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INITIAL EFFICIENCIES OF AIR CLEANERS FOR THE REMOVAL OF NITROGEN DIOXIDE AND VOLATILE ORGANIC COMPOUNDS

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Abstract—The objective of this research was to measure the initial effective cleaning rates (ECRs) of selected air cleaners for removing nitrogen dioxide (NO_2) and six representative volatile organic compounds (VOC) from air. Four portable air cleaners, representing different principles of particle removal and incorporating activated carbon, were investigated. Experiments were conducted in a closed room-size environmental chamber using analyte concentrations similar to those reported in residences. Effects of relative humidity, temperature, filter particle loading and saturation of the adsorbents on the ECRs were not investigated in this preliminary study. However, the effect of extended usage was investigated for one air cleaner.

Two of the air cleaners were found to be reasonably effective *initially* in removing NO_2 and five of the six VOC. These two devices had relatively high flow rates and the greatest amounts of activated carbon. None of the devices removed dichloromethane, the VOC with the highest vapor pressure. One air cleaner emitted 1,1,1-trichloroethane and formaldehyde. After being used in a residence for 150 h, the ECRs for the air cleaner which had the highest initial values decreased to 50% or less of the initial ECRs. This use was only about 15% of the recommended filter lifetime. Conversion of NO_2 to NO was also observed for this device but only after it had been used in the residence.

Key word index: Air cleaner, effective cleaning rate, nitrogen dioxide, volatile organic compounds.

INTRODUCTION

An increased public awareness of indoor air pollution has resulted in the development of a substantial market for portable air cleaners for use in residences and offices. Portable air cleaners are designed primarily for removal of suspended particles such as pollen and tobacco smoke. An earlier study in this laboratory evaluated a variety of portable air cleaners for removal of respirable particles (Offermann *et al.*, 1985) and radon progeny, both free and particulate-attached (Sextro *et al.*, 1986). Recently, some manufacturers have claimed that their devices also remove gaseous pollutants such as NO_x, SO_x and volatile organic compounds (VOC). There is, however, little information available to consumers on the performance of these devices for these gaseous pollutants.

The objective of this research was to investigate the effective cleaning rates (ECRs) of selected portable air cleaners for removing NO_2 and VOC from air when first exposed to concentrations typical of those found indoors. This investigation did not examine effects of relative humidity and temperature, the effects of filter loading with particles, saturation of the C adsorbents or possible later releases of adsorbed compounds. The effect of more long-term usage on removal efficiencies was investigated for only one air cleaner.

Nitrogen dioxide and VOC were specifically selected as the indoor pollutants of interest for this research because they are commonly found at elevated concentrations in residential indoor air and because they can cause adverse health effects at high concentrations. High concentrations of NO_2 have been observed in homes with gas stoves (Spengler *et al.*, 1982; Harlos *et al.*, 1987) and kerosene space heaters (Leaderer *et al.*, 1984) and in emissions from gas stoves, kerosene space heaters, and other unvented combustion appliances (Girman *et al.*, 1982; Traynor *et al.*, 1983). The VOC are an ubiquitous mixture of compounds which includes a number of carcinogens and teratogens. Major classes of VOC which have been found in indoor environments include aliphatic and aromatic HCs, chlorinated HCs, aldehydes and ketones (DeBortoli *et al.*, 1986; Lebret *et al.*, 1986; Wallace, 1986; Hodgson and Girman, 1989).

Four portable air cleaners, representing three different principles of particle removal, were selected for the study. All incorporated some activated carbon (C). Experiments were conducted in a 20-m^3 environmental chamber operated in static mode (without mechanical ventilation). For each air cleaner, the chamber was spiked with NO_2 and a mixture of six VOC. The decays in concentrations of these compounds were measured over a period of at least 4-h while the air cleaners were in operation.

