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Efficiencies of Portable Air Cleaners for Removal of Nitrogen Dioxide and Volatile Organic Compounds: Final Report

J.M. Daisey and A.T. Hodgson

March 1988

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

Interagency Agreement CPSC-IAG-86-1259

FINAL REPORT

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TABLE OF CONTENTS

ABSTRACT iii

1.0 INTRODUCTION 1

2.0 EXPERIMENTAL METHODS 3

2.1 Concentration of NO_2 3

2.2 Composition of the Gas Mixture 3

2.3 Description of Air Cleaners 4

2.4 Description of Environmental Chamber 5

2.5 Determination of Air Flow Rates and Power Consumption of the Air Cleaners 5

2.6 Experimental Protocols for Chamber Experiments 6

2.7 Air Sampling and Analysis 8

2.8 Other Instrumentation 10

2.9 Data Analysis 11

3.0 RESULTS 13

3.1 Air Flow Rates and Power Consumption of the Air Cleaners 13

3.2 Air Cleaner Removal Rates for NO_2 and VOC 15

3.3 Effective Cleaning Rates and Efficiencies of Removal for NO_2 and VOC 18

3.4 Evidence of Chemical Reactions 19

4.0 DISCUSSION 20

5.0 REFERENCES 24

APPENDIX 1 Environmental Conditions in the Chamber During the Experiments

APPENDIX 2 Quality Assurance Protocols

APPENDIX 3 Graphical Presentations of the Variations in the Environmental Chamber Concentrations of NO_2 and VOC with Time

ABSTRACT

The objective of this research was to measure the initial effective cleaning rates (ECRs) of selected air cleaners for removing NO_2 and six representative volatile organic compounds (VOC) from air. The six VOC, dichloromethane, 2-butanone, n-heptane, toluene, tetrachloroethylene and hexanal, have all been reported in indoor air. Four portable air cleaners, representing three different principles of particle removal and incorporating activated carbon, were investigated. Experiments were conducted in a closed 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.

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-trichlorethane. Since the effective cleaning rates and efficiencies of removal for the gaseous pollutants investigated in this study are likely to decrease with filter use, the values reported here are likely to be maxima for the temperature and humidity of these experiments. Further investigation of the effects of extended use on the ECRs of the two most effective air cleaners is recommended.

KEY WORDS: Air cleaners, effective cleaning rate, nitrogen dioxide, volatile organic compounds

1.0 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. Two earlier studies 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 oxides of nitrogen and sulfur and volatile organic compounds (VOC). There is, however, little information available to consumers on the performance of these devices for either particles or gaseous pollutants, other than that provided by the manufacturers. Results of tests conducted by New Shelter magazine (Canine, 1983; New Shelter, 1986), Consumer Union (1985), and Stockham *et al.*, (1985) are of limited usefulness for evaluation of the effectiveness of these devices for removal of gaseous pollutants. There is also speculation that certain of these devices may increase indoor levels of ozone.

The objective of this research was to determine the <u>initial</u> efficiencies of selected portable air cleaners for removing nitrogen dioxide (NO_2) and VOC from air when first exposed to these pollutants at concentrations typically found indoors. This investigation <u>did not examine</u> the efficiencies of these devices during or after long-term usage (e.g., the effects of filter loading with particles, saturation of the charcoal adsorbents or possible later releases of adsorbed materials). Although the study was conducted under conditions typical of residential environments, it did not systematically examine the effects of varied levels of temperature and humidity.

Nitrogen dioxide and VOC were specifically selected as the analytes of interest for this research because they are commonly found in residential indoor air at concentrations

significantly above those of outdoor air and because they have documented health effects. Elevated concentrations of NO_2 have been observed in homes with gas stoves and kerosene heaters and in emissions from these and other unvented combustion appliances (Palmes and Tomczyk, 1979; Dockery *et al.*, 1981; Spengler *et al.*, 1983; Girman *et al.*, 1982; Traynor *et al.*, 1983; Leaderer *et al.*, 1986). Exposures to elevated concentrations of NO_2 have been associated with pulmonary edema, broncho-constriction and increased respiratory infection (U.S. E.P.A., 1982). There is also epidemiological evidence indicating that increased respiratory infection in children and adult males and reduced pulmonary function in humans are associated with exposure to emissions from gas-stove cooking (U.S. E.P.A., 1982).

The VOC are an ubiquitous mixture of compounds which include a number of carcinogens and teratogens. Major classes of VOC which have been found in indoor environments include aliphatic and aromatic hydrocarbons, chlorinated hydrocarbons, aldehydes, ketones, alcohols and esters (DeBortoli, *et al.*, 1986; Lebret, *et al.*, 1986; Wallace, 1986; Hodgson and Girman, In Press). The concentrations of the VOC in indoor air are typically two to five times greater than in outdoor air. Irritant and central nervous system effects as well as hypersensitivity reactions have been associated with exposures to these compounds. The VOC may be emitted continuously from building materials and furnishings and/or intermittently by combustion appliances and from the use of a variety of household and personal products.

Four portable air cleaners, representing three different principles of particle removal, were selected by the Consumer Product Safety Commission (CPSC) for this study. All incorporated some activated carbon to adsorb gaseous contaminants. The experiments were conducted in a 20-m^3 Environmental Chamber operated in static mode (sealed, without mechanical ventilation). This chamber is designed to give low backgrounds of particulate matter and gaseous inorganic and organic pollutants (Girman and Hodgson, 1986). For each air cleaner, the chamber was spiked with NO_2 and a mixture of six VOC. The six VOC were selected in consultation with the CPSC to represent the major classes of organic compounds found in

indoor air. Each air cleaner was operated in the chamber for several hours. The concentration of NO_2 was continuously monitored during this time and samples of VOC were periodically collected for subsequent analysis. Background-corrected decay rates were calculated from the concentration data; effective cleaning rates and efficiencies of removal for NO_2 and VOC were subsequently calculated from the decay rates.

There is some evidence that NO_2 can be converted to other compounds on activated carbon, e.g., nitrogen oxide (NO), nitrous (HNO_2) and nitric (HNO_3) acid (Gundel *et al.*, 1987). Since all of the air cleaners in this investigation had activated carbon in their filter assemblies, the concentration of NO in the chamber was monitored as an indicator of possible chemical reactions involving NO_2. Concentrations of ozone were monitored in the chamber during the experiment with the air cleaner which used an electrostatic precipitator for particle removal; electrostatic precipitators sometimes generate ozone which is itself a pollutant of concern and can also react with organic compounds to form other products.

2.0 EXPERIMENTAL METHODS

2.1 Concentration of NO_2

Air cleaner removal efficiencies for NO_2 were determined at an initial chamber concentration of ~500 $\mu g\ m^{-3}$. This concentration is about five times the mean NO_2 level reported for kitchens equipped with gas stoves (Harlos *et al.*, 1987) but is within the range of peak (<30 minutes) indoor concentrations recently reported by Harlos and Spengler (1987).

2.2 Composition of the VOC Mixture

Six VOC, representative of five major classes of VOC typically found in indoor environments were selected for the experiments: 1) n-heptane for aliphatic hydrocarbons, 2)

toluene for aromatic hydrocarbons, 3) dichloromethane (methylene chloride) and tetrachloroethylene for chlorinated hydrocarbons, 4) hexanal for aldehydes, and 5) 2-butanone (methylethylketone) for ketones. The targeted initial chamber concentrations for these compounds were: 1) n-heptane - 800 $\mu g\ m^{-3}$, 2) toluene - 800 $\mu g\ m^{-3}$, 3) dichloromethane - 250 $\mu g\ m^{-3}$, 4) tetrachloroethylene - 400 $\mu g\ m^{-3}$, 5) hexanal - 200 $\mu g\ m^{-3}$, and 6) 2-butanone - 150 $\mu g\ m^{-3}$. These concentrations and the relative proportions of the six VOC were selected, in part, to reflect those reported for their respective classes in indoor air (DeBortoli *et al.*, 1986; Lebret *et al.*, 1986; Hodgson and Girman, In Press).

2.3 Description of the Air Cleaners

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

Air flow rates for the four air cleaners, either stated or estimated from product information provided by the manufacturers, range between 40 and 400 $ft^3\ min^{-1}$ (68 to 680 $m^3\ h^{-1}$). The devices designated PF1 and PF2 have multiple stage filter cartridges employing layers of glass fibers for particle removal. The ES unit has a HEPA filter for particle removal. The fourth device, EP, removes particles by electrostatic precipitation. All of the devices have varied quantities of activated carbon positioned after the primary particle removal device. The ES air cleaner contains activated carbon combined with potassium permanganate. The PF2 air cleaner contains activated carbon in combination with an oxidation catalyst; the manufacturer claims in its brochure that this device removes gaseous pollutants.

2.4 Description of the Environmental Chamber

The Environmental Chamber used in this study is located within an air-conditioned laboratory. The chamber encloses a volume of 20 m^3 with interior dimensions of 3.66 m (length) x 2.46 m (width) x 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 and interior seams are sealed with silicone gasket material. Electrical and plumbing feedthroughs are also sealed. The synthetic materials used in the construction of the chamber were selected, in part, for their low emissions of VOC. Background concentrations of ten common low-boiling organic compounds were previously measured in the chamber air and were found to be less than 2 ppbv for each compound (Girman and Hodgson, 1986).

The chamber is equipped with a single-pass ventilation system. Inlet air is drawn from outside the laboratory building by a variable-speed blower and passes through a coarse filter, a a HEPA filter, and a charcoal filter in series. Prior to each experiment, the chamber was purged with purified outdoor air. Then the air inlet and exhaust were sealed at the chamber wall and the chamber was operated in static mode. The infiltration rate previously determined for the chamber operated in static mode was $0.03 \pm 0.01\ h^{-1}$ (Girman and Hodgson, 1986).

Atmospheric pressure inside the chamber averaged 742 ± 5 torr during the experiments. Air temperature in the chamber was maintained at 23 ± 2 °C by controlling the temperature of the laboratory. The chamber's insulation dampens thermal fluctuations due to the heating-cooling cycle. Relative humidity in the chamber was not controlled but averaged 47 ± 9%. Appendix 1 presents the environmental conditions for each experiment.

2.5 Determination of Air Flow-Rates and Power Consumption of the Air Cleaners

Air flow-rate measurements were made at each speed setting of each air cleaner. The

flow-rate measurement was made using either a pitot tube or an orifice plate flowmeter constructed in accordance with the American Society of Mechanical Engineers specification (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 minimally affected by the attachment of the measurement system. Differential pressure measurements were made with either a micromanometer or a Magnahelic gauge, depending upon the air flow rate (and pressure drop) for a given air cleaner. Air flow rates were also measured using a calibrated hot-wire anemometer. Each air cleaner was set at its maximum speed and a minimum of nine measurements of air velocity were made across the face of the air inlet. The flow rates measured with the anemometer were found to be very uniform. Flow rates for each device were calculated as the average of the measurements multiplied by the inlet area and were compared to those determined using the orifice plate or pitot tube.

Power consumption measurements were made for each device at its maximum speed setting at 115V using a digital volt-ohm meter. These data can be used to calculate the absolute or relative costs of operating the air cleaners and of removing gaseous pollutants.

2.6 Experimental Protocols for Chamber Experiments

Prior to an experiment, the laboratory and chamber were stabilized at the desired temperature and the chamber was ventilated at a rate of approximately 10 h^{-1} for at least one-half hour. During this period, the air cleaner and an oscillating fan were positioned in the chamber but not operated. The oscillating fan, used for uniform mixing of the chamber atmosphere, was placed on the floor, in a corner of the chamber about 1 meter from the air

cleaner. The ventilation system was then turned off and the air inlet, air outlet, and the door were closed. These remained closed until the conclusion of the experiment. At this point, 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 known amounts of the analytes to produce the desired concentrations. For NO_2, a gaseous standard was injected into a port connected to an air stream flowing to the mixing fan. For all experiments except the last with the EP cleaner, the VOC were introduced into the Chamber by injecting a small volume of a liquid mixture of the VOC into a port which was heated. For the last experiment, a measured volume of a liquid mixture of VOC was placed in a Petri dish on a hot plate near the mixing fan and evaporated over a 10-minute period. The purpose of this was to determine if more stable chamber concentrations of dichloromethane could be obtained during the mixing period and the initial stage of the experiment. Chamber air was mixed for approximately 30 minutes after injecting the analytes. Monitoring for NO_2 and NO commenced with the injection of the analytes. Sample collection for VOC commenced approximately ten minutes after the injection of the VOC. A Photovac 10S50 portable gas chromatograph (Photovac, Inc., Thornhill, Ontario, Canada), equipped with a CSP 20M column and a photoionization detector, was used for near real-time monitoring of the VOC. This information was used to determine the collection intervals and sample volumes for the VOC samples obtained with the multisorbent sampler.

