in accordance with American Society of Mechanical Engineers specifications (ASME, 1971) and installed in a 6-m length of 10-cm-diameter PVC pipe. A blower was installed on one end of this pipe to move air through the pipe and orifice plate. The intake of the air cleaning device was coupled to the other end of the pipe with a 1-m-long lightweight polyethylene bag. Flows through the blower-orifice plate system and the air cleaning device were matched by adjusting a valve in the pipe so that the static pressure in the polyethylene bag was zero. Thus the air flow rate through the device was not affected by the attachment of the orifice plate system. Fan power consumption was measured using an AC wattmeter (Weston Instruments).

Experimental Procedure

Evaluation of each unducted device typically followed a 24-hour time sequence. The instrumentation and data logging remained in operation throughout the 24-hour period. The cigarette smoking machine and extinguisher were controlled by a timer; thus after manual ignition of the

cigarette, the test space was not entered again during the test sequence. A typical six-minute cigarette burn consumed approximately 600 mg of tobacco and produced a peak concentration of 1 to 2 x 10^5 particles cm^{-3}, corresponding to a peak mass concentration of 350 to 400 µg m^{-3}.

These studies were conducted concurrently with experiments on the use of air cleaning for control of radon progeny. Radon was injected into the test space following cigarette ignition; the initial radon concentrations were ~18,000 Bq m^{-3}. Details of these experiments are given in Sextro et al., (1984). The measured decay rate of the radon concentration, corrected for radioactive decay, represents the ventilation rate of the chamber, and was typically 0.05 h^{-1}.

Following a four-hour mixing and natural decay period, the air cleaner was turned on for a three to five hour period. After the control period, monitoring continued for a six to eight hour period which provided another measurement of the natural decay rate for particles. The test space was then ventilated for a three to four hour period using the range hood. While no direct control of humidity was possible during the test without interfering with the particulate removal processes, a portable dehumidifier was operated for a four to five hour period preceding the test to produce an initial relative humidity of 40 to 50 percent which then slowly increased to 50-65 percent during the test sequence.

RESULTS AND DISCUSSION

Description Of Air Cleaners Evaluated

We studied ten air cleaning devices representative of four types: four panel-filter units, two extended-surface filter units, two electrostatic precipitators, and two negative-ion generators. In addition we evaluated the effect of simple air circulation from two oscillating desk-top fans on particle removal. Compiled in Table 1 are data describing the type and cost of each device studied, and the results of our air flow and power consumption measurements.

The four panel-filter devices (PF1-PF4) ranged in retail price (1983) from $30 to $150. Each of these units has a small fan which draws or pushes air through a thin flat panel of filter media. Charged electret filter media is used in the PF2, PF3, and PF4 devices while a relatively porous uncharged foam filter is used in the PF1 device. The PF4 device also incorporates a pair of negative ion-generators with electrode voltages of -3.4 kV just upstream of the filter medium. The maximum air flow rates in these devices were relatively small, ranging from 17 to 49 m^3h^{-1}.

The two extended surface filters cost $295 and $395. The ES1 device uses approximately 0.21 m^2 of electret filter media folded into a 0.06 m^2 face area (i.e. 3.8 m^2 media/m^2 face). The ES2 device uses a glass fiber HEPA-type (i.e., 95% efficient on 0.3 μm particles) filter with a much larger surface area to face area ratio (i.e. 32 m^2 media/m^2 face). The ES1 device also has a negative ion-generator with an electrode voltage of -6.1 kV located just behind the airstream discharge grill. The

air flow rates ranged from 49 to 112 m^3h^{-1} for the ES1 device, and from 173 to 343 m^3h^{-1} for the ES2 device, depending upon the fan speed setting.

The two electrostatic precipitators cost $370 and $395. Both units are two-stage flat-plate electrostatic precipitators and both use positive voltage for ionization. The collection stage of both units consists of alternately charged and grounded plates. A single high-voltage D.C. power supply is used to charge both the ionization electrodes and collection plates. The EP1 device operates at 6.2 kV DC and has a total collector surface of 0.98 m^2 compared with 6.5 kV DC and a 1.20 m^2 collector surface for the EP2 device. The air flow rates ranged from 248 to greater than 425 m^3h^{-1} for the EP1 device and from 204 to 434 m^3h^{-1} for the EP2 device.

The two ion-generators both generate negative ions. The IG1 device is a table-top residential-type ionizer which has an electrode voltage of -19 kV D.C. The IG2 device is a ceiling-hung commercial-type ionizer which has an electrode voltage of -32 kV D.C. In addition, the IG1 device includes a 7.8 kV positively charged collection surface just beneath the ion-emitting electrode. According to the manufacturer this is designed to help collect the charged particles and thereby reduce soiling of indoor surfaces, which is a major complaint associated with ionizers.

The circulating fans, CF1, are typical multi-speed desk-top oscillating fans. The blade diameter is 0.30 m and the air flow rate reported by the manufacturer ranges from 2250 to 3060 m^3h^{-1}.

Data Analysis Procedures

To calculate the effective cleaning rates and system efficiencies for each air cleaner the data were first organized as semi-logarithmic plots of particle concentration as a function of time, where the slopes of the lines then represent the decay constants. Figure 3 shows results from a test of a HEPA-type air cleaner (device ES2). The top line in this figure is the total particle concentration as determined by the CNC, and the lower four curves are particle concentrations in selected size ranges as measured by the optical particle counter.

Since the calculations of effective cleaning rates require measurement of the steady-state decay rates with and without the device operating, it is necessary first to determine when the natural decay rates have reached steady state. Following injection there is an initial transient period during which concentrations of particles are changing rapidly, principally due to coagulation. In our experiments a steady state decay rate developes for all sizes counted by the OPC within one half hour and for the CNC data within two to three hours. Similarly there exists a short transition period following activation of the air cleaner (i.e. mixing effects) before the decay rate becomes constant. We exclude these nonlinear transient portions of the (semi-logarithmic) decay curves and use the linear portions as the basis for our removal rate calculations. With air cleaners having high particle removal rates (see Figure 3), the observed particle concentrations decay very rapidly to values two to three orders of magnitude lower than the initial concentration. The particle concentration eventually equilibrates when the particle removal rate balances the particle production rate, which is

Particle Size Distributions and Surface Deposition Rates

Particle concentration measurements were made for twenty two different size ranges, however, only eleven of these size ranges contained data of sufficient precision to be useful in calculating decay rates. Data from the six channels of the electrostatic classifier (i.e. 0.005 to 0.20 μm diameter) were inconsistent over time during a number of the experiments. In addition, data from the five largest channels of the optical particle counter are not included in our analyses because of the poor counting statistics associated with the relatively low concentrations of particles above 1.25 μm diameter. Thus, our measurements of effective cleaning rate and system efficiencies as a function of particle size are based on eleven channels of the optical particle counter which span the particle size range of 0.09 to 1.25 μm diameter.