EXPERIMENTAL METHODS

Description of the air cleaners

Table 1 presents descriptions of each of the four air cleaners used in these experiments. The air cleaners were

Table 1. Descriptions of air cleaners

Air cleaner type	Air cleaner ID	Dimensions $W \times H \times D$ (in)	Dimensions $(ft)^2$ and location of air intake	Maximum airflow rate* ($m^3\ h^{-1}$)	Amount of carbon (g)	Blower and filtration system
Panel filter	PF1	$10 \times 7 \times 8$	0.24 left	78	†	2-speed; foam prefilter; 3-stage filter cartridge with pleated and smooth layers of Filtrete material and activated charcoal pad; filter life ~3 months.
	PF2	$17 \times 30 \times 12$	1.30 back	226	115	3-speed; foam prefilter; 2-stage filter cartridge with pleated layer of borosilcate glass fibers and bonded filter of activated charcoal and a catalyst (99 g) which removes or adsorbs CO, O_3, NO_x, SO_2; filter life 1000 h or ~3 months.
Extended-surface filter	ES	$14 \times 11 \times 19$	0.69 front	228	130	Variable speed; foam prefilter; H.E.P.A.‡ filter; activated charcoal/Purasorb (93 g) after-filter; H.E.P.A. filter life 2–4 years; charcoal filter life 4–6 months with average use (3–6 h^{-1} day).
Electrostatic precipitator	EP	$23 \times 14 \times 8$	0.55 bottom	274	55	Variable speed; expanded metal prefilter; electrostatic precipitator cell; activated charcoal after-filter; charcoal filter life 3–6 months.

* Measured at highest speed setting with pitot tube or orifice plate for the PF1, ES and EP devices and with anemometer for the PF2 device.
† The carbon could not be separated from the filter for weighing.
‡ High Efficiency Particulate Arrestance.

selected to represent a range of sizes as well as somewhat different principles of particle removal. All are intended primarily for use in residences and are portable, stand-alone devices, *not* intended for duct installation. All of the devices have some activated C positioned after the primary particle removal device, although the amount of C varies considerably among the devices. The ES air cleaner contains the largest amount of activated C which is combined with potassium permanganate. Both are in the form of pellets of 1–2-mm diameters, contained in a 1.5 cm thick panel consisting of a grid of open triangles in which the pellets are loosely dispersed. The EP air cleaner has a panel of similar design. The activated C and catalyst in the PF2 device are 1–2-mm diameter pellets held in rectangular pockets formed by two fused layers of a synthetic fibrous mat, about 1.3 cm thick. The PF1 air cleaner has finely divided C impregnated in a fibrous filter. The C could not be separated from the filter and weighed; by visual inspection, this device has the least amount of C.

Air flow rate measurements were made at each speed setting of each air cleaner, using either a pitot tube or an orifice plate flowmeter (ASME, 1971). These devices were installed in a 4-m length of 15-cm ID pipe. A blower was installed at one end of the pipe to exhaust air through the pipe. The intake of the air cleaner was coupled to the other end of the pipe with a flexible polyethylene bag. Flows through the system were matched by adjusting the speed of the blower motor with a Variac so that the static pressure in the polyethylene bag was zero when the air cleaner was operating at the desired speed. Thus, the air flow through the air cleaner was not affected by the attachment of the measurement system. Differential pressure measurements were made with either a micromanometer or a Magnahelic gauge. Air flow rates were also measured using a calibrated hot-wire anemometer and were compared to those determined using the orifice plate or pitot tube.

Table 1 presents the maximum air flow rates measured for each of the four air cleaners. The EP air cleaner had the highest flow rate while the PF1 air cleaner, the smallest device, operated at the lowest flow rate. Air flow rates measured by the pitot tube or orifice plate and by the hot-wire anemometer were within 10% for three of the devices. For the PF2 unit, the flow rate determined with the anemometer was 21% higher than that determined by the other method. Because of the design of the PF2 device, the flow rate is very sensitive to the pressure drop across the fan and the polyethylene-bag interface probably introduced a small additional pressure resulting in an erroneously low flow rate. For this device, the flow rate measured with the anemometer was judged to be the more accurate measure and was used in calculations.