Approximately 30 minutes after injection of the NO_2 and the VOC, the mixing fan was turned off and the air cleaner was turned on remotely from outside 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. The sampling interval was varied depending upon the decay rate of the VOC, determined from the semi-quantitative Photovac measurements. If the decay rate was relatively high, the initial intervals were ten minutes and were then extended as the experiment progressed.

The air cleaners were used as received without modification. Each air cleaner was operated at its maximum speed setting. The air cleaner was positioned in the center of the chamber on a table at a base height of 70 cm. New filter cartridges or activated carbon 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. The only prior usages of the devices were during an initial checkout and during air flow rate measurements. Air cleaners were operated for at least four hours, except for the experiment with the ES device which was for three hours.

2.7 Air Sampling and Analysis

Air for measurement of NO_2 and NO was drawn from multiple locations in the chamber to a common mixing manifold. Fifteen sample locations were used. The sample locations were near the four corners and near the center of the chamber at three heights - near the floor, mid-height and near the ceiling. With the exception of the central sampling location, sample locations were 25-30 cm from adjacent chamber surfaces. Total flow rate was 2 L min^{-1}. All sampling lines were of equal length and diameter. Measurements made in a previous study showed that the flow rates in the individual lines were all equal within $\pm$ 10% (Girman and Hodgson, 1986). Components of the sample line were Teflon and stainless steel.

A chemiluminescent NO_x analyzer (Model 14 D/E, Thermo Electron Corp., Hopkinton, MA) was used for the analysis of NO_2 and NO. The instrument has a noise level of 10 $\mu g\ m^{-3}$ and a lower limit of detection of 20 $\mu g\ m^{-3}$ for NO_2. 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 $\pm 0.1°C$ in a permeation oven (Model 8500 Permacal, Monitor Labs, Inc., San Diego, CA) which had been modified in this laboratory for better flow control. Electronic mass-flow controllers were used to regulate flow through the oven and the flow of dilution gas. 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.

During the experiment with the EP air cleaner, ozone concentrations in the chamber were monitored continuously with a Model 1003AH Ozone Monitor (Dasibi Environmental Corp., Glendale, CA). The instrument zero and span were checked at the beginning and end of the experiment as recommended by the manufacturer. Air was drawn from mid-chamber (about 50 cm from the air cleaner exhaust) to the Ozone Monitor through Teflon tubing.

Samples for VOC were collected from air drawn from a location near the center of the chamber (about 50 cm from the air cleaner) through Teflon tubing. Duplicate samples were collected on multisorbent samplers containing Tenax-TA, Ambersorb XE-340 and activated charcoal (Part No. ST-032, Envirochem, Inc., Kemblesville, PA). Sampling flow rates were 113 cm^3 min^{-1} (20°C, 760 torr). Flow rates were regulated with electronic mass-flow controllers placed between the sampler and the vacuum source. Sample volumes were varied according to expected analyte concentrations, and typically ranged between 0.5 and 2 L. Sampling intervals were typically 10 minutes (see Appendix 3 for details). 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, In Press). In brief, a sample is thermally desorbed from a sampler and introduced into a capillary gas chromatograph (GC) with a UNACON® Model 810A (Envirochem, Inc., Kemblesville, PA) sample concentrating and inletting system. Sample components are resolved with a GC (5790A series, Hewlett Packard Co., Palo Alto, CA) equipped with liquid-nitrogen subambient cooling and a fused-silica capillary column (DB-1701, J and W Scientific, Inc., Cordova, CA). The GC is connected via a direct capillary interface to a 5970B series Mass Selective (MS) Detector (Hewlett-Packard Co.). The detector was operated to monitor multiple, individually-selected mass ions. For each compound of interest, a mass ion with high relative intensity is chosen as

the quantitative ion, and a characteristic ion is chosen as a qualifying ion for confirmation of compound identity. A standard gas mixture was prepared by injecting an aliquot of the liquid mixture of the six VOC used to spike the chamber into a helium-filled 2-L flask with septum cap which was then heated and maintained at 65°C. A sample was withdrawn from the flask with a gas-tight syringe and was injected onto a multisorbent sampler 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-MS scan analysis to determine if compounds other than the six VOC added to the chamber were present.

Details of the quality assurance protocols followed for these experiments are presented in Appendix 2.

2.8 Other Instrumentation

A chilled-mirror dew-point hygrometer (Model 911 Dew-All; EG&G, Inc., Waltham, MA) was used to measure the dewpoint of the air in the chamber. A continuous sample of chamber air was drawn at 0.5 L min^{-1} through the instrument and vented back into the chamber.

Type T thermocouples were used to measure air temperatures in the chamber. Five of these thermocouples were positioned at five of the 15 sample points and an average temperature was calculated for each 1 minute interval of the experiment. Atmospheric pressure was measured with a mercury barometer immediately prior to each experiment.

The background particle concentration in the Environmental Chamber was measured with a condensation nucleus counter (CNC), Model No. 3020 (TSI, Inc.,St. Paul, MN). This instrument counts total number of particles with diameters between 0.01 and 0.3 μm.

Analog output signals from the NO_x analyzer, thermocouples and dew-point hygrometer

were sampled throughout an experiment with a microprocessor-based data acquisition system (Series 500, Keithly/DAS, Cleveland, OH). The data sampling interval was one second for the NO_x analyzer and five seconds for the environmental data. Data were stored on magnetic diskettes for subsequent analysis.

2.9 Data Analysis

Data analysis was similar to that used for previous studies of particle removal by air cleaners[1,2]. The rate of decay of NO_2 or VOC concentration (spatially averaged), C, within a chamber of volume, V, with the air cleaner in operation, can be described by the differential mass balance equation:

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

where

Q_v = The flow rate of ventilation air (infiltration),

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

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 constant mechanical ventilation. Past experiments indicate that infilitration is $0.03 \pm 0.01\ h^{-1}$. Therefore, Q_v is approximately zero and equation (1) may be written

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

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

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

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 with the air in the chamber. Thus, a short-circuiting factor, E_d, is defined as:

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

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

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

This 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 = o and t = t_1 yields

$$\ln C = - \lambda_{ex} t_1 + \ln C_o \quad , \tag{6}$$

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

The slope of a plot of ln C versus 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.

Two additional parameters were calculated from the experimental data, the effective cleaning rate (ECR) and the system efficiency. The ECR is the product of λ_{ac} and the chamber volume. 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. The system efficiency is the ECR divided by the actual air flow through the air cleaner, Q_d. The uncertainties in these calculated quantities were estimated by the propagation of errors.

The standard errors of the slopes of the decay curves were used as the basis for estimating uncertainties. For the average chamber background decay rate, the standard error, s_B, was estimated as $1/2\ (s_1^2 \pm s_2^2)^{0.5}$, where s_1 and s_2 are the standard errors of the slopes of the decay curves for experiments 1 and 2 on chamber background decay rates. For the air cleaner decay rates, corrected for chamber background decay rates, the uncertainties were estimated based on $(s_{AC}^2 \pm s_B^2)^{0.5}$, where s_{AC} is the standard error of the slope for the decay curve determined in and experiment with an air cleaner. The 95 % confidence intervals were then calculated by multiplying the standard errors by Student's t for the appropriate number of degrees of freedom. Uncertainties in the ECRs and efficiencies were estimated by propagation of errors. The estimated 95 % confidence intervals in the means of the measured flow rates, used in the propagation of errors, ranged from about 5 to 12 % and were typical of uncertainties associated with flow rate measurements.

3.0 RESULTS

3.1 Air Flow Rates and Power Consumption of the Air Cleaners

Table 2 summarizes the air flow rates measured for each of the four air cleaners measured with the pitot tube or orifice plate flowmeter. The ES and EP air cleaners had variable speed controls; measurements were made only at maximum speeds for these devices. The EP air cleaner had the highest flow rate. The PF1 air cleaner, the smallest device, operated at the lowest flow rates. Air flow rate measurements were also made using a hot-wire anemometer

for the PF2 air cleaner because there were difficulties maintaining a steady zero static pressure in the interface between the device and the tube used for the flow rate measurement. Hot-wire anemometer measurements were then made for the other air cleaners as well. The results of these measurements are compared to the flow rates determined with the pitot tube and orifice plate flowmeter in Table 3.

For three of the air cleaners, the agreement in the air flow rates measured by the two methods was within ten percent. For the PF2 unit, the flow rate determined with the anemometer was 21% higher than that determined by the other method. It appears that because of the design of this device, the flow rate is very sensitive to the pressure drop across the fan. The polyethylene bag interface may have introduced a small additional pressure resulting in an erroneously low flow rate. For this reason, the flow rate measured with the anemometer was judged to be more accurate and was used to calculate the efficiency of the PF2 device.

Air flow rates stated directly or calculated from other data in the product information provided by the manufacturers are also presented in Table 3. With the exception of the PF1 air cleaner, the measured flow rates were all much lower than those indicated by the manufacturers. Olander *et al.* (1987) have reported similar discrepancies between the flow rates reported by manufacturers and those measured in the laboratory. The reason for these large discrepancies is not known. It is possible that the manufacturers' rates are based on measurements without the filter assemblies in place.

Power consumption at the maximum flow rate is presented in Table 2 for each device. The air moving efficiencies for the four devices (calculated as the air flow rate divided by the power consumption) ranged from 1.1 to 2.2 $m^3\ h^{-1}\ watt^{-1}$. These data can be used to calculate the cost of operating each of the air cleaners. In order to calculate the energy efficiency of cleaning the air of the pollutants in this study, these air moving energy efficiencies must be

multiplied by the efficiences of pollutant removal.

3.2 Air Cleaner Removal Rates for NO_2 and VOC

Table 4 presents the concentrations of NO_2 and VOC at the start of the decay experiments with the air cleaners. There was some difficulty in obtaining stable concentrations of dichloromethane during the mixing period and at the beginning of the experiment for unknown reasons. Consequently, decay rates for this compound were calculated using the highest stable concentration as the initial concentration point. The method of injection of VOC was altered in the final experiment of the study with the EP device with the result that the initial concentrations of dichloromethane were more stable in this experiment. Some data points for toluene were lost in the experiment with the EP device because the sample volumes were too large and the mass analyzer became saturated. During experiments with the PF1 and EP air cleaners, there were several periods during which there were large, anomalous variations in the output of the the NO_2 analyzer signal, presumably due to blockage of the catalytic converter or to some other mechanical/electrical problem. However, the analyzer was never turned off and the calibrations at the beginning and end of each of these experiments were identical. Since the decay rates of NO_2 were low in these experiments and the data extended over four hours, the segments of erroneous data were simply excluded from the linear regression analyses.

Experiments were generally conducted for four hours. If the decay rates of NO_2 and VOC were relatively low, all of the valid data for this period, starting with the time the air cleaner was turned on, were included in the linear regression analyses. In experiments in which the decay rates were rapid, concentrations decreased to very low values before the end of the experiment. In this case, NO_2 decay rates were calculated from the time the air cleaner was turned on until concentrations decreased to the range of 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 chamber infiltration at low concentrations. In addition, the equilibrium between adsorption and desorption from the activated carbon may have been reached at this level (Gruber and Burgess, 1981). For VOC, in the cases of rapid decays, decay rates were calculated using the data from the start of air cleaner operation until concentrations declined to less than 5 $\mu g\ m^{-3}$ (approximately 1 ppbv for the compounds in this study). This cut-off was selected since the VOC sample volumes were not optimized for these lower concentrations.

Several experiments were conducted to measure the background decay rates of NO_2 and VOC in the Environmental Chamber. In a preliminary chamber background experiment, only the decay rate of NO_2 was measured. After a ten-minute mixing period, the mixing fan was turned off and there was no additional mixing. The NO_2 decay rate in this experiment was $0.087 \pm 0.001\ h^{-1}$. In the next two experiments, the PF2 air cleaner was operated, without its filter cartridge, to provide mixing which would be similar to that which would occur during decay experiments with the air cleaners. Table 5 summarizes the background removal rates for NO_2 and the VOC for the latter two experiments, which are designated Experiments 1 and 2. The data for these experiments are presented graphically in Appendix 3.

The differences in the background decay rates for the VOC compounds between the chamber background experiments 1 and 2, ranged from about three to ten percent and were not statistically significant ($p<0.05$). The average background decays for these two experiments, shown in Table 5, 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. For the air cleaners with the higher removal rates, the background decay rates were generally 10 % or less of the total decay rate. For the less effective devices, the uncorrected decay rates were generally at least twice those of the background decay rates.

Concentrations of suspended particles in the chamber were measured before and after the experiment with the PF1 air cleaner. The purpose of the initial measurement was to determine

chamber background concentrations of particles. At the start of the experiment, the concentration was 2.4 x 10^3 particles cm^{-3} compared to a laboratory air concentration of 1.0 x 10^4 particles cm^{-3}. At the conclusion of the experiment, the concentration in the chamber was 30 particles cm^{-3}.