Typical size distributions for tobacco smoke are presented in Figure 4 for five measurement times during a natural decay experiment conducted without an air cleaner operating. The figure also shows the data from one of these measurement times converted to a mass size distribution assuming spherical particles with a density of 1 g cm^{-3}. Concentrations in particles cm^{-3} are normalized by the logarithm of the width of the particle size bin. The data obtained with the electrostatic classifier (i.e. less than 0.09 μm diameter) have been normalized to the OPC data at a particle diameter of 0.20 μm, where data from the two instruments overlap. Typically, the tobacco smoke aerosol had a near log-normal size distribution with a geometric count median diameter of 0.15 μm and a geometric standard deviation of 2.0. Other researchers have reported log-normal distributions for tobacco smoke, with geometric

count median diameters ranging from 0.1 to 0.5 μm (Hinds, 1978). The mass median diameter was typically 0.5 μm.

The size distribution measured at 10:01 represents the background aerosol normally present in the test room. The four sharply peaked distributions represent successive measurements following the smoking of a cigarette at 10:25. The effects of decay rate on the aerosol size distribution can be seen by comparing the four different curves. The decay in number concentrations for particles less than 0.1 μm diameter is significantly greater than that for particles with diameters greater than 0.2 μm.

Figure 5 is a plot of the natural particle deposition rate and deposition velocity as a function of particle size during this same experiment. Deposition rates were calculated as the observed particle decay rate less the decay rate associated with air exchange. Since the indoor particle concentration was much higher than the outdoor concentration, the infiltration of outdoor air as a source of particles was not considered. For particles with diameters between 0.2 and 0.4 μm the natural particle deposition rates are a minimum, 0.05 h^{-1}. The mass-averaged surface deposition rate of tobacco smoke particles was observed to be 0.1 h^{-1}. Figure 5 also shows the particle deposition velocities, which equal the deposition rate divided by the 2 m^{-1} surface-to-volume ratio.

Results of Air Cleaner Performance Measurements

The last two columns of table 1 summarizes the air cleaner performance measurements. For comparative purposes, our effective cleaning

rates are based on removal rates observed for 0.45 μm size particles. This size is close to the mass median diameter for cigarette smoke, and thus the corresponding removal rate is a reasonable index for the total mass removal rate of the aerosol. Effective cleaning rates ranged from 0 m^3h^{-1} for the PF1 panel filter to 306 m^3h^{-1} for the HEPA-type filter unit. The least effective devices tested were the four small panel filters and the one residential negative ion generator, which had effective cleaning rates ranging from 0 to 12 m^3h^{-1}. The two circulating fans, which circulated 6120 m^3h^{-1} or 174 room volumes per hour, had almost no effect on the removal rate of cigarette smoke. Data obtained during the experiment using device PF1 are shown in Figure 6, and are illustrative of results obtained with the other three panel-filter units (PF2, PF3, PF4), the IG1 ionizer, and the circulating fans. The two electrostatic precipitators tested had effective cleaning rates of 207 and 197 m^3h^{-1}. These effective cleaning rates are graphically depicted as the unshaded bars in Figure 7.

One approach to put the effective cleaning rate data into perspective is to consider the time it takes the air cleaner to remove 98% of the smoke from a room. The removal time for each device is indicated on the right hand axis of Figure 6 for the 35.1 m^3 test space. The time periods range from 1/2 hour for the ES2 HEPA-type filter to more than 16 hours for any of the panel filters or the IG1 negative ion-generator. The measured air flow rates of each air cleaner are depicted as shaded bars in Figure 7. The system efficiency for each air cleaner can be seen by comparing the unshaded and shaded bar for each device.

Panel Filters: The low effective cleaning rates of the four panel filter devices can be attributed to a combination of low air flow rates and low particulate removal efficiencies. The air flow rates of these devices ranged from 17 to 49 m^3h^{-1}. If the filters in these devices were 100% efficient, the effective cleaning rates would also range from 17 to 49 m^3h^{-1}, which means they would still require between 3 and 8 hours to remove 98% of the smoke in a 35 m^3 room.

The PF2, PF3, and PF4 panel filter units all use an electret filter media. While this type media is recognized to have moderate to high particulate collection efficiency one reason these units did not perform well is that a large percentage of the entering air bypasses the filter through a gap between the filter and device housing. In the case of the PF2 panel-filter device, the gap surrounding the filter element was 1 cm wide and appeared to be more a design feature than a manufacturing flaw. While this strategy increases the total flow rate of air through the unit it decreases the flow rate of air through the filter media and hence reduces the air cleaning rate.

Extended surface filters: The most efficient devices studied were the two extended surface filters. The high efficiencies of these devices results from minimal air by-pass and from use of a high efficiency filter medium. Device ES2 had a measured system efficiency of 115 $\pm$ 17%. This air cleaner uses a high efficiency filter composed from a high density of fine glass fibers, and is specified by the manufacturer as having a 95% efficiency for 0.3 μm diameter particles at the operating flow rates. The system efficiency of the ES1 device was 86 $\pm$ 9%. This air cleaner uses electret filter media in a three-fold convoluted

format. In addition the ES1 device has a negative ion-generator. We did not separately evaluate the effect of this ionizer on particle removal.