Protocols for chamber experiments

Experiments were conducted in a room-sized environmental chamber with a volume of 20 m^3 and interior dimensions of 3.66 m (length) × 2.46 m (width) × 2.23 m (height). The walls, floor and ceiling are insulated with a 10-cm layer of high-density polyurethane foam. All interior surfaces are clad with stainless steel. The door, interior seams, and electrical and plumbing feedthrough are sealed with silicone gasket material. Inlet air for the chamber is drawn from outside the laboratory building by a variable-speed blower and passes through a coarse filter, a HEPA filter, and a charcoal filter in series. Background concentrations of ten common low-boiling organic compounds were found to be less than 2 ppbv for each compound. Atmospheric pressure inside the chamber averaged 742 ± 5 (standard deviation) torr during the experiments. Air temperature in the chamber was maintained at 23 ± 2°C. Relative humidity in the chamber was not controlled but averaged 47 ± 9%.

The air cleaners were used as received without modification. Each air cleaner was positioned in the center of the chamber on a table at a base height of 70 cm and operated at its maximum speed setting. New filter cartridges or charcoal filters were used in all experiments, except for the duplicate experiments conducted with the PF2 device in which the same filter cartridge was used in both experiments.

During the ventilation period prior to each experiment, the air cleaner and an oscillating fan used for mixing were positioned in the chamber. The ventilation system was then turned off, the mixing fan was turned on, and the air inlet, air outlet, and the door were closed. The laboratory and chamber background of NO_2 and NO were measured and a sample for the determination of the chamber background of VOC was collected. Next, the chamber was spiked with the analytes to the desired concentrations. For NO_2, a gaseous standard was injected into a port connected to an air stream flowing to the mixing fan. The VOC were introduced into the chamber by injecting a measured volume of a liquid mixture into the chamber. Chamber air was mixed for approximately 30 min after injecting the analytes. At the end of this period, the mixing fan was turned off and the air cleaner was turned on remotely from the outside of the chamber. Nitrogen dioxide and NO were monitored continuously throughout the remainder of the experiment. Duplicate samples of VOC were collected at regular intervals throughout the experiment beginning at 10 min after injection of the VOC.

The average initial concentration of NO_2 for five experiments was 484 ± 53 (S.D.) $\mu g\ m^{-3}$. The six VOC and their average initial chamber concentrations were: (1) *n*-heptane—$683 \pm 150\ \mu g\ m^{-3}$, (2) toluene—$651 \pm 131\ \mu g\ m^{-3}$, (3) dichloromethane—$258 \pm 100\ \mu g\ m^{-3}$, (4) tetrachloroethylene—$353 \pm 102\ \mu g\ m^{-3}$, (5) hexanal—$185 \pm 17\ \mu g\ m^{-3}$, and (6) 2-butanone—$131 \pm 27\ \mu g\ m^{-3}$. These concentrations and the relative proportions of the six VOC were selected to reflect those reported for their respective classes in indoor air (De Bortoli *et al.*, 1986; Lebret *et al.*, 1986; Wallace, 1986).

Experiments were generally conducted over 4-h. For NO_2, decay rates were calculated from the time the air cleaner was turned on until concentrations decreased to 15 to 40 $\mu g\ m^{-3}$ and the decay rate began to decline. This leveling off of concentrations was due in part to the increased significance of infiltration at low concentration. In addition, the equilibrium between adsorption and desorption from the activated C may have been reached at this level (Grubner and Burgess, 1981). For VOC, decay rates were calculated using the data from the start of air cleaner operation until concentrations declined to about 5–10 $\mu g\ m^{-3}$ (approximately 1 ppbv for the compounds in this study).

Background decay rates of NO_2 and VOC in the chamber were determined in two initial experiments in which an air cleaner was operated without its filter to provide mixing which would be similar to that which would occur during subsequent experiments. Duplicate experiments were conducted with one air cleaner, PF2, which was expected to have relatively high removal rates. At the conclusion of the study, an additional experiment was conducted with the same air cleaner, after it had been used in a residence, to obtain an indication of the effects of extended use on removal rates.