The figures in Appendix 3 graphically present the changes in the chamber concentrations of the NO_2 and the VOC (uncorrected for chamber background) over the course of each experiment. The concentrations are plotted on a logarithmic scale because they varied over several orders of magnitude and because the data analysis assumes a first order rate of decay. In general, the semi-logarithmic plots are highly linear; the correlation coefficients for all but three of the decay curves were equal to or greater than 0.92. The correlation coefficients for dichloromethane in several experiments and for 2-butanone in Experiment 2 (chamber background) were greater than 0.84. For the NO_2 decay curves, instrumental noise increased as the NO_2 concentrations approached the 20 $\mu g\ m^{-3}$ (ln = 3) detection limit. Within the experimental uncertainties, the slopes of the decay curves for the dichloromethane were the same as the slopes of chamber background decay curves. The slopes of the decay curves for the other five VOC were generally similar for any given air cleaner. At concentrations near the lower limits of quantitation, the variability in VOC concentrations also tended to increase.

Table 6 presents the removal rates (corrected for chamber background decays) for NO_2 and the six VOC due to operation of the four air cleaners. The estimated uncertainties, reported as 95% confidence intervals, are also presented. Duplicate experiments were conducted with the PF2 air cleaner to assess experimental variability. The same filter was used in both experiments. The removal rate for NO_2 decreased from 3.95 to 3.52 h^{-1} in the second experiment. This difference was statistically significant (p=0.01) when tested using Student's t-test. The removal rates for n-heptane, hexanal, and toluene were also lower and significantly different (p=0.01 for the first two and p=0.05 for the third compound) in the second experiment. Differences in removal rates for the remaining VOC were not significantly

different ($p<0.05$). The differences observed for NO_2, n-heptane, toluene and hexanal may be due to a variability in the experimental method which was not reflected in the estimated uncertainties. Alternatively, these differences may represent a real reduction in the efficiency of removal with filter use.

Of the four air cleaners, the PF2 device had the highest removal rate for NO_2. The PF1 and EP devices had the lowest removal rates for NO_2, which were only 2.5 to 3 times greater than the background decay rate. None of the air cleaners effectively removed dichloromethane. The PF2 and ES air cleaners had similar removal rates for the remaining VOC of about 2 h^{-1}. The PF1 air cleaner did not remove 2-butanone and had low removal rates for the remaining VOC. The PF2 device was found to emit 1,1,1-trichloroethane at a rate of about 19.2 mg h^{-1}. 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.

3.3 Effective Cleaning Rates and Efficiencies of Removal for NO_2 and VOC

Table 7 summarizes the effective cleaning rates (ECRs) for NO_2 and the six VOC.. The ECR is the product of the removal rate times the volume of the Chamber (20 m^3) and provides a measure of the effective volume of air from which NO_2 and VOC are removed by the air cleaner in one hour. This measure is useful for evaluating the effects of air cleaners in rooms of different sizes and for comparing air cleaning to ventilation as an indoor air quality control technique.

There were substantial variations among the air cleaners with respect to the ECR for NO_2 and VOC. Since all of the experiments were conducted in the same chamber volume, these variations are the same as the variations among the removal rates in Table 6. For the PF2 and

the ES air cleaners, the ECRs ranged from 18 to 51 $m^3 h^{-1}$ for five of the VOC. The ECRs for the EP device ranged from 8 to 18 $m^3 h^{-1}$ for the same five VOC. The ECR for NO_2 averaged 74 $m^3 h^{-1}$ for the PF2 device and was 41 $m^3 h^{-1}$ for the ES air cleaner. The ECRs for dichloromethane show that none of the air cleaners is useful for removing this compound from air.

Table 8 presents the efficiencies of removal for NO_2 and VOC which are the ECR divided by the measured air flow rates. Of the four air cleaners, PF2 had the highest efficiency for removal of NO_2 (40% versus 2 to 18%) while the PF2 and ES devices had similar efficiencies of about 20 % for the removal of VOC, exclusive of dichloromethane. The PF1 and EP air cleaners had the lowest efficiencies for removal of both NO_2 and VOC, ranging from 0 to 6.3%.

The product of the efficiency of removal and the flow rate of a given air cleaner can be divided by the power consumption (Table 2) to estimate the energy requirements for pollutant removal. For example, for NO_2 removal by the ES device, this would be 228 $m^3 h^{-1}$ x 0.18 / 178 watts or 0.23 $m^3 h^{-1}$ $watts^{-1}$, i.e., 0.23 m^3 of air cleaned per hour per watt. Since this was a preliminary investigation, these calculations were not reported.

3.4 Evidence of Chemical Reactions

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 carbon. There was no evidence of NO formation in any of these experiments. In the experiment with the EP device, no ozone generation was observed. The GC-MS scan analyses for additional VOC that might have been formed by reactions on the activated carbon showed no evidence of such compounds.

4.0 DISCUSSION

Whitby *et al.* (1983) have suggested as a criterion for evaluating air cleaners that the ECR should be equivalent to one air change per hour 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. The air flow through the device as well as the amount of activated carbon and configuration of the activated carbon filter will affect the ECRs for any individual air cleaner.

The PF2 and ES air cleaners have high air flows and, from visual inspection, have the highest amounts of activated carbon. Correspondingly, these two devices had the highest ECRs for both NO_2 and VOC, exclusive of dichloromethane which was not removed by any device. The ECRs for these two units generally meet the criterion suggested by Whitby *et al.* for a room volume of about 40 m^3 (approximately 13 ft x 13 ft x 8 ft). With the PF2, device which had a catalyst mixed with the activated carbon, the ECRs for NO_2 were almost twice those for the five VOC. More effective removal of NO_2 than of VOC was not observed for any of the other devices. This suggests that the catalyst (and/or its support) enhances the removal of NO_2 over that obtainable with activated carbon alone.

The other two air cleaners, the small PF1 device and the EP device had lower ECRs and efficiencies for the removal of NO_2 and VOC. The PF1 device has the lowest air flow rate and also, from inspection, only a small amount of activated carbon. The EP device has the highest flow rate and more carbon 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 filter in the EP device has granulated activated carbon (1-2 mm in diameter) loosely dispersed throughout a cardboard grid of open triangles. There was considerably less carbon and more void space between the carbon pellets in the EP device than in the ES device which has an activated carbon filter of

similar design. Thus, in order to be adsorbed by the carbon, the gases have to diffuse across greater distances in the EP device compared to the ES. The high volumetric flow rate of the EP air cleaner also reduces the residence time of the gases in the vicinity of the carbon.

The results reported here for NO_2 can be compared to those reported by Humphreys (1987) and by Canine (1986). Humphreys tested two air cleaners with activated carbon, 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 carbon. The ECRs, which can be calculated from the data reported by Canine, 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, 427 mm (CRC Rubber Handbook, 1974), is four times the vapor pressure of the compound with the next highest vapor pressure, 2-butanone (95.5 mm). Variations among the ECRs of the remaining VOC were generally small or not significant for any air cleaner.

The effects of extended operation of the air cleaners on the ECRs and removal efficiencies were not investigated in this study. However, the second experiment with the PF2 unit, in which the same filter cartridge was used, suggests that there was some reduction in ECRs for NO_2, n-heptane, toluene and hexanal when the air cleaner was operated for only a very short

period relative to the manufacturer's stated filter life. Further investigation of changes in the ECRs with use over extended periods would be warranted for air cleaners which have high initial ECRs and removal efficiencies.

Under the conditions of the experiments conducted here, no products resulting from chemical reactions occurring on the surface of the activated carbon were observed in the chamber air. Even if such reactions do occur, perhaps with longer operation and higher pollutant loading of the carbon, they would not be of importance unless the products were toxic and were released in significant quantities from the carbon. One air cleaner, the PF2 device, did, however, emit 1,1,1-trichloroethane. This solvent was presumably residual from the manufacture of some component.

In summary, both the PF2 and ES air cleaners are reasonably effective, at least initially, in removing NO_2 and five of the six VOC from moderate-sized rooms. The PF1 device, however, has little effect on the removal of these compounds and the EP device is only slightly better. None of the four air cleaners removes dichloromethane. Since both the ECRs and efficiencies of the air cleaners are likely to decrease with filter use, the values reported here are likely to be the maxima for the temperature and humidity of these experiments.

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5.0 REFERENCES

Association of Home Appliance Manufacturers (1985) AHAM standard method for measuring performance of portable household electric cord connected room air cleaners (AC-1). Draft Report. Chicago, IL.

ASME (1971) *Fluid Meters: Their Theory and Application.* The American Society of Mechanical Engineers, New York, NY.

Canine, C. (1986) Clearing the air. *Rodale's New Shelter*, January, pp.64 - 67.

Consumer Union (1985) Air cleaners, *Consumer Reports*, 50(1): 7-11.

CRC Rubber Handbook of Physics and Chemistry, 55th edition, CRC Press, Cleveland, OH, 1974.

DeBortoli, M., H. Knoppel, E. Pecchio, A Peil, L. Rogar, H. Schauenburg, H. Schlitt and H. Vissers. (1986) Concentrations of selected organic pollutants in indoor and outdoor air in northern Italy, *Environ. Int.*,12: 343-350.

Dockery, D.W., Spengler, J.D., Reed, M.P. and Ware, J. (1981) Relationships among personal, indoor and outdoor NO_2 measurements. *Environ. Int.*,5: 101-107.

Girman, J.R., Apte, M.G., Traynor, G.W., Allen, J.R. and Hollowell, C.D. (1982) Pollutant emission rates from indoor combustion appliances and sidestream cigarette smoke. *Environ. Int.*, 8: 213-221.

Girman, J.R. and A.T. Hodgson (1986) Source characterization and personal exposure to methylene chloride from consumer products. Paper No. 86-52.7, *Proceedings of the 79th Annual Meeting of the Air Pollution Control Association*, Minneapolis, MN, June, 1986. Lawrence Berkeley Laboratory Report LBL-20227, Berkeley, CA.

Grubner, O. and W.A. Burgess. (1981) Calculation of adsorption breakthrough curves in air cleaning and sampling devices. *Environ. Sci. Technol.*, 15: 1346-1351.

Gundel, L.A., N. Somorjai and T. Novakov. (1987) The interaction of nitrogen oxides with particles: Chemical transformation on activated carbon and alumina surfaces. In: *Proceedings of the 4th International Conference on Indoor Air Quality*, Berlin (West), August 17-21, 1987, B. Seifert *et al.*, Eds., Institute for Water, Soil and Air Hygiene, Berlin, Vol. 1, pp. 330-332.

Harlos, D.P., M. Marbury, J. Samet and J.D. Spengler. (1987) Relating indoor NO_2 levels to infant personal exposures. *Atmos. Environ.*, 21: 369-376.

Harlos, D.P. and Spengler, J.D. (1987) Continuous nitrogen dioxide monitoring during cooking and commuting: personal and stationary exposures. In: *Proceedings of the 4th International Conference on Indoor Air Quality*, Berlin (West), 17-21 August, 1987, Seifert, B. et al., Eds., Institute for Water, Soil and Air Hygiene, Berlin, Vol. 1, pp.278-282.

Hodgson, A.T., and Girman, J.R. (In Press) Application of a multisorbent sampling technique for investigations of volatile organic compounds in buildings. In: *Proceedings, ASTM Symposium on Design and Protocol for Monitoring Indoor Air Quality*, April 26-29, 1987, Cincinnati, OH. (LBL-23087).

Hodgson, A.T., J. Binenboym and J.R. Girman. (1986), A multisorbent sampler for volatile organic compounds in indoor air, Paper No. 86-37.1, *Proceedings of the 79th Annual Meeting of the Air Pollution Control Association*, Minneapolis, MN, June 22-27, 1986, Air Pollution Control Association, Pittsburgh, PA.

Humphreys, M.P. (1987) Performance testing of residential indoor air cleaning devices. Paper presented at the *1987 EPA/APCA Symposium on Measurement of Toxic and Related Air Pollutants*, Research Triangle Park, NC, May 3-6, 1987.

Leaderer, B., R. Zagranski, M. Berwick and J.A.J. Stolwijk (1986) Assessment of exposure to indoor air contaminated from combustion sources: methodology and application. *Amer. J. Epidem.*, **124**: 275-289.

Lebret, E., H.J. van de Wiel, H.P. Bos, D. Noij and J.S.M Boleij. (1986) Volatile organic compounds in Dutch homes. *Environ. Int.*, **12**: 323-332.

New Shelter (1983) Home Products Report. Rodale Press, Emmaus, PA.

Offermann, F.J., Sextro, R.G., Fisk, W.J., Grimsrud, D.T., Nazaroff, W.W., Nero, A.V., Revzan, K.L. and Yater, J. (1985) Control of respirable particles in indoor air with portable air cleaners, *Atmos. Environ.*, **19**: 1761-1771.

Olander, L., J. Johansson and R. Johansson. (1987) Air cleaners for tobacco smoke. In: *Proceedings of the 4th International Conference on Indoor Air Quality*, Berlin (West), 17-21 August, 1987, Seifert, B. et al., Eds., Institute for Water, Soil and Air Hygiene, Berlin, Vol. 2, 39-43.