Electrostatic Precipitators: The efficiencies of the two electrostatic precipitators studied were less than those observed for the extended surface filters but still relatively high; 57 $\pm$ 11% for the EP1 device and 58 $\pm$ 6% for the EP2 device. While the performance of these two electrostatic precipitators for the removal of cigarette smoke is similar, we observed a sharp increase in total particle concentration following initial decreases during operation of the EP1 precipitator. We noted this phenomenon in repeated tests with the EP1 precipitator, but saw it only in the small particle size channels of the electrostatic classifier (0.01-0.05 μm); we saw no indication of an increase in particle concentration in the OPC data (greater than 0.1 μm). We have no immediate explanation for these observations, although sparking in the electrostatic precipitator between the corona wire and the plate at ground potential could be a source of ultrafine particles, as could gas-phase reactions with ozone produced in the corona discharge.

Ionizers: We evaluated the residential model negative ion-generator, the IG1 device, in two different locations. One experiment was performed with the ionizer located on a wooden-topped metal stool in the corner of the test space, at location 3 in Figure 2. The ECR for these conditions was 10 $\pm$ 2 m^3h^{-1}. Following upon a recommendation from the manufacture the device was moved to an all-wood table in the center of the room (position 4 in Figure 2) where it produced an ECR of 2 $\pm$ 2 m^3h^{-1}, which we report in Table 2. It is possible that for the test with the device

in the corner of the room, additional air cleaning resulted from deposition of some of the particles on the nearby walls and/or was due to the additional convective air flow along the wall surfaces that may have helped to circulate particles near the ionizer. In either case the removal rate was small.

The effective cleaning rate for the commercial model IG2 device, 51 $\pm$ 2 m^3h^{-1}, was measured with the device suspended about 30 cm from the center of the ceiling (position 4 in Figure 2) and with the ionizer needles pointed toward the floor. The room conditions were similar for both the IG1 and the IG2 tests. One possible reason for the difference in performance between the two ionizers may be related to the positively charged collection surface used with the IG1 device. Although we did not measure the ion flux lines coming from this device it seems plausible that the field lines would be confined to a relatively small volume surrounding the corona discharge electrode and the collector. This configuration, while reducing the deposition of particles onto indoor surfaces, also reduces the ion concentration produced in the remainder of the room.

As we noted earlier, ion generators such as the IG1 and IG2 rely on air circulation (either natural or externally-generated) to help transport charged particles to indoor surfaces. To test this hypothesis, we repeated our experiment with the IG1 in the center of the room using four-inch diameter wall-mounted mixing fans (with the fan axis parallel to the wall surface) which were operated continuously during the test period. Two different tests conditions were used, one with four fans operating (one fan per wall) and one using two fans (opposite walls).

An effective cleaning rate of 17 $\pm$ 2 m^3h^{-1} was observed for both tests, which is significantly higher than the 2 $\pm$ 2 m^3h^{-1} observed when no mixing fans were operated.

Another factor relevant to the use of ionizers and which deserves consideration is the effect of particle charging on deposition in the human respiratory system. In experiments conducted by Melandri et. al. (1983) total respiratory deposition has been observed to increase linearly with an increase in the number of charges per particle. Further studies are needed to determine whether the use of ionizers on balance reduces the dose of indoor respirable particles to humans.

Air Circulation: The two table top oscillating fans, designated CF1, were operated at high speed, positioned about 60 cm from the wall, and directed to blow air on the wall surface. The combined air flow rate was 6120 m^3h^{-1} or 174 room volumes per hour. The effect of the fans was small, increasing the mass-averaged surface deposition rate from 0.10 to 0.15 h^{-1}, which translates into an ECR of 2 m^3h^{-1}.

With regards to the air moving efficiency of these various devices, performance may be characterized by the air flow rate per watt of power consumed, as noted in Table 1. The small panel filter devices moved 0.9 - 2.0 m^3h^{-1} per watt while the larger extended-surface filters and electrostatic precipitators moved volumes of air two to three times larger; 3.4 to 4.4 m^3h^{-1} per watt.

SUMMARY AND CONCLUSIONS

We have demonstrated an in situ chamber decay test method for evaluating unducted air cleaning devices. Tobacco smoke is easily

generated and was used as a test aerosol because of its size distribution which spans the respirable size range. Furthermore, the mass median diameter of tobacco smoke is approximately 0.5 μm and thus represents a size which is associated with the minimum collection efficiency in both mechanical and electrostatic air cleaning devices. Particles smaller than 0.1 μm, such as particles generated by gas stoves or airborne virus, and particles greater than 1.0 μm, such as pollen and bacteria, will be collected equally or more efficiently than tobacco smoke particles. The natural deposition rate of tobacco smoke particles onto indoor surfaces was observed to be small, 0.1 h^{-1} based on mass.

The performance studies of the air cleaners show a substantial variation in the abilities of various classes of devices to remove particles from indoor air. Based on our results, simple panel-filter devices are not effective in removing particles generated by tobacco combustion. While these types of air cleaners appear to have a large share of the consumer air cleaner market, our studies indicate they provide very little air cleaning. We investigated the effects of additional air circulation, and found that it does not provide any measurable reduction in tobacco smoke particle concentrations, although we observed that additional air circulation helps dissipate the visible smoke plume. Our results for the two negative ion generators are mixed. The residential unit which had both an emitter and collector surface only removes particles at a low rate unless there is substantial air circulation. Even then, the removal rate is still very modest. For the commercial ionizer which had a higher negative voltage on the emitter and no integral collector surface, the overall performance is better, although since room walls and furniture become the particle collection surfaces, soiling of

these surfaces may be a concern. The electrostatic precipitators and extended surface filters we evaluated removed particles at a substantial rate. The best of these devices had effective cleaning rates ranging from 100 to 300 m^3h^{-1}. We note that following all of our tests, even those conducted with the electrostatic precipitators or the HEPA-type filter where essentially all particulate matter was removed, there remained a strong odor of tobacco smoke. This odor is from the gas phase contaminants of tobacco smoke and requires separate control measures for removal (e.g. ventilation).