Air sampling and analysis

Air for measurement of NO_2 and NO was drawn through Teflon lines from 15 sampling locations in the chamber to a common mixing manifold. A chemiluminescent NO_x analyzer (Model 14 D/E, Thermo Electron Corp.), was used for the analysis of NO_2 and NO. Standards of NO_2 for calibration of the analyzer were generated by gas dilution of the output of a NO_2 permeation cylinder held at 50 ± 0.1°C in a permeation oven (Model 8500 Permacal, Monitor Labs, Inc.) modified for more accurate flow control. Standards of NO were generated by dilution of the output of a 5.4 ppmv gas standard cylinder. Multipoint calibration curves for NO_2 were generated immediately before and after each experiment.

Duplicate samples of VOC were collected at 113 cm^3 min^{-1} (20°C, 760 torr) from air drawn from a location near the center of the chamber through Teflon tubing on multisorbent samplers containing Tenax-TA, Ambersorb XE-340 and activated charcoal (Envirochem, Inc.). Sample volumes were varied according to expected analyte concentrations, and typically ranged between 0.5 and 2 ℓ. Samplers were capped and stored at −10°C in glass tubes until analysis. The analytical procedure for samples collected on multisorbent samplers has previously been described (Hodgson *et al.*, 1986; Hodgson and Girman, 1989). In brief, the VOC are thermally desorbed from a sampler and introduced into a capillary gas chromatograph (GC) with a UNACON® Model 810A (Envirochem, Inc.) sample concentration and inletting system. Sample components are resolved with a GC equipped with liquid-nitrogen subambient cooling and a fused-silica capillary column. The GC is connected via a direct capillary interface to a 5970B series Mass Selective Detector (MSD) (Hewlett-Packard Co.). The detector is operated to monitor multiple, individually-selected mass ions. A standard gas mixture was prepared by injecting an aliquot of a liquid mixture of the six VOC into a He-filled 2-ℓ flask with septum cap which was then heated and maintained at 65°C. A sample of the mixture was injected onto a multisorbent sampler with a gas-tight syringe for analysis. Multiple-point calibration curves were prepared for the six VOC for each experiment. At the beginning and end of each experiment, a large air-volume sample was collected for GC-MSD scan analysis to determine if compounds other than the six VOC added to the chamber were present.

Data analysis

Data analysis was similar to that used for the previous study of particle removal by air cleaners (Offermann *et al.*, 1985; Sextro *et al.*, 1986). The rate of decay of NO_2 or VOC concentration within a chamber of volume, V, with the air cleaner in operation, can be described by the differential mass balance equation:

$$\frac{dC}{dt} = -\frac{Q_v(C_0 - C)}{V} - KC - \frac{Q_d(C_{in} - C_{out})}{V}, \quad (1)$$

where

C = average concentration in the chamber,
Q_v = the flow rate of ventilation air (infiltration),
C_o = the concentration of analyte in incoming ventilation air ≃ 0,
K = a constant that accounts for analyte removal by mechanisms other than ventilation, such as losses to walls,
Q_d = the flow rate of air through the air cleaner,
C_{in} = the analyte concentration in the air entering the air cleaner, and
C_{out} = the analyte concentration in the air leaving the air cleaner.

The chamber was used in static mode, i.e. without mechanical ventilation. Experiments indicate that infiltration is about 0.1 h^{-1}. Therefore, Q_v is approximately zero and Equation (1) may be written

$$\frac{dC}{dt} = -KC - \frac{Q_d(C_{in} - C_{out})}{V}. \quad (2)$$

The efficiency of the air cleaner in removing gaseous pollutants is defined as:

$$\eta = \frac{(C_{in} - C_{out})}{C_{in}}, \quad (3)$$

Because of the close proximity of the inlet and outlet of the air cleaner, there may be a short-circuiting effect, i.e. some of the 'cleaned' air is re-entrained into the inlet of the device rather than mixing completely within the air in the chamber. Thus, a short-circuiting factor, E_d, is defined as:

$$E_d = \frac{C_{in}}{C}. \quad (4)$$

Substituting Equations (3) and (4) into Equation (2) yields

$$\frac{dC}{dt} = -\left[K + \frac{\eta E_d Q_d}{V}\right] C. \quad (5)$$

This equation describes the experimental decay rate of the analyte in the chamber with the air cleaner in operation, and the term in brackets is the experimental decay constant, λ_{ex}. Integration of Equation (5) between $t = 0$ and $t = t_1$ yields

$$\ln C = -\lambda_{ex} t_1 + \ln C_0, \quad (6)$$

where C_0 is the initial concentration in the chamber and C is the concentration at time t_1.