Palmes, E.D. and Tomczyk, C. (1979) Relationship of indoor NO_2 concentrations to use of unvented gas appliances. *J. Air Pollut. Control Assoc.*, **29**: 392-393.

Sextro, R.G., Offermann, F.J., Nazaroff, W.W., Nero, A.V., Revzan, K.L. and Yater, J. (1986) Evaluation of indoor aerosol control devices and their effects on radon progeny concentrations. *Environ. Int.*, **12**: 429-438.

Spengler, J.D., C.P. Duffy, R. Letz, T.W. Tibbitts and B.G. Ferris, Jr. (1983), Nitrogen dioxide inside and outside 137 homes and implications for ambient air quality standards and health effects research, *Environ. Sci. Technol.*, **17**: 164-168.

Stockham, J.D., D.R. Jones, and D.J. Moschandreas (1985) Performance of portable household air cleaners. Report prepared by IITRI, Chicago, IL for the Association of Home Appliance Manufacturers (AHAM).

Traynor, G.W., Allen, J.R., Apte, M.G., Girman, J.R. and Hollowell, C.D. (1983) Pollutant emissions from portable kerosene-fired space heaters. *Environ. Sci. Technol.*, **17**: 369-371.

U.S. Environmental Protection Agency, Environmental Criteria and Assessment Office, *Air Quality Criteria for Oxides of Nitrogen*, Research Triangle Park, N.C., 1982.

Wallace, L. (1986) Personal exposures, indoor and outdoor concentrations, and exhaled breath concentrations of selected volatile organic compounds measured for 600 residents of New Jersey, North Dakota, North Carolina and California. *Toxicol. Environ. Chem.*, **12**: 215-236.

Whitby, K.T., G.R. Anderson and K.L. Rubow. (1983) Dynamic method for evaluating room-size air purifiers. *ASHRAE Transactions*, *89*-2A, 172-182.

APPENDIX 1

ENVIRONMENTAL CONDITIONS IN THE CHAMBER DURING THE EXPERIMENTS

EXPERIMENT ID	ATMOSPHERIC PRESSURE (torr)	TEMPERATURE[a] (°C)	RELATIVE HUMIDITY[a] (%)
Background, Exp 1	743	23.4 ± 1.4	48.1 ± 2.2
Background, Exp 2	742	23.6 ± 1.2	42.4 ± 1.8
PF1	742	21.9 ± 0.6	54.5 ± 3.3
PF2, Exp 1	743	23.0 ± 1.2	48.7 ± 1.4
PF2, Exp 2	740	22.8 ± 0.6	51.9 ± 2.4
ES	740	24.2 ± 1.6	42.5 ± 2.4
EP	746	23.0 ± 1.2	44.5 ± 2.0

a. Mean ± 95% confidence interval

APPENDIX 2 QUALITY ASSURANCE PROTOCOLS

Introduction

In the protocol for the investigation of "Air Cleaner Efficiency for Removal of NO_2 and Volatile Organic Compounds", research objectives were defined, experimental apparatus and methods were described, and experimental protocols were established. The quality assurance plan establishes the procedures and guidelines to be followed to ensure the validity of the data.

Project Organization and Responsibilities

This study was conducted by the Indoor Environment Program at Lawrence Berkeley Laboratory (LBL) for the U.S. Consumer Product Safety Commission (CPSC) under interagency agreement IAG-86-1259. Dr. Joan M. Daisey was the LBL Project Officer for the study. The research was directed and carried out by Dr. Daisey and Mr. Alfred T. Hodgson. Dr. David Grimsrud was the Quality Assurance Manager for the study. The CPSC Project Officer was initially Dr. Pauline Johnston. Dr. Bharat Bhooshan became the Project Officer when Dr. Johnston left CPSC.

Quality Assurance Objectives

The sampling measurement and calibration procedures used are described in the protocol. Measurement techniques are summarized in Table A2-1. The quality assurance objectives for the measurements are presented in Table A2-2. The objectives are given in terms of measurement accuracy and precision required for quality assurance. Accuracy and precision are defined below. No objectives for data completeness were specified; experiments would have been repeated if missing or incomplete data, due to instrument failure or other factors, significantly affected the quality of the research effort.

Accuracy is the maximum difference between a measured value and its true value. Since the true value is unknown, the value obtained by an inherently more accurate and precise

technique is used as an estimate for the true value.

Precision is expressed by the standard deviation of repeated measurements or by the relative standard deviation which is the standard deviation expressed as a percentage of the mean value.

Measurement accuracy and precision for air temperature are sufficient to assure that this parameter stays within the specified limit during the course of an experiment.

Measurements of concentrations of NO_2 and the six VOC are the most important to the objectives of the study and are also the most difficult. The accuracies of these measurements were determined by comparing measured concentrations at the initiation of an experiment to concentrations calculated from the masses of the analytes that are injected into the chamber. Precision of the VOC measurements were determined from the analysis of three replicate samples of spiked chamber air collected during a preliminary experiment.

Sample and Data Handling

At the time of sample collection, VOC samplers were labeled with a unique number and the sample collection time and date. Sample flowrate and start and end times were recorded in a log book. Samplers were capped, placed in capped tubes and stored in a freezer at -10°C until analysis. Since the same individuals conducting the experiments were also analyzing the samples, no special sample custody procedures were required.

The continuous analog outputs of NO_x analyzer, thermocouples, and dew-point hygrometer were sampled by a microprocessor-based data acquisition system with 14-bit analog to digital conversion. These data were stored on a magnetic diskette. Each diskette was assigned a magnetically recorded identification number prior to use. A hardcopy of the continuous real-time analog output of the NO_x analyzer was made with a strip-chart recorder. Sampling

events were noted on this chart and recorded in a log book. Chromatographic and mass spectral data were stored on a 1/4 inch tape cartridge. Peak area and quantitation reports were computed and stored on the same cartridge. Hardcopies of chromatograms and reports were made with a line printer. Data diskettes, cartridges, hard copy, and log books are stored for future reference.

Reduction of the data was performed as soon as practical after completion of each experiment so that deficiencies could be promptly corrected. As reduced data become available, they were reviewed for consistency.

Internal Quality Control Checks

Internal quality control checks consisted of instrument calibrations, analysis of multisorbent sampler blanks, analyses of ambient chamber air for NO_2 and the six VOC prior to each experiment and near real-time display of NO_2 and environmental data.

A summary of instrument calibrations is presented in Table A2-3. The NO_x analyzer was calibrated prior to and immediately following each experiment. The MSD was tuned and calibrated prior to analyzing samples for each experiment. Calibration standards for the six VOC were analyzed on each day that samples were analyzed.

External Quality Control Checks

External quality control checks consisted of the duplicate experiments which were conducted for the background decay rates using one of the air cleaners without a filter. These duplicate experiments were performed and the data were reduced prior to initiating experiments with the air cleaners. The acceptability of the data were determined primarily from a comparison of the effective cleaning rates for NO_2 and the VOC between experiments. If the variability of these rates had exceeded 15%, an attempt would have been made to identify and reduce the source of this variability before proceeding with additional

experiments. This was not necessary.

Performance and System Audits

The quality assurance procedures established in this document were adequate to ensure reliable results. Prompt reduction of data following an experiment assisted in revealing any systematic problems. If problems in system performance were encountered, they were corrected before proceeding with additional experiments.

Corrective Action

The need for corrective action can be determined during instrument calibrations, during the course of an experiment, in the initial data reduction, and in the final evaluation of the data and results. This final evaluation was done in comparison with quality assurance objectives outlined in Table A1-2. Appropriate corrective action ranged from repair of instruments during, or as a short interruption to, an experiment to repetition of an entire experiment.

Quality Assurance Report to Management

One quality assurance report in the form of a memorandum was prepared during the course of the study by the Quality Assurance Manager and submitted to the LBL project officer. The primary duty of the quality assurance manager was to determine if the procedures established in the protocol and this quality assurance plan were being followed and to report on significant discrepancies

Table A2-1. Summary of measurement techniques and instrumentation

Parameter	Measurement Technique	Instrumentation
Air temperature	Seebeck electromotive force	Type T Thermocouple with digital voltmeter
Air pressure	Absolute pressure	Mercury barometer
Air humidity	Dew-point temperature	Chilled-mirror dew point hygrometer; Model 911 Dew-all, EG&G, Inc.
Air flow rates	Turbine speed	Turbine flowmeter with frequency counter; Model 2011-0 Daniel Industries, Inc.
	Differential pressure across an orifice plate	Micromanometer, see above
	Heat loss	Hot-wire anemometer Model 8500D-I, Compuflow, Alnor Instr. Co.
	Differential temperature	Thermal mass flow controller; Model 5810, Emerson Elec. Co.
	Volume displacement/ elapsed time	Bubble flowmeter and wet test meter
NO_2 concentration	Chemiluminescence	NO-NO_2-NO_x analyzer; Model 14D/E, Thermo Electron Corp.
VOC concentrations	Gas-liquid phase separation, electron impact mass spectrometry	Capillary gas chromatograph; 5790A series, Hewlett Packard Co., and Mass Selective Detector; 5970B series, Hewlett Packard Co.

Table A2-2. Quality assurance objectives

Parameter measured	Measurement range	Measurement precision	Measurement accuracy
Air temperature	21-27°C	±1.0°C	±1.5°C
Air dew-point temperature	6-19°C	±0.1°C	±0.3°C
Air flowrate	3-300 m^3h^{-1}	±2%	±10%
Calibration gas flowrate	0.5-30 L min^{-1}	±0.2	±2%
NO_2 concentration	20-250 $\mu g\ m^{-3}$	±5%	±10%
VOC concentration	10-1000 $\mu g\ m^{-3}$	±5%	±10%

Table A2-3. Calibration frequencies.

Instrument or Sensor	Calibration Method	Frequency
Thermocouples	Multipoint with precision thermometer	Prior to study
Dew-point hygrometer	Single point with reference instrument	Prior to study by manufacturer
Turbine flowmeter	Multipoint with orifice plate flowrate	Prior to study
Hot-wire anemometer	Multiple readings with orifice plate reference	Prior to study
Mass flow controllers	Multipoint with wet test meter	Prior to study
NO_x analyzer	Multipoint with permeation standard	Beginning and end of each experiment
	Zero and span with permeation standard	Beginning of each experiment
Mass Selective Detector	Perfluorotributylamine mass standard	Beginning of each experiment
Capillary GC-Mass Selective Detector	Multipoint with standard gas mixture	Each experiment and at least one standard on each day of analysis