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Table 1. Portable air cleaner descriptions and results

Device type	Device Number	Device Description	Retail costs ($)[a]		Speed	Power	Flow rate	Ratio	Efficiency[b]	ECR[c]
			device	filter		(watts)	(m^3h^{-1})	(m^3h^{-1}/watt)	(%)	(m^3h^{-1})
Panel Filters	PF1	foam filter	30	4	high	20	17	0.9	0±1	0±2
	PF2	electret filter	40	5	high	27	49	1.8	11±1	5±2
	PF3	electret filter	35	6	high	18	36	2.0	16±3	5±2
	PF4	negative corona charging and electret filter	150	12	med.	28	29	1.0	39±11	12±3
Extended Surface Filters	ES1	electret filter and negative ion-generator	300	16	high	32	112	3.5	86±9	97±3
	ES2	HEPA filter	395	77	med.	67	267	4.0	115±17	306±14
Electrostatic Precipitators	EP1	two-stage flat plate positive corona	370	15 (carbon)	med.	109	366	3.4	57±11	207±32
	EP2	two-stage flat plate positive corona	395	15 (carbon)	med.	77	340	4.4	58±6	187±9
Ion-Generators	IG1	residential model negative corona positive collector	80	none	--	2	0	--	--	2±2
	IG2	commercial model negative corona no collector	120	none	--	3	0	--	--	51±2
Circulating Fan	CF1	oscillating fan 2 units	52 each	none	high	44 each	3060[d] each	69.6	0±1	2±2

a. Retail costs obtained from manufacturers or local distributors (prices as of mid-1983).

b. Efficiency calculated as the observed effective cleaning rate (ECR) divided by the measured air flow rate (± 90% confidence limits).

c. Effective cleaning rate (ECR) calculated as the flow rate of particle free air required to produce the observed decay rate in cigarette smoke (± 90% confidence limits).

d. Flow rate as reported by the manufacturer.

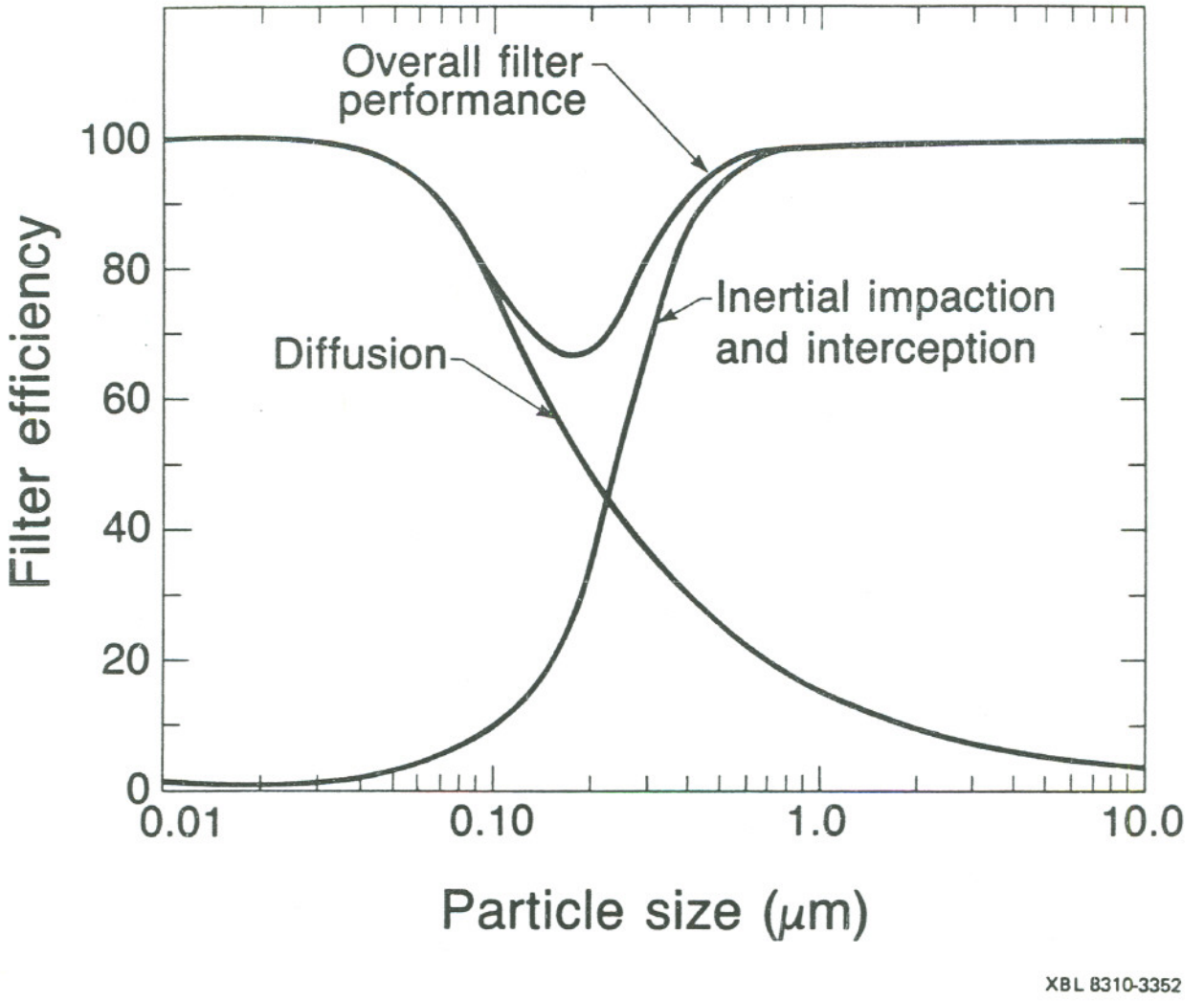

Figure 1 Particle removal efficiency as a function of particle size for a typical fibrous filter. (Adapted from Hinds, W.C. (1982), Aerosol Technology).