The slope of a plot of ln C vs time is then equal to λ_{ex}. This slope was determined by a least squares analysis of the data. The standard error of the slope was used to estimate the 95% confidence interval of λ_{ex}. Assuming that the decay in analyte concentration due to chamber losses, K, is the same with mixing only and with the air cleaner in operation, then the rate of removal by the air cleaner, $\lambda_{ac} = \eta E_d Q_d / V$, can be determined as the difference between the slopes determined with mixing only and with the air cleaner in operation. It should be noted that the terms η and E_d are not separable under the conditions of these experiments. Thus, λ_{ac} is a measure of the operation of the air cleaner in a 'real-world' environment rather than a measure of η alone for the filter unit of the air cleaner, such as might be measured by a manufacturer. The effective cleaning rate (ECR), the product of λ_{ac} and the chamber volume, was then calculated. This is an air flow rate that represents the effective amount of analyte-free air produced by the air cleaner per unit time and is useful in estimating the effects of the air cleaner in rooms of various sizes and in comparing air cleaning to ventilation as a mitigation technique.

RESULTS

The PF2 air cleaner was operated, without its filter cartridge, in the two experiments which were conducted to measure the chamber background decay rates of NO_2 and VOC. Background removal rates for NO_2 and the VOC ranged from 0.08 to 0.12 h^{-1} and were not significantly different (±3–10%) for the individual compounds in the two experiments. The average background decays for the individual compounds were subtracted from the total removal rates measured in the experiments with the air cleaners to obtain the removal rates due only to the operation of the air cleaners.

Figure 1 presents the decay curves for NO_2 and the VOC which were obtained during the second experiment with the PF2 air cleaner, which had relatively high initial rates of removal. The concentrations range over several orders of magnitude and are plotted on a logarithmic scale. The decay of NO_2 is very linear. Instrumental noise increased as the NO_2 concentration approached the 20 $\mu g\ m^{-3}$ detection limit. The slopes of the decay curves for 2-butanone, *n*-heptane, toluene, hexanal and tetrachloroethylene are also very linear and are nearly equivalent to each other.

Mass spectral scan analysis of a sample collected in the first experiment with the PF2 device showed the

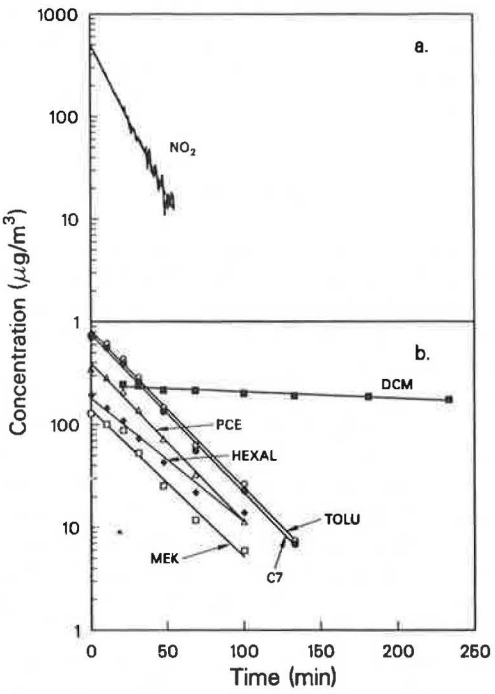

Fig. 1. Decay curves for NO_2 (a) and the six VOC (b) in the second experiment with the PF2 air cleaner. DCM = dichloromethane; MEK = 2-butanone (methyl ethyl ketone); C7 = *n*-heptane; TOLU = toluene; PCE = tetrachloroethylene (perchloroethylene); and HEXAL = hexanal.

presence of 1,1,1-trichloroethane in the chamber. In the second experiment with this air cleaner, an emission rate of about 19.2 mg h^{-1} of 1,1,1-trichloroethane was measured. This compound reached a maximum concentration in the chamber of 740 $\mu g\ m^{-3}$ after about an hour of operation. The concentration then decayed at a rate of 0.09 h^{-1} (chamber background decay rate) over the remainder of the experiment. This organic solvent is presumably used in the manufacture of one of the components of the air cleaner.