APPENDIX 3

GRAPHICAL PRESENTATIONS OF THE VARIATIONS IN THE ENVIRONMENTAL CHAMBER CONCENTRATIONS OF NO_2 AND VOC WITH TIME

KEY TO VOC ABBREVIATIONS

DCM = Dichloromethane

C7 = n-Heptane

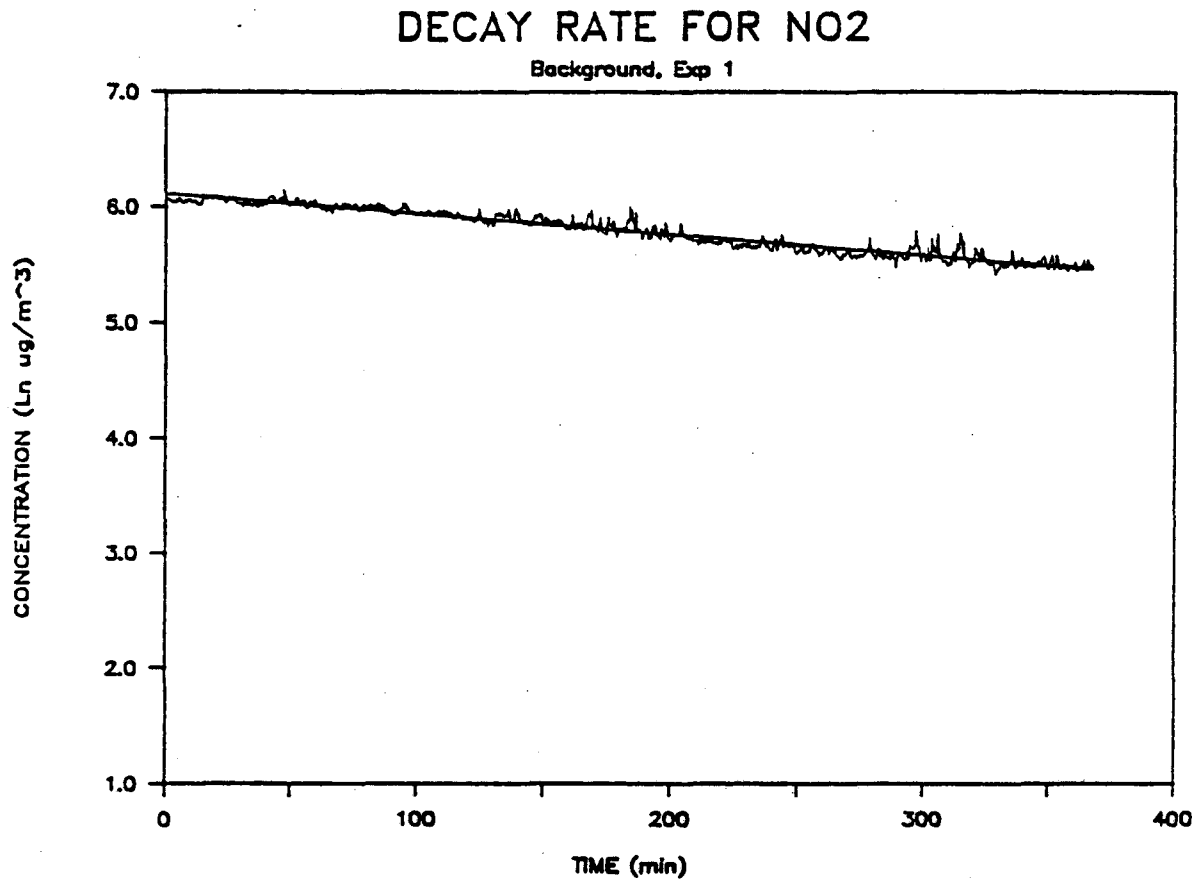
HEXAL = Hexanal

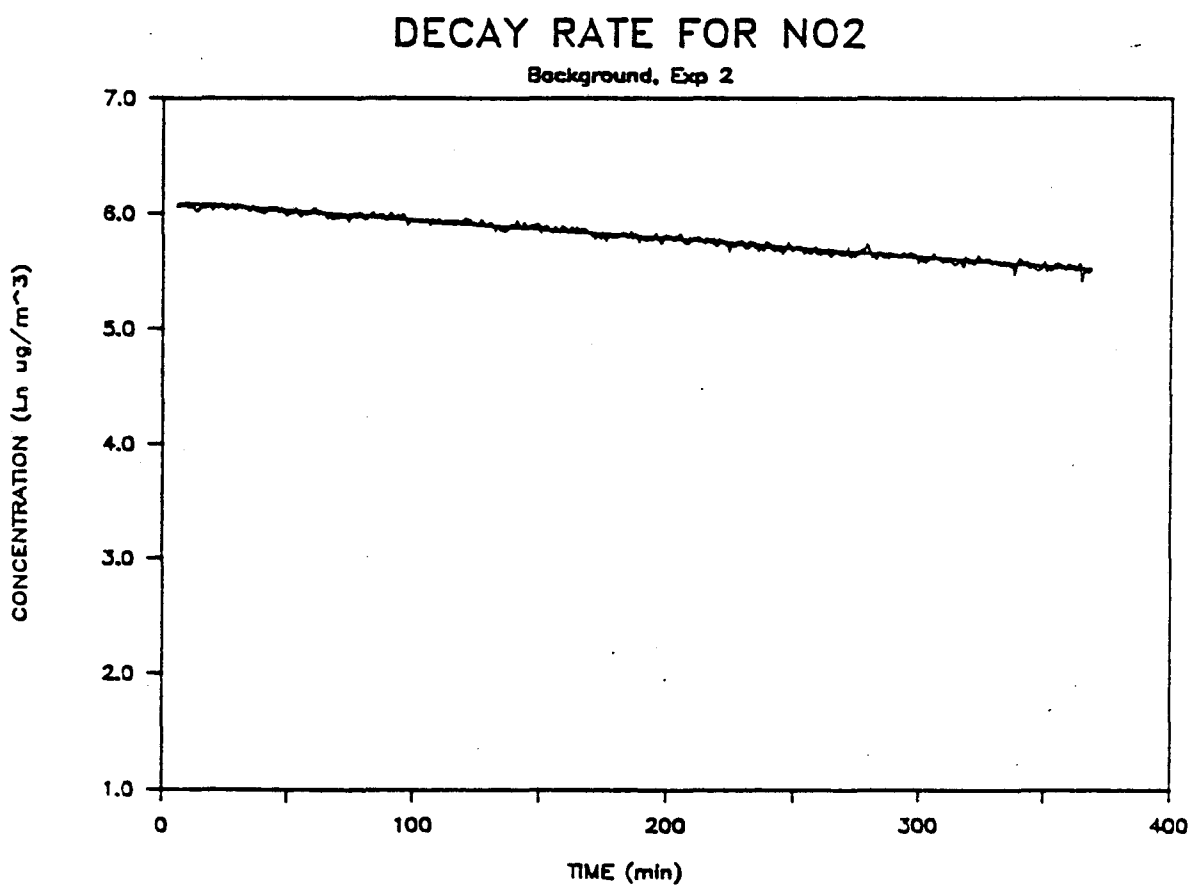
MEK = 2-Butanone (Methyl ethyl ketone)

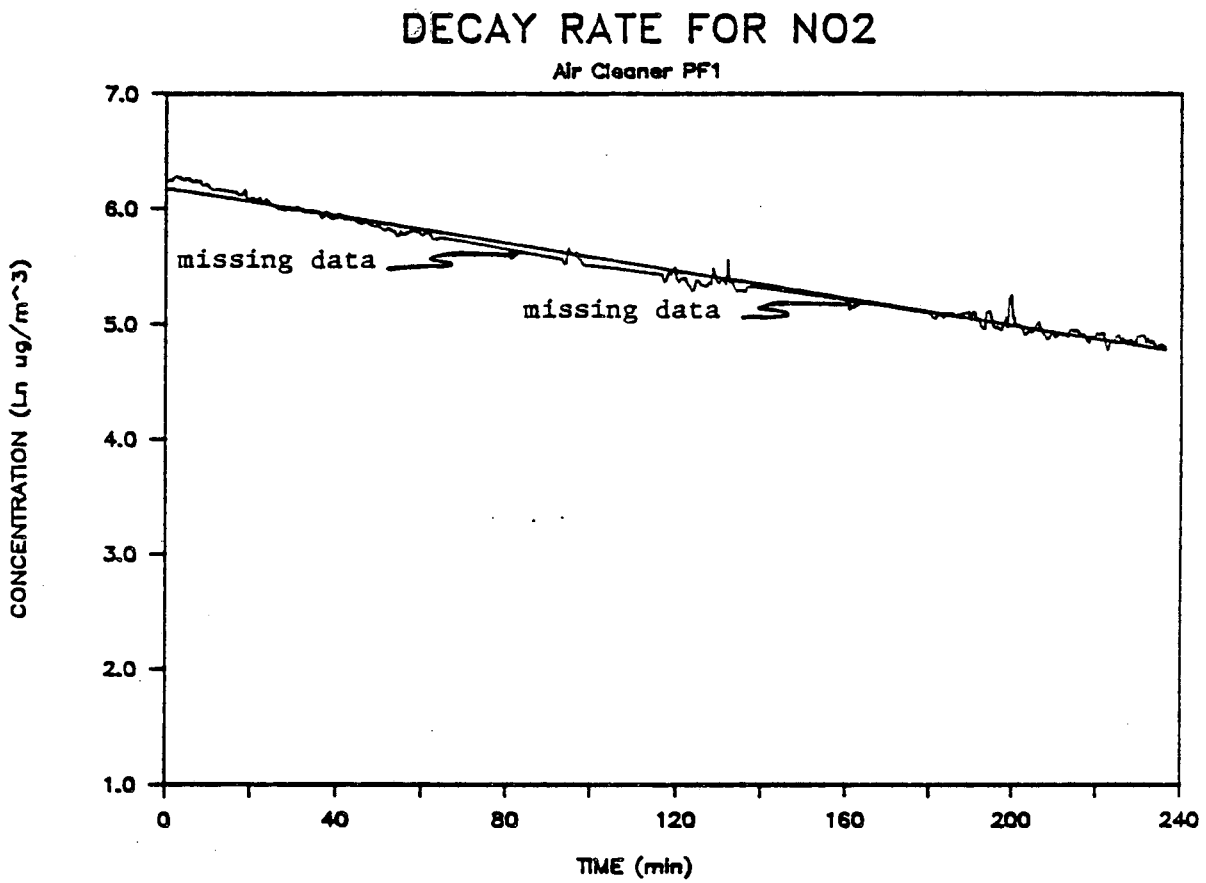
TOLU = Toluene

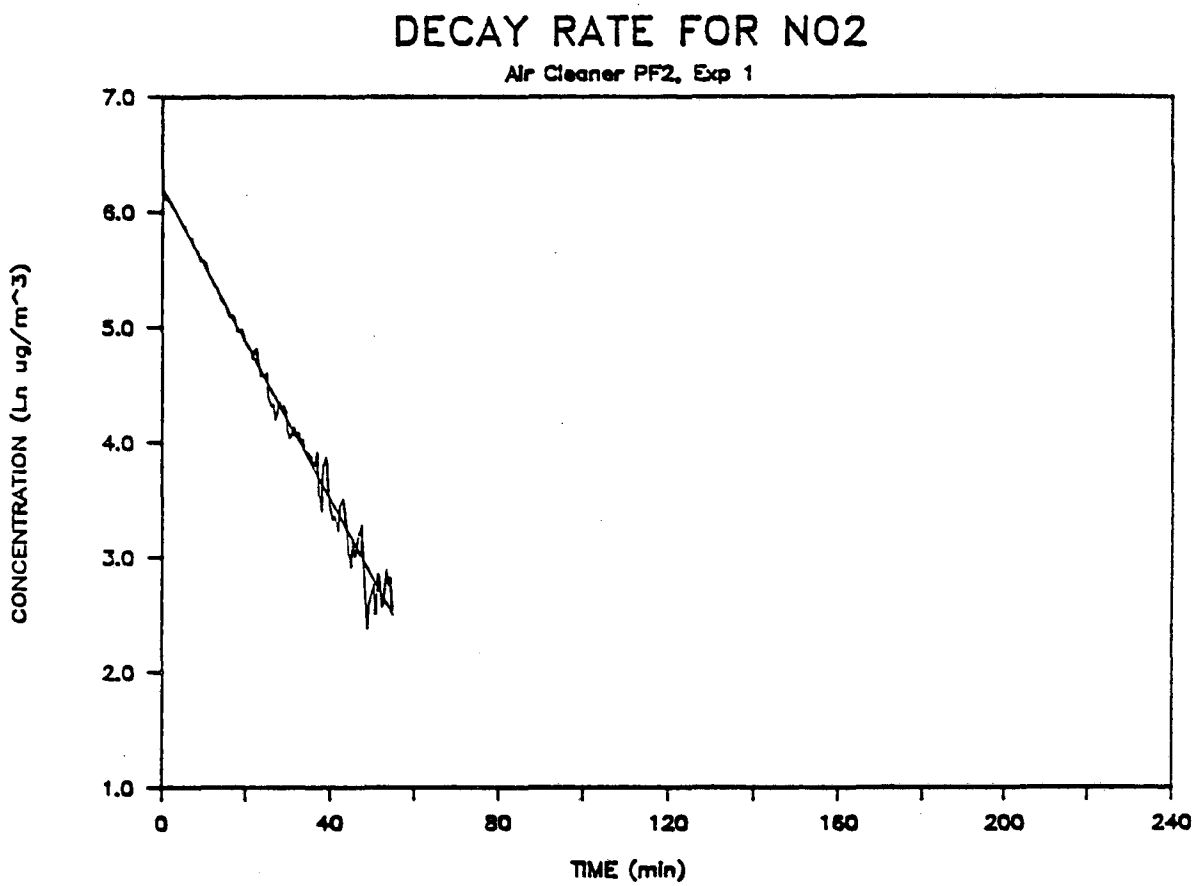
PCE = Tetrachloroethene (Perchloroethylene)