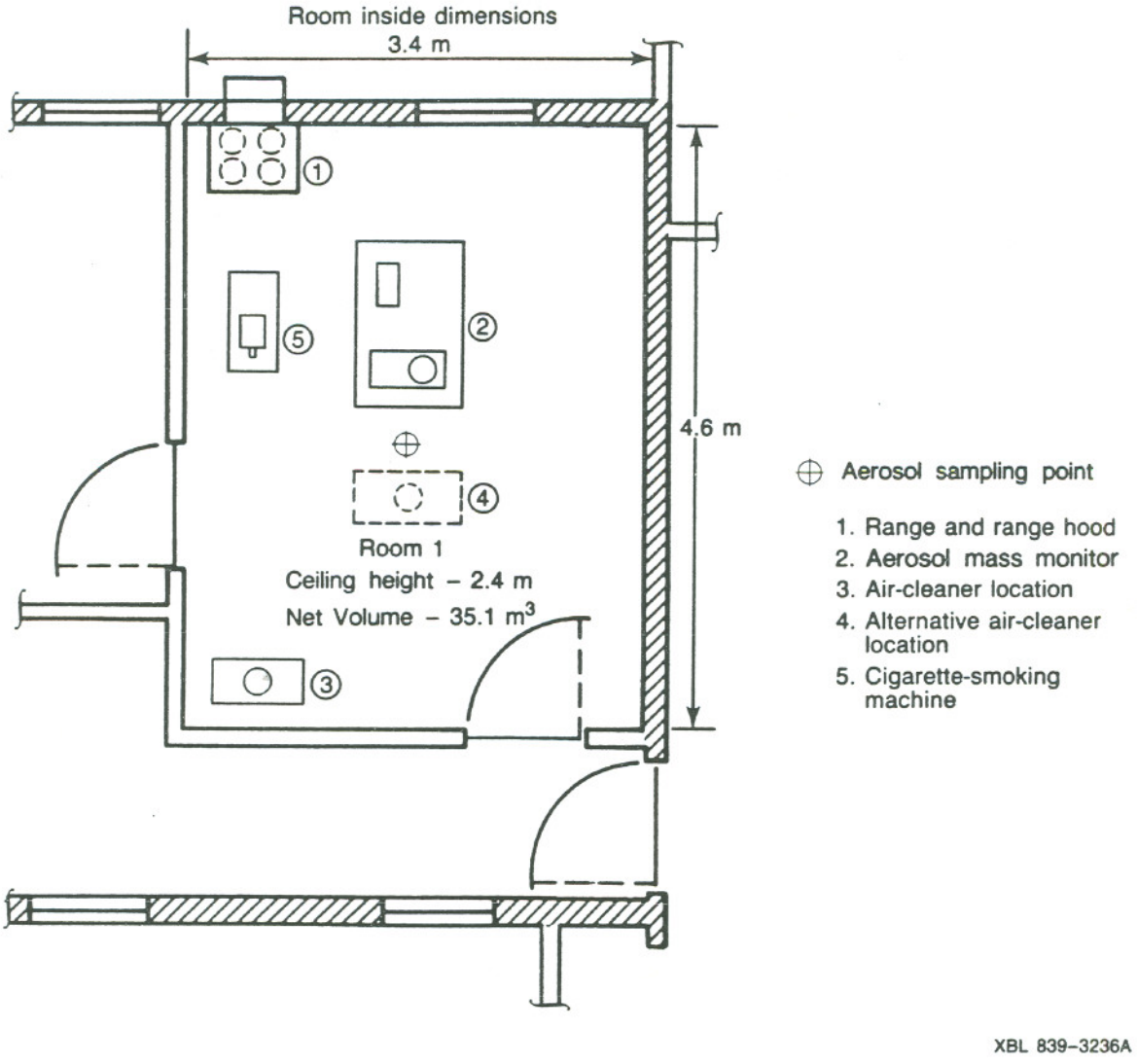

Figure 2 Floor plan of the Room 1 test space in the Indoor Air Quality Research House.