The four air cleaners were evaluated on the basis of their ECRs for NO_2 and the six VOC. These results are summarized in Table 2 which shows that there were substantial variations among the air cleaners with respect to ECRs. The PF2 device had the highest ECR for NO_2, which averaged 74 $m^3\ h^{-1}$. The ES air cleaner had the next highest ECR for NO_2 of 41 $m^3\ h^{-1}$, while the remaining devices were quite ineffective for NO_2 removal. None of the air cleaners removed dichloromethane. Both the PF2 and ES devices had nearly equivalent ECRs of 30 to 50 $m^3\ h^{-1}$ for the other five VOC. The EP air cleaner was less effective for these compounds with ECRs of 8 to 18 $m^3\ h^{-1}$ while the PF1 device was relatively ineffective for VOC removal.

In the second experiment which was conducted with the PF2 air cleaner, the ECR for NO_2 decreased from 79 to 71 $m^3\ h^{-1}$, which was a statistically significant difference ($p = 0.01$). The ECRs for 2-butanone, *n*-heptane and hexanal in the second experiment were also significantly lower ($p \leqslant 0.05$) than in the first. The differences which were observed for three of the compounds may reflect changes in the capacity of the filter element due to use (the same filter was used in both experiments), e.g. saturation of adsorption sites with VOC, NO_2 and water vapor, or other variables in the experiments which are not reflected in the uncertainties estimated from the 95% confidence intervals of the slopes of the decay curves in the two experiments.

Concentrations of NO were monitored in the chamber in all of the experiments to investigate possible chemical reactions that might occur on the surface of the activated C. There was no evidence of NO formation in any of the experiments using new filter elements. The mass spectral scan analyses for additional VOC that might have been formed by reactions on the activated carbon showed no evidence of such compounds.

After the experiments to determine the initial effectiveness of the air cleaners with new filters were completed, the PF2 air cleaner was operated for two and a half months in a 35-year old residence of nonsmokers who used a gas range for cooking. The same filter cartridge that was used in the first two experiments with this air cleaner in the chamber was used in the residence. The device was operated in the residence at the medium speed setting (111 $m^3\ h^{-1}$) for several

Table 2. Effective cleaning rates for NO_2 and VOC

	Effective cleaning rate ±95% C.I.* ($m^3\ h^{-1}$)					
		PF2				
Compound	PF1	EXP 1	EXP 2	150 h exposure	ES	EP
NO_2	5.14±0.08	79±1	71±2	24±1	42±1	6.2±0.2
Dichloromethane	0	0	0	0	2±1	0
2-Butanone	0	49±13	37±4	14±3	31±4	8±2
n-Heptane	3.1±0.6	51±2	41±3	23±4	47±1	18±1
Toluene	3.2±0.6	45±2	41±2	19±4	43±4	17±1
Tetrachloroethylene	2.5±0.6	44±2	41±2	19±4	41±2	14±1
Hexanal	4.6±0.9	39±6	32±3	18±4	37±6	10±2

* C.I. = confidence interval.

hours a day, for a total time of about 150 h. Thus, total operating time was about 160 h and total air volume was approximately 18,500 m^3. The PF2 air cleaner was then tested a third time in the chamber with the same filter cartridge. Table 2 also compares the ECRs measured in the first two experiments in the chamber to those measured in the third experiment. For NO_2, the ECR was reduced to about 1/3 of the initial value. For the five VOC which were removed by the air cleaner, the ECRs after field operation were about half of the initially measured values. The product literature for this device states the estimated filter life is about 1000 h or about 3 months.