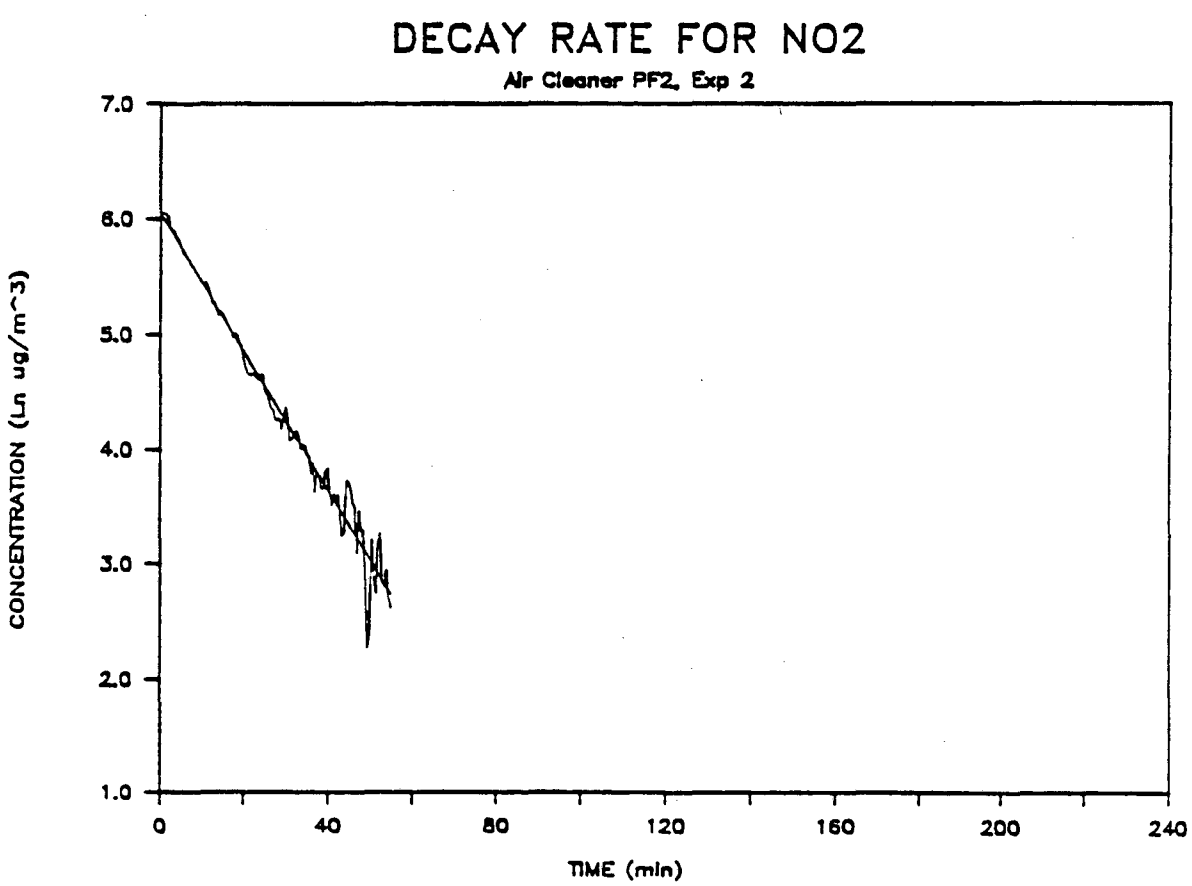
Time zero is the time at which the air cleaner was turned on

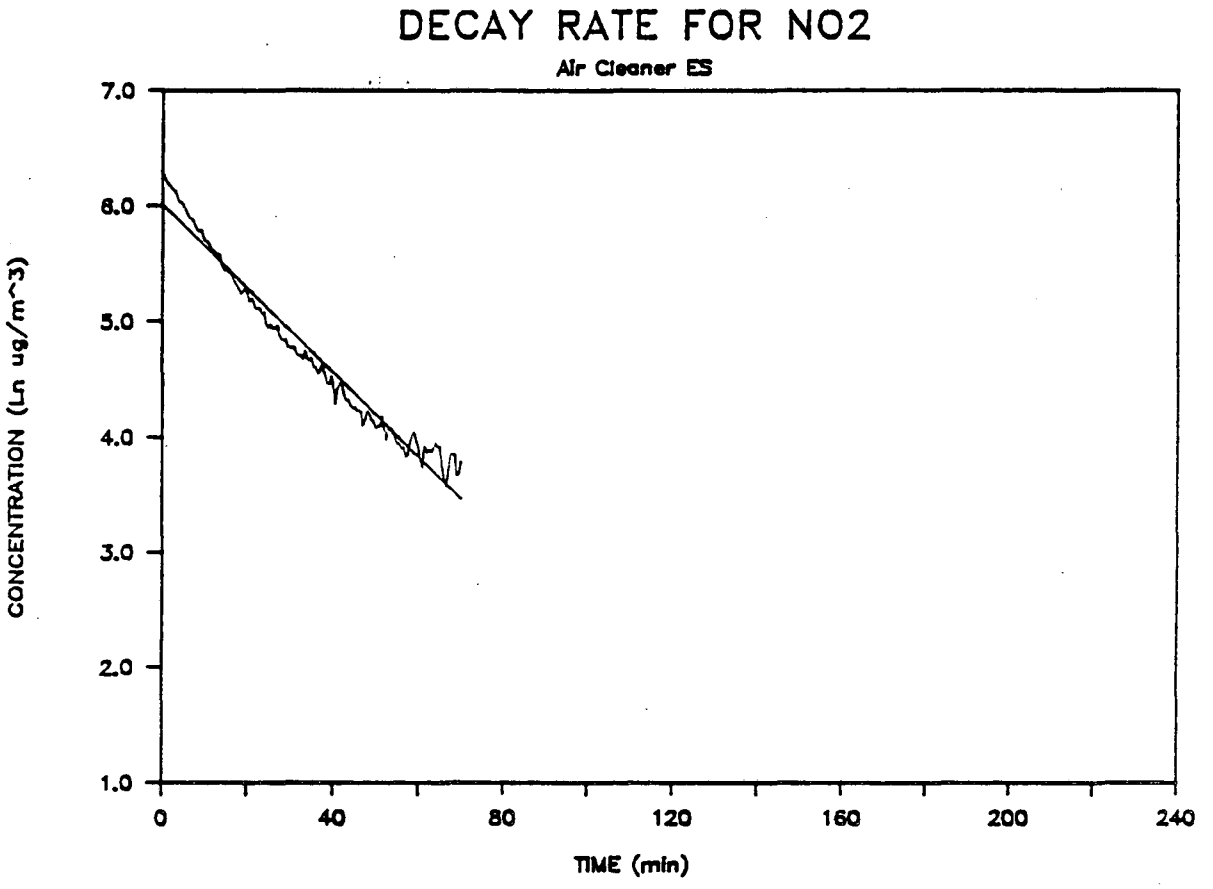

DECAY RATE FOR NO2
Background, Exp 1
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
100
200
300
400
TIME (min)

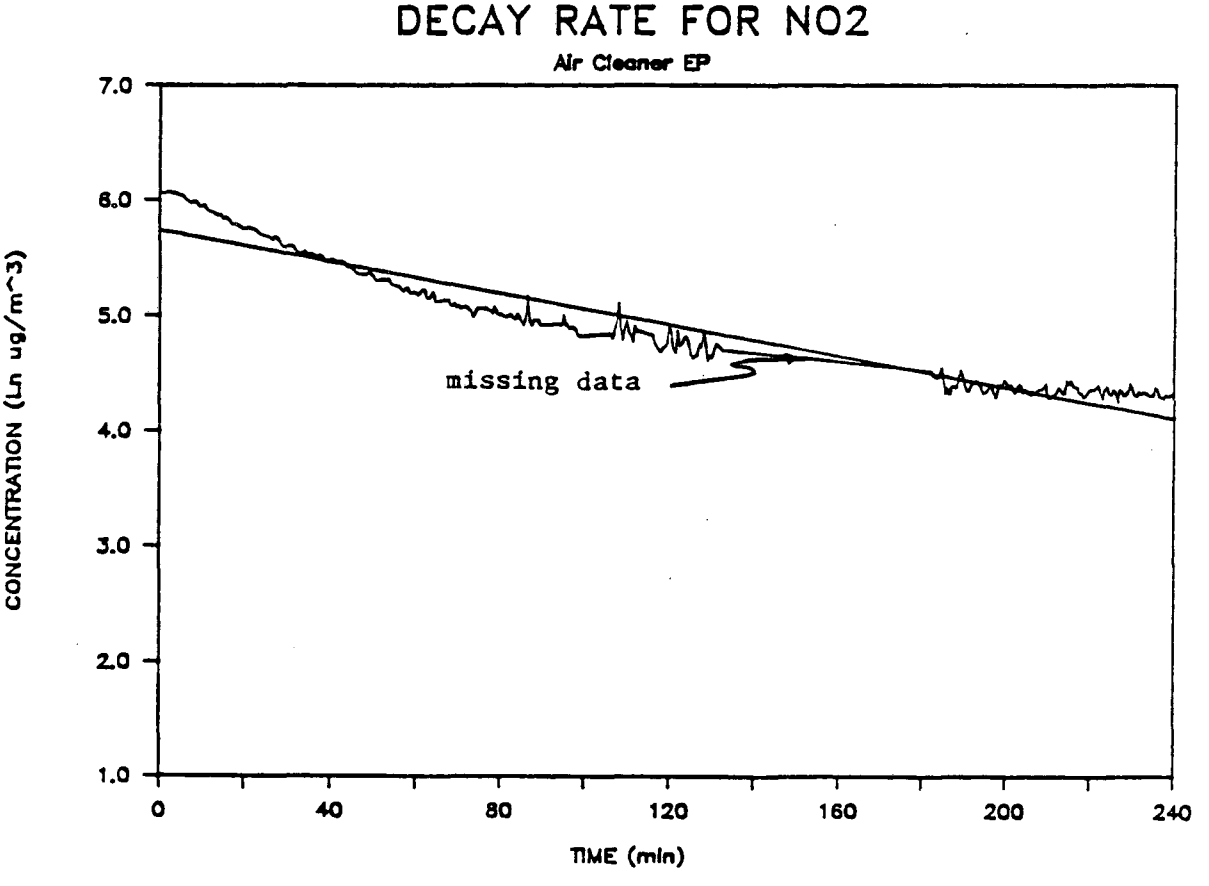

DECAY RATE FOR NO2
Background, Exp 2
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
100
200
300
400
TIME (min)

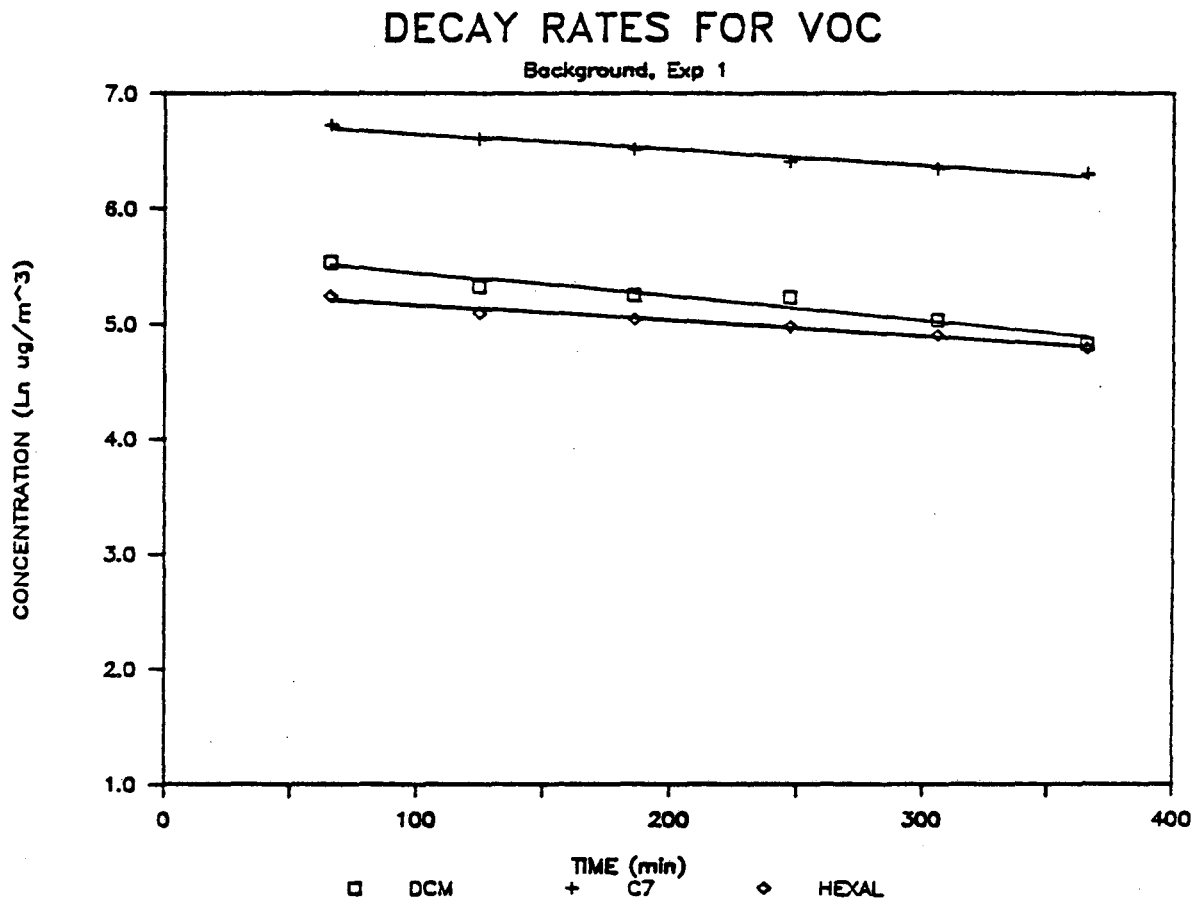

DECAY RATE FOR NO2
Air Cleaner PF1
7.0
6.0
5.0
4.0
3.0
2.0
1.0
CONCENTRATION (Ln ug/m^3)
missing data
missing data
0
40
80
120
160
200
240
TIME (min)