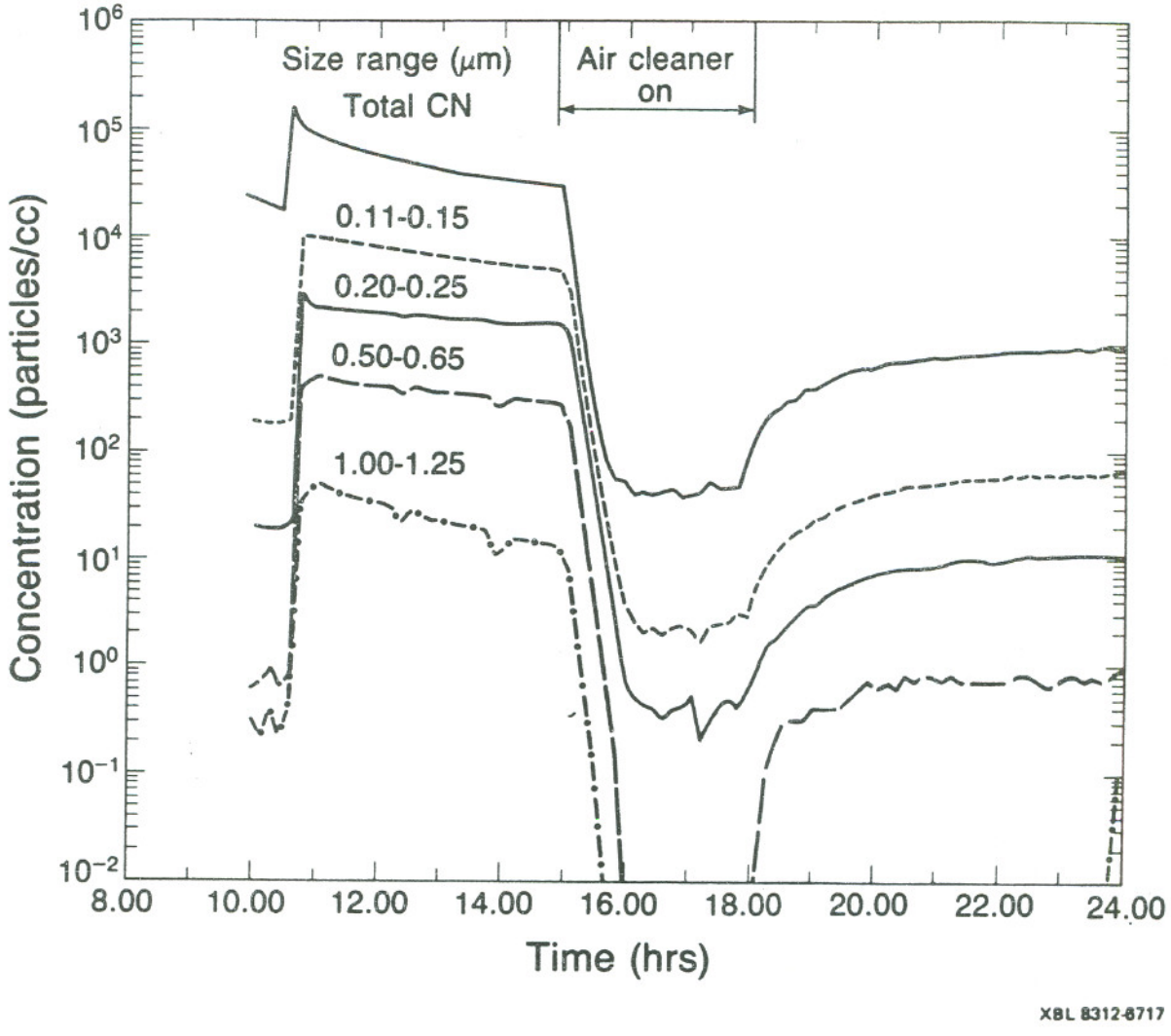

Figure 3 Semi-log plot of particle concentration as a function of time for a single-room decay experiment using tobacco smoke and a HEPA-type filter.

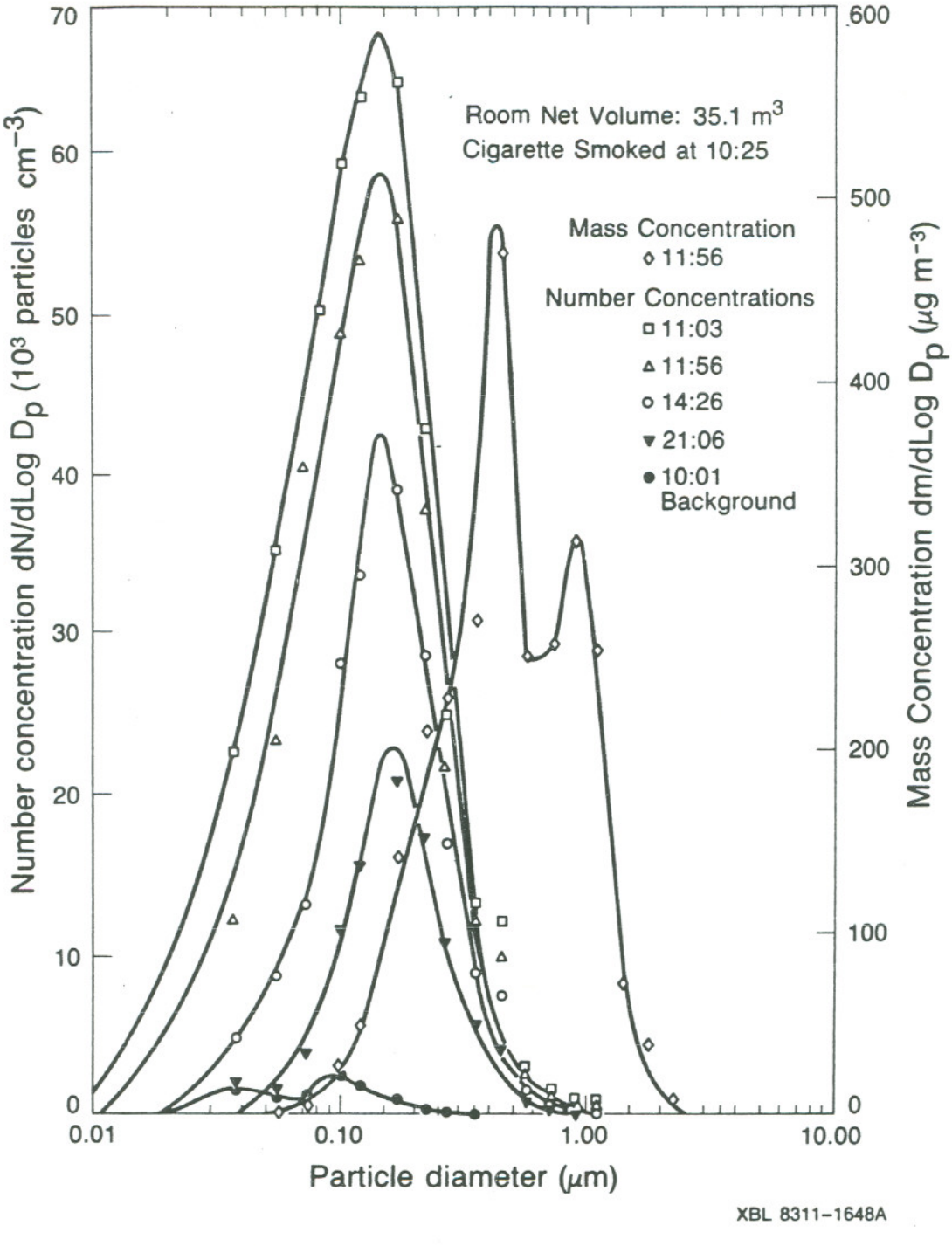

Figure 4 Size distributions of tobacco smoke generated from mainstream and sidestream emissions from one mechanically-smoked filtered cigarette in a 35.1 m^3 room. The number distributions are based on concentration measurements, while the mass distribution is derived from the number distribution at 11:56, assuming spherical particles with a density of 1 g cm^{-3}.