The occupants of the residence had complained of a formaldehyde-like odor emitted by the air cleaner. Since the housing of this device is particleboard with an exposed surface area of 1 m^2, formaldehyde samples were also collected in the chamber during this last experiment and analyzed by the Air and Industrial Hygiene Laboratory of the California Department of Health Services. The measured formaldehyde emission rate of 0.5 mg h^{-1} is consistent with values reported in the literature for particleboard with this surface area (Matthews *et al.*, 1986). Emissions of 1,1,1-trichloroethane from the PF2 air cleaner in this third experiment were considerably reduced compared to the initially measured rate. The presence of acetone and isopropanol were also noted in the chamber during this experiment. These compounds, which were known to have been used in the house, were presumably adsorbed in the house and subsequently desorbed in the chamber.

Figure 2 shows the concentrations of NO, NO_2 and NO_x in the chamber over the course of the third experiment. In contrast with previous experiments, conversion of NO_2 to NO, a less toxic compound, was observed. Nitrous and nitric acids were not measured but, within the experimental uncertainties, all of the NO_2 can be accounted for by conversion to NO. The mass spectral scan analysis of a large volume air sample collected at the end of this experiment gave no evidence of the formation of nitro-organic compounds.

DISCUSSION

Whitby *et al.* (1983) have suggested as a criterion for evaluating air cleaners that the ECR should be equivalent to one air change h^{-1} for a given room. This is based on the assumption that this is about the minimum ventilation rate needed to control a moderate contamination problem. Natural ventilation rates in homes are typically in the range of 0.1 to about 1 air changes h^{-1} (M. Sherman, personal communication).

For any individual air cleaner, the air flow through the device as well as the amount of adsorbent material and the configuration of the adsorbent filter will affect the ECRs. The PF2 and ES air cleaners have relatively high air flow rates and the highest amounts of activated carbon of the four air cleaners investigated. Correspondingly, these two devices had the highest ECRs for both NO_2 and the VOC, exclusive of dichloromethane which was not removed by any device. The ECRs for these two air cleaners generally meet the criterion suggested by Whitby *et al.* for a room volume of about 40 m^3 (approximately 13 ft × 13 ft × 8 ft). With the PF2, device which had a catalyst mixed with the activated C, the ECR for NO_2 was almost twice those for the five VOCs. More effective removal of NO_2 than of the VOC was not observed for any of the other devices. This suggests that the catalyst enhances the removal of NO_2 over that obtainable with activated C alone.

The other two air cleaners, the small PF1 device and the EP device had lower ECRs for the removal of NO_2 and VOC. The PF1 device had the lowest air flow rate

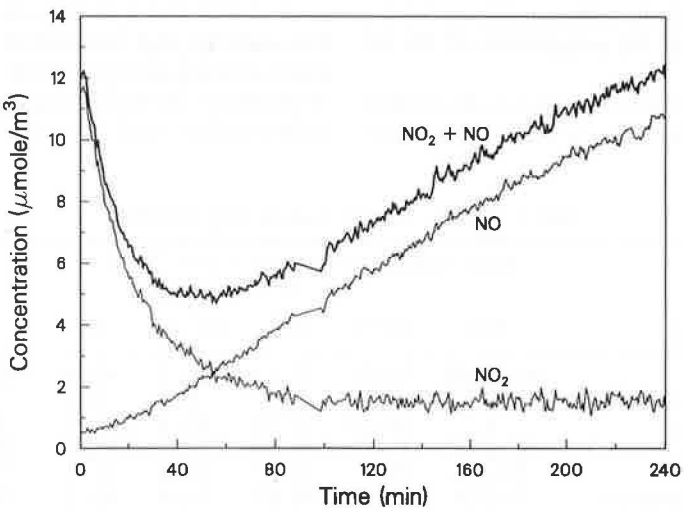

Fig. 2. Concentrations of NO_2, NO and NO_x during the experiment with the PF2 air cleaner which was previously operated in a residence for 150 h.

and also, from inspection, only a small amount of activated C. The EP device had the highest flow rate and more C than the PF1 device but was much less effective than either the PF2 or the ES air cleaners in removing NO_2 and the VOC. The filters in both the PF2 and EP devices have granulated activated C (1–2 mm in diameter) loosely dispersed throughout a cardboard grid of open triangles. There was considerably less C and more void space between the C pellets in the EP device than in the ES device which has an activated C filter of similar design. Thus, in order to be adsorbed by the C, the gases have to diffuse across greater distances. The high volumetric flow rate also reduces the residence time of the gases in the vicinity of the C.