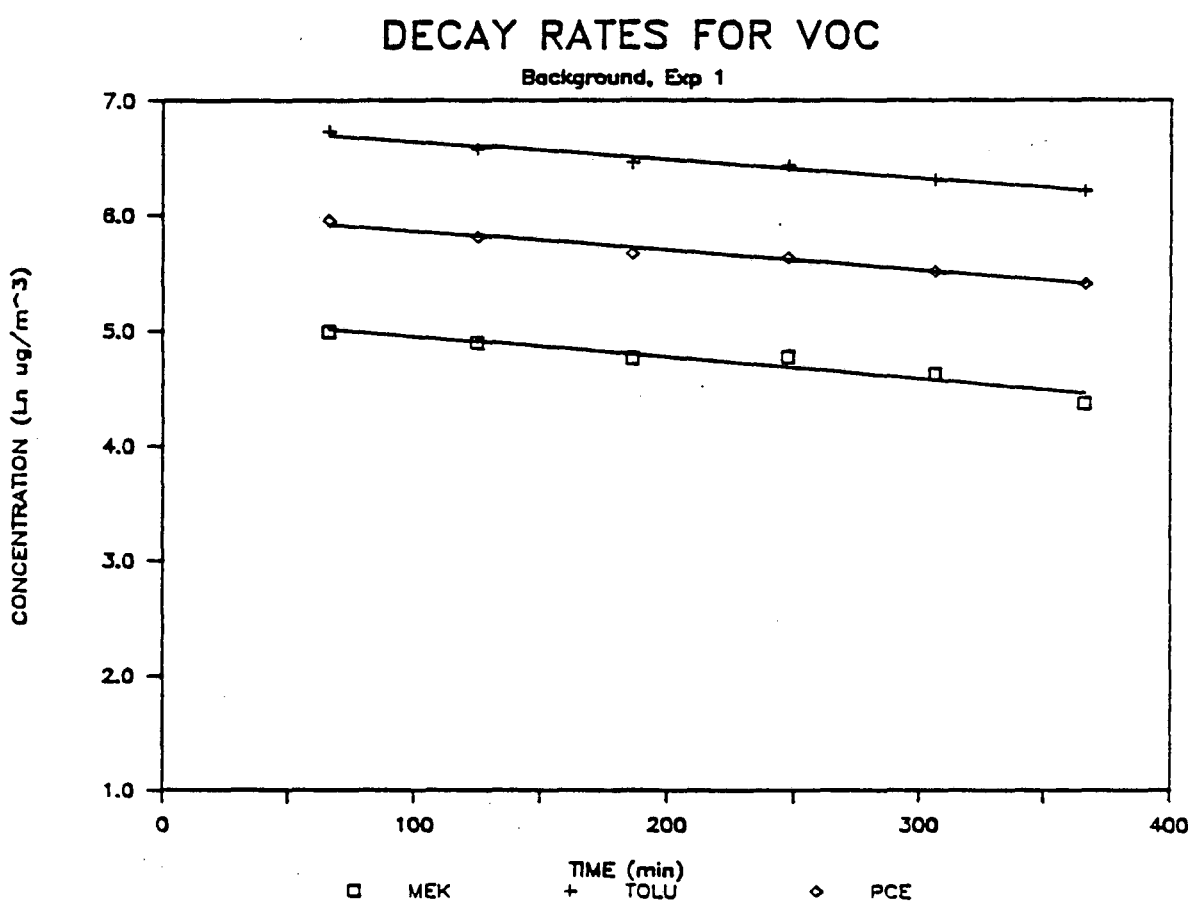

DECAY RATE FOR NO2
Air Cleaner PF2, Exp 1
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
40
80
120
160
200
240
TIME (min)

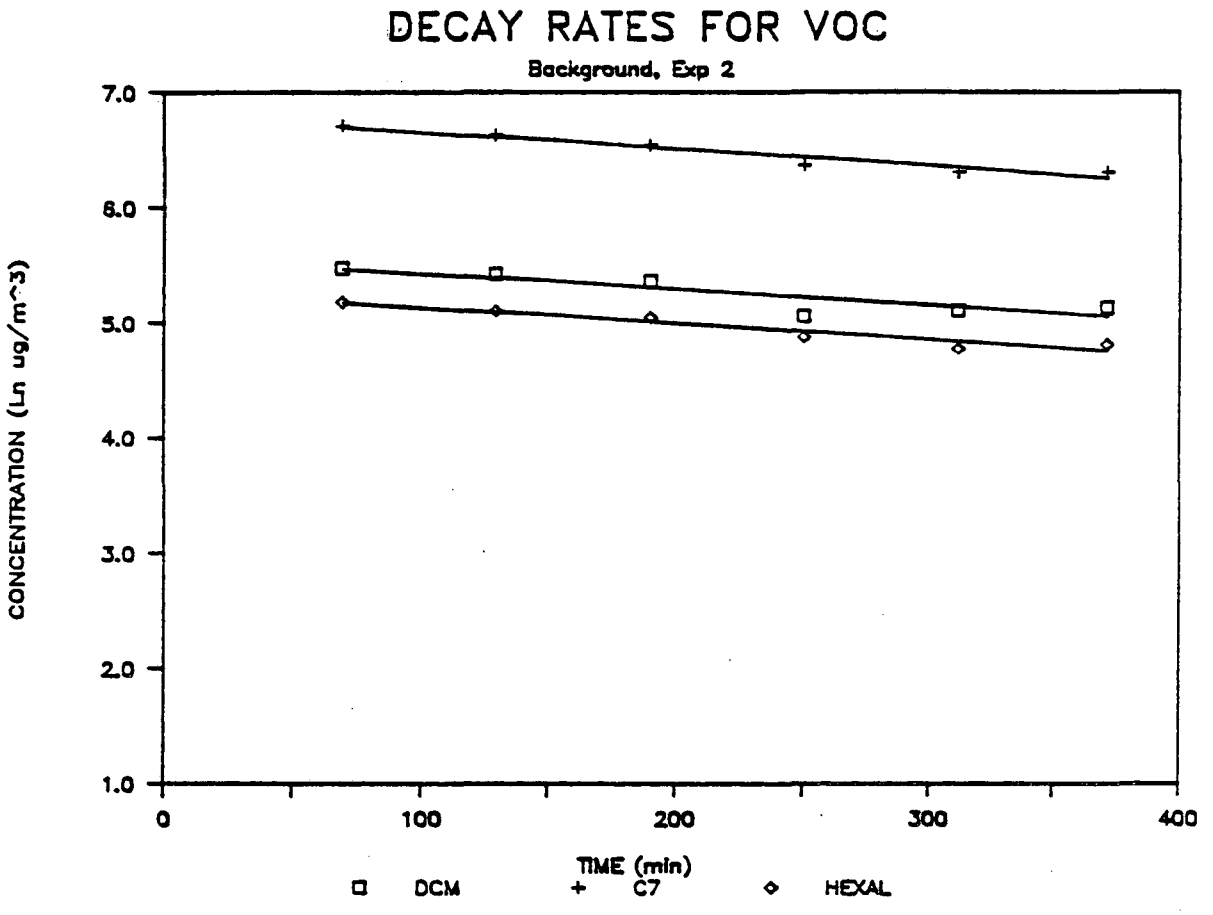

DECAY RATE FOR NO2
Air Cleaner PF2, Exp 2
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
40
80
120
160
200
240
TIME (min)

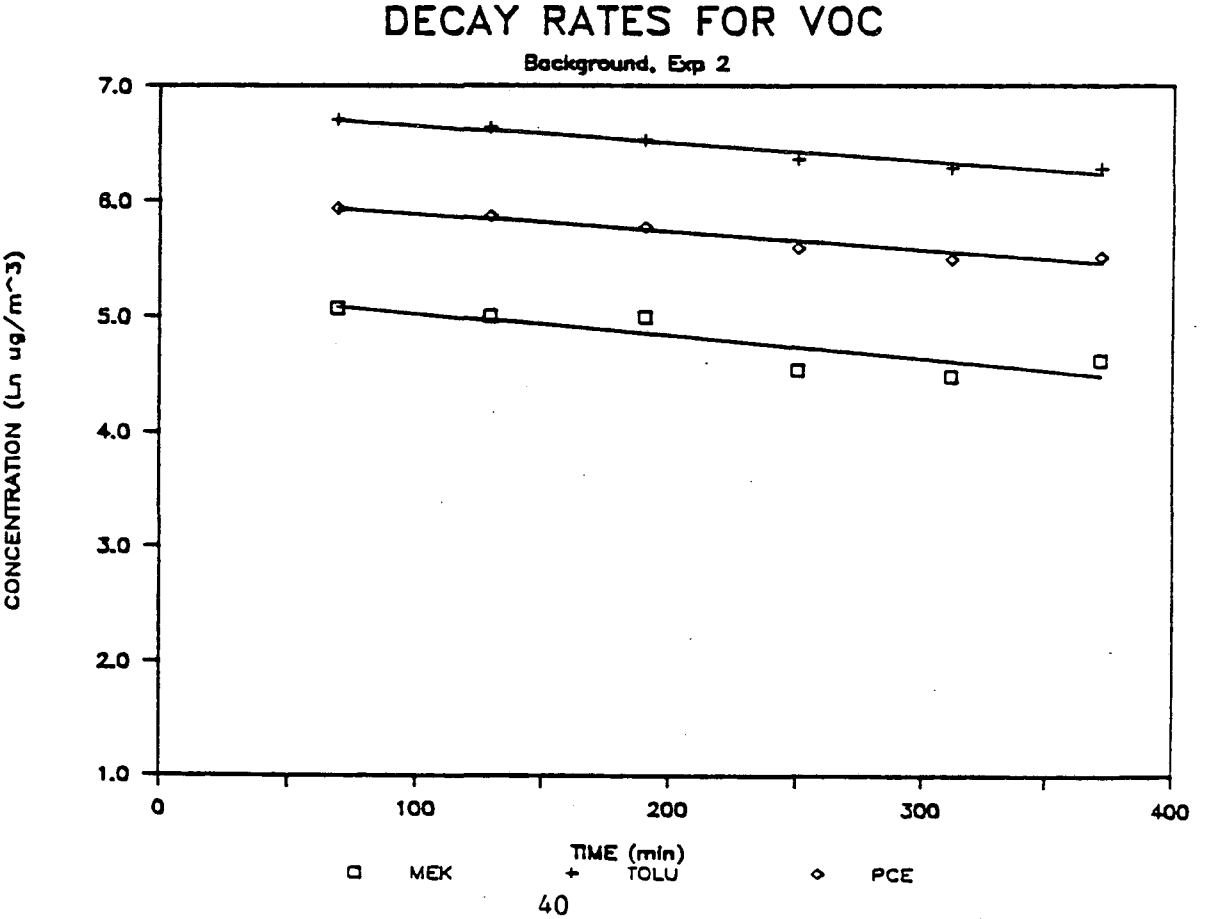

DECAY RATE FOR NO2
Air Cleaner ES
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
40
80
120
160
200
240
TIME (min)