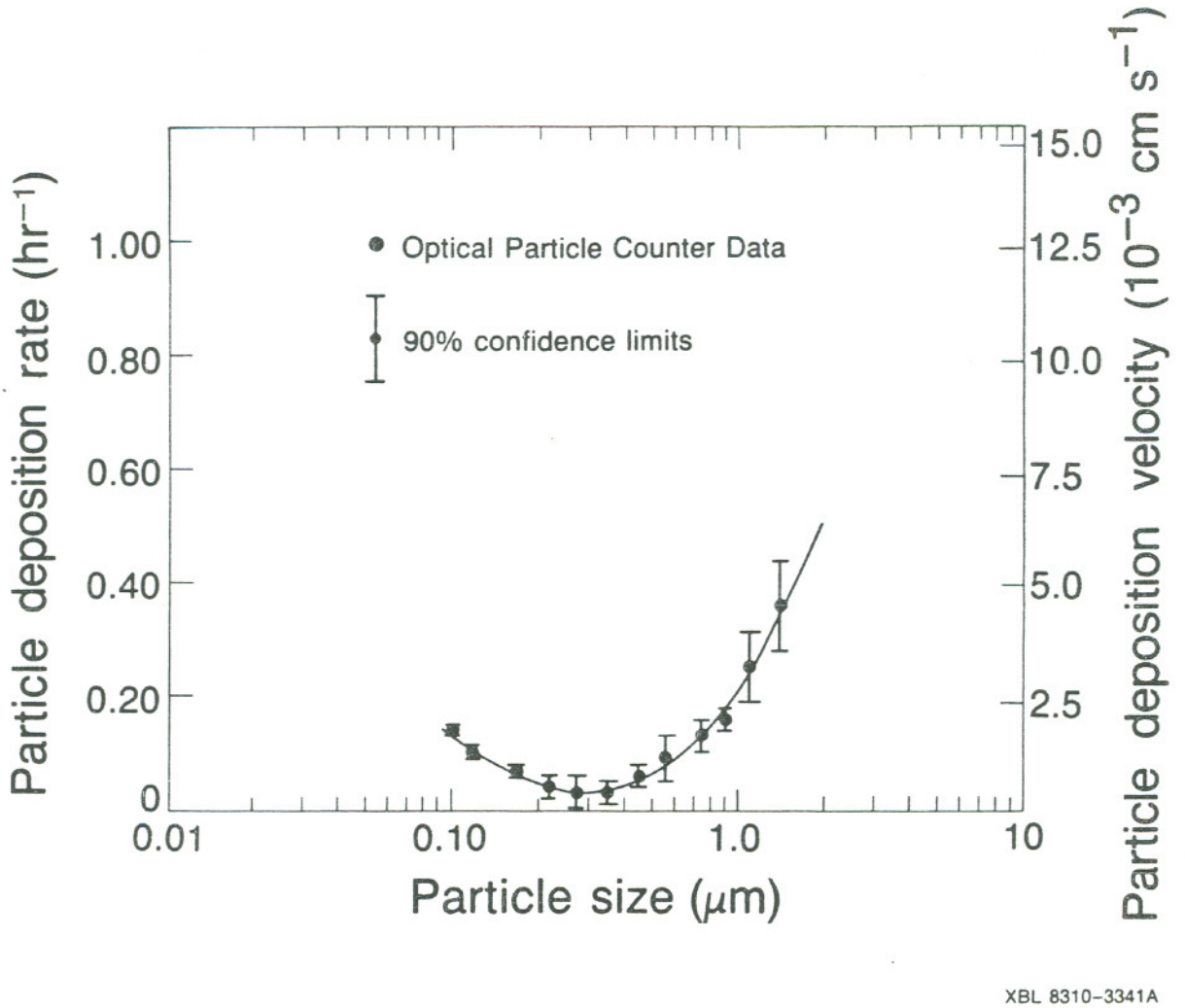

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Figure 5 Particle deposition rates as a function of particle size, calculated as the observed decay rate less the measured air exchange rate. Deposition velocities were calculated assuming a surface-to-volume ratio of 2 m^{-1}.

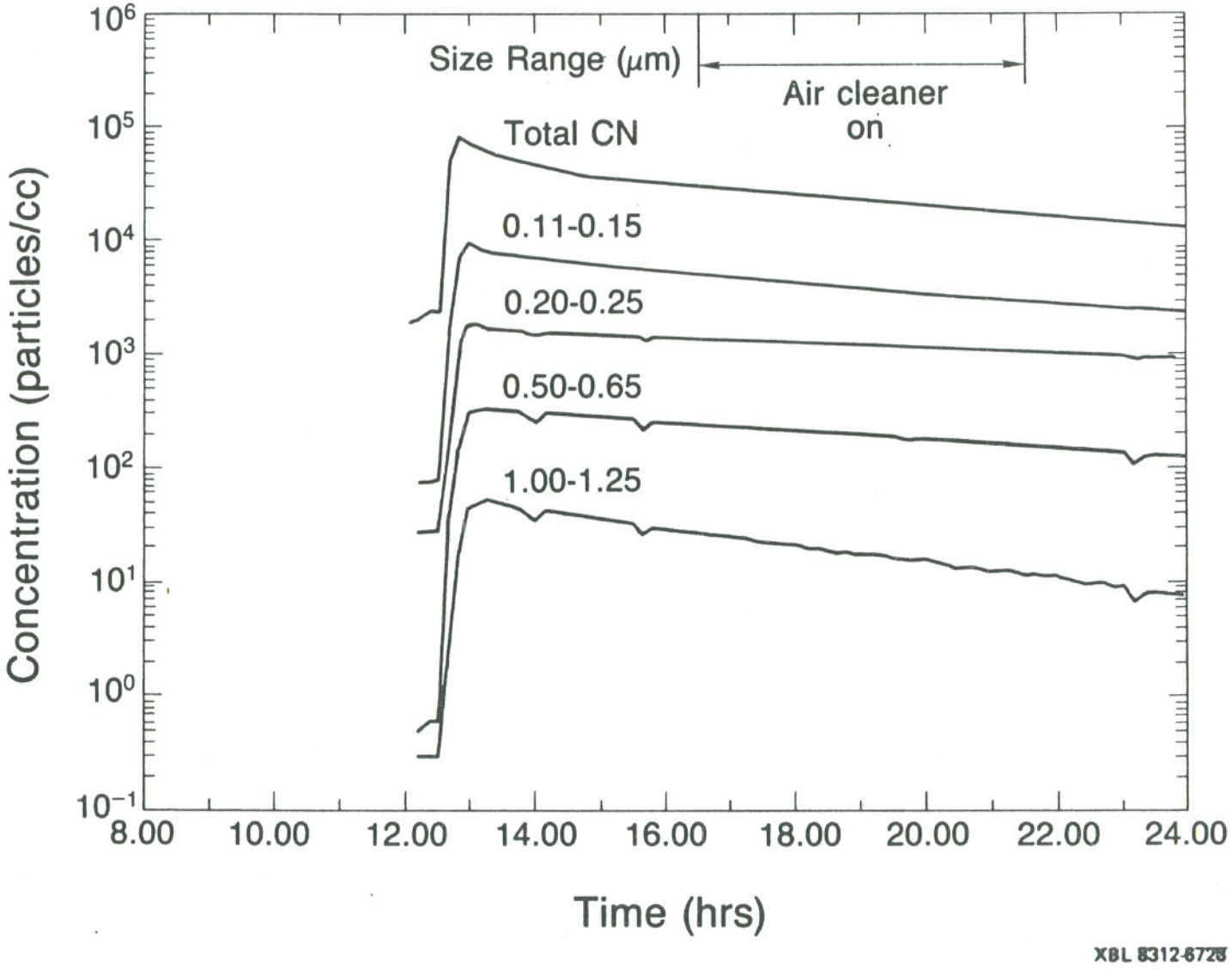

Figure 6 Semi-log plot of particle concentration as a function of time for a single-room decay experiment using tobacco smoke and a small panel-filter air cleaner.