The results reported here for NO_2 can be compared to those reported by Humphreys (1987) and by Canine (1974). Humphreys evaluated two air cleaners with activated C, one of which incorporated a catalyst. He reported ECRs of 13 and 68 $m^3\ h^{-1}$ for NO_2 removal, with the higher value found for the device with the catalyst. The high value is in very good agreement with the average of 74 $m^3\ h^{-1}$ measured for the PF2 device which also incorporates a catalyst. Canine reported removal rates for NO_2 and formaldehyde for 15 air cleaners, most of which had activated C. The ECRs which can be calculated from the data ranged from 0 to 10.2 $m^3\ h^{-1}$ for NO_2 and from 0 to 5.1 $m^3\ h^{-1}$ for formaldehyde. Although air cleaners of comparable size and type to those in this study were included, the values for NO_2 removal are low relative to those for the PF2 and ES devices. The reason for this discrepancy cannot be determined since the Canine report contained little experimental detail.

None of the air cleaners investigated here removed dichloromethane, an organic solvent commonly used in paint removers and other consumer products. The vapor pressure of this compound at 25°C of 427 mm (CRC Rubber Handbook of Physics and Chemistry, 1974) is four times higher than that of the compound with the next highest vapor pressure, 2-butanone (95.5 mm).

The effects of extended operation of the air cleaners on the ECRs were investigated for only one air cleaner in this study, the PF2 unit. The manufacturer of this device recommends changing the filter after about 1000 h of operation. When the PF2 air cleaner was reexamined after about 160 h of operation (approximately 15% of the filter lifetime), the ECRs were half or less than half of the initially measured values. Further investigation of changes in the ECRs with use over extended periods would be of value for air cleaners which have high initial ECRs and removal efficiencies.

For all of the experiments conducted with new filters, no products resulting from chemical reactions occurring on the surface of the activated C were observed in the chamber air. One air cleaner, the PF2 device, did, however, emit 1,1,1-trichloroethane and formaldehyde. The 1,1,1-trichloroethane was presumably from the materials used in the manufacture of some component, while the formaldehyde was probably from the exposed particleboard used as the air cleaner housing. After this air cleaner had been operated in a residence for about 150 h, it converted NO_2 almost entirely to NO in a subsequent experiment (Fig. 2). There was no evidence of the formation of nitro-organic compounds in this experiment from mass spectral analyses of air samples. Nitrous and nitric acid were not measured; however, the sum of the concentrations of NO and NO_2 at the end of the experiment were very close to the initial concentration of NO_2, suggesting little or no formation of these compounds. The work of Gundel *et al.* (1987) in conversion of NO_2 to HNO_2 and HNO_3 on C surfaces suggests that, for more extended operation at high concentrations of NO_2, both HNO_2 and HNO_3 might be formed. In view of this, further investigations of possible chemical reactions would be prudent.

In summary, both the PF2 and ES air cleaners were reasonably effective *initially* in removing NO_2 and five of the six VOC from a room-sized chamber. The PF1 device, however, was not effective for these compounds, and the EP device was only slightly better. None of the four air cleaners removed dichloromethane. The ECRs and efficiencies of the PF2 air cleaner decreased substantially after about 150 h of operation in a residence. Similar decreases in ECRs and efficiencies with use can reasonably be expected for the other air cleaners, as well. There was also evidence of chemical reactions occurring after extended operation which was not observed in the initial experiments. Further investigation is needed to determine ECRs and efficiencies over periods of extended use for air cleaners which have relatively high ECRs. Investigation of possible chemical reactions occurring with extended use is also warranted.

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