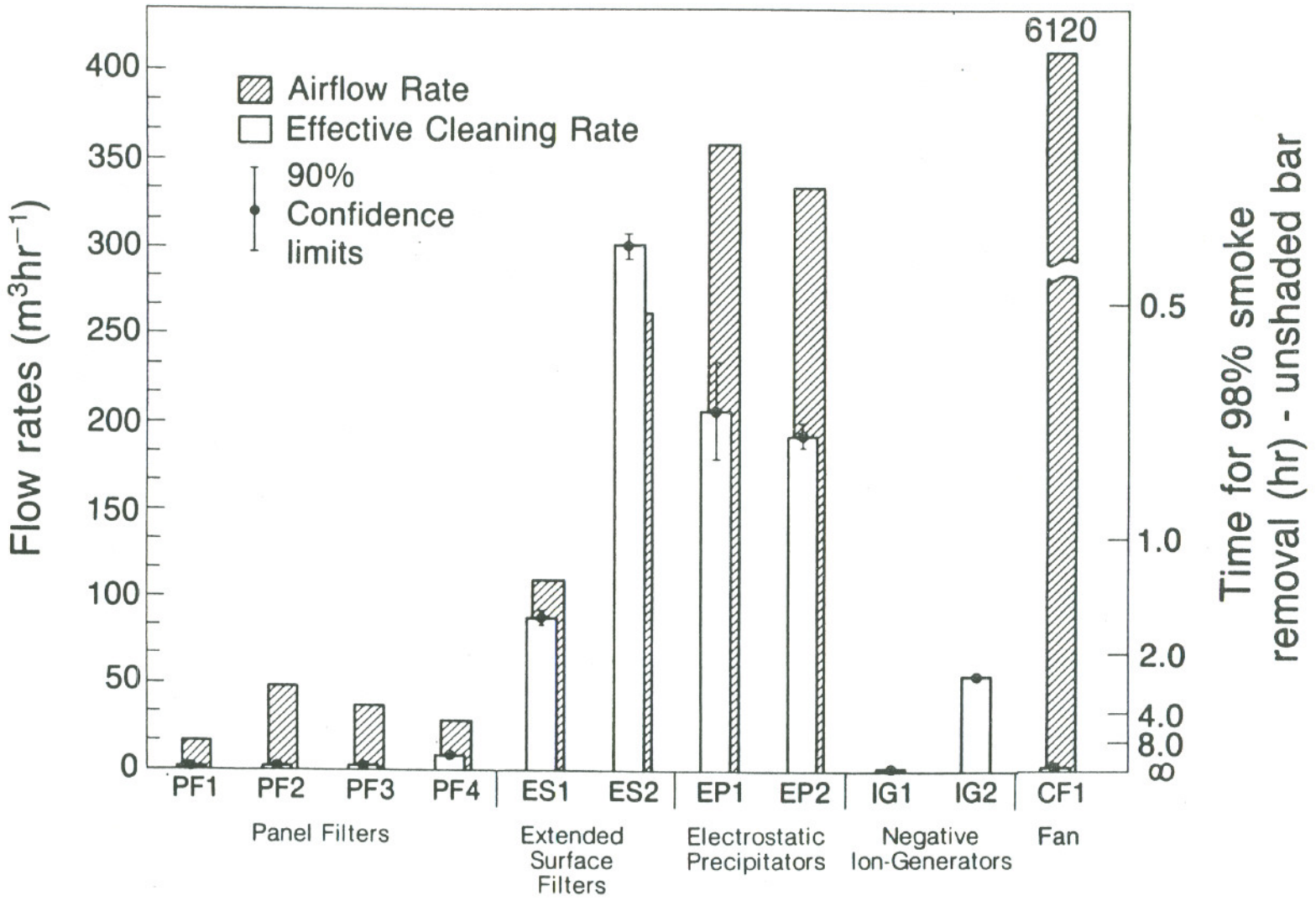

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Figure 7 Performance of various unducted air cleaning devices. Shaded bar-air flow rates in m^3h^{-1}; unshaded bar - effective cleaning rates in m^3h^{-1} and time required for 98% smoke removal in hours. Effective cleaning rates calculated as the flow rate of particle-free air required to produce the observed decay rate of cigarette smoke.

roughly that expected from the 0.05 h^{-1} infiltration rate of outside air. The decay constants for the natural and control periods of each experiment were calculated by fitting the experimental data to an exponential curve using a precision-weighted least squares regression (Picot, 1980). The quality of the fit was then checked by calculating the 90% confidence limits of the decay constants (Bowker and Lieberman, 1972).

Uncertainties in the ECR arise from several sources. Uncertainties due to measurement of particle concentration do not affect the ECR, if we assume that the measurement accuracy of the instruments are independent of time (i.e. no drift) and concentration change (i.e. negligible changes in counting efficiency). This also assumes that any remaining systematic errors in the measurement of particle concentrations are percentage errors, and thus cancel when the decay rates are computed. With these assumptions, the major source of uncertainty in our decay rate calculations arises from the number of data points and the degree of fit of the decay curves to the data points. The uncertainty in the volume measurement was estimated to be $\pm$4%. For calculating system efficiencies, we estimated the uncertainty in our flow rate measurements to be $\pm$10%, except for the ES2 device, where the flow rate uncertainty was estimated to be $\pm$14%, due to the imprecision of setting the variable speed fan control. The uncertainties associated with each measurement were assumed to be independent of one another and were added together in quadrature to obtain the uncertainties for the various performance parameters.