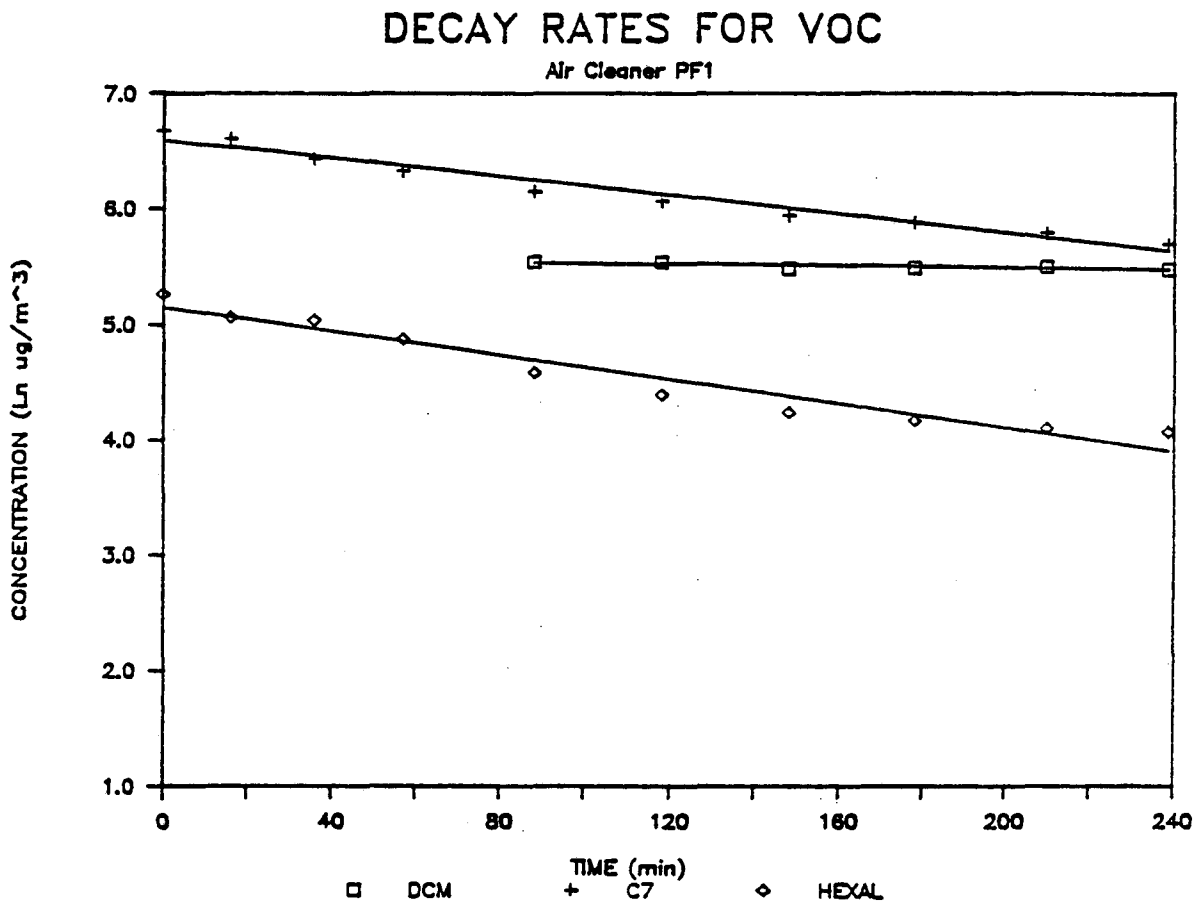

DECAY RATE FOR NO2
Air Cleaner EP
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
missing data
0
40
80
120
160
200
240
TIME (min)

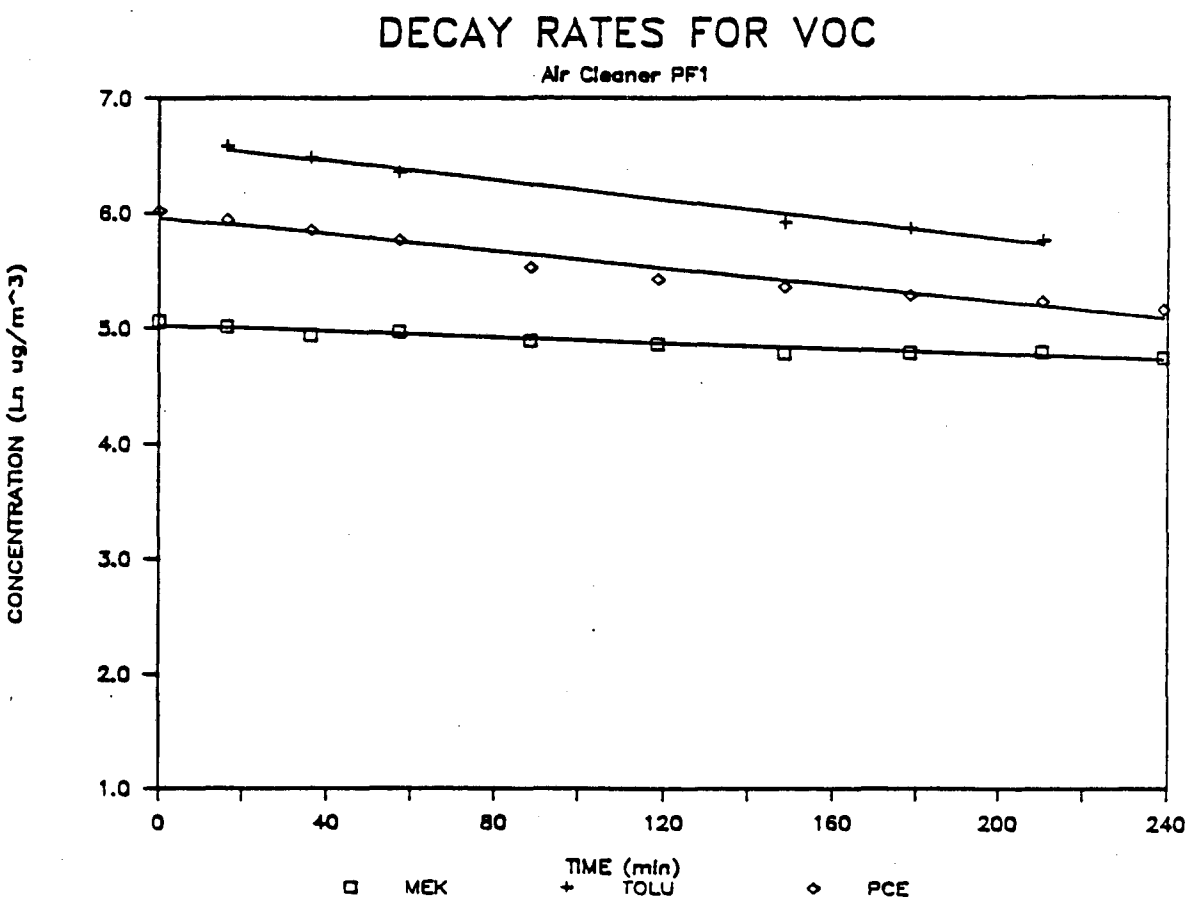

DECAY RATES FOR VOC
Background, Exp 1
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
100
200
300
400
TIME (min)
DCM
C7
HEXAL

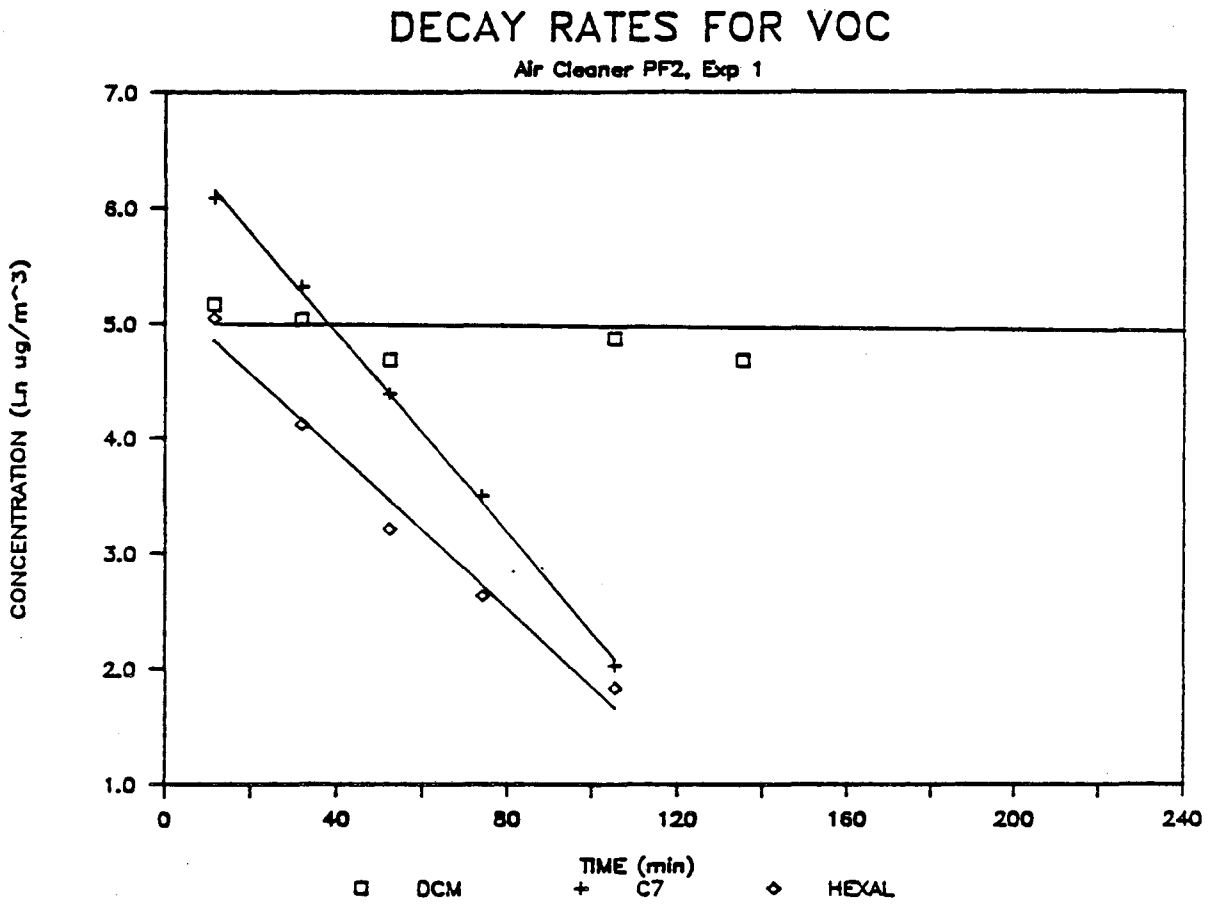

DECAY RATES FOR VOC
Background, Exp 1
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
100
200
300
400
TIME (min)
MEK
TOLU
PCE

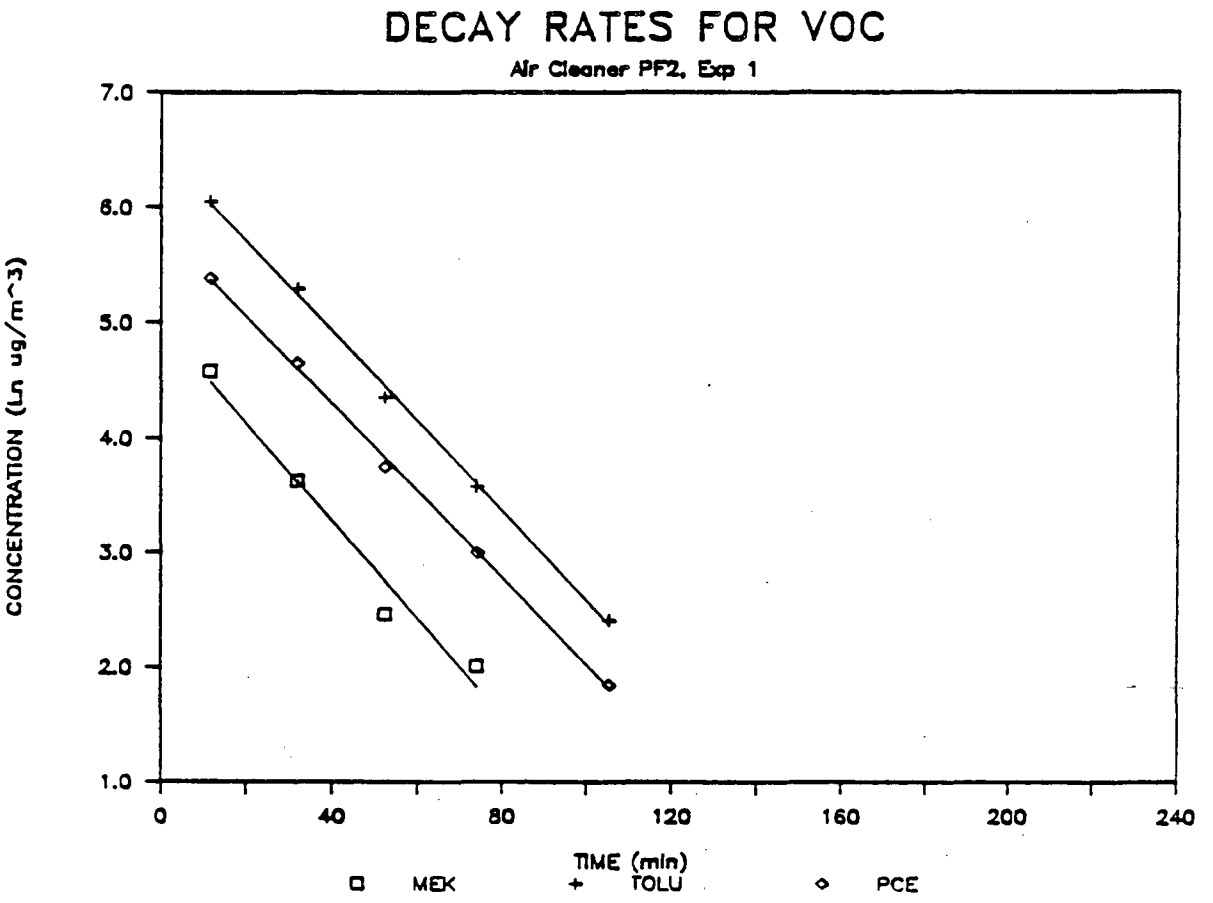

DECAY RATES FOR VOC
Background, Exp 2
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
100
200
300
400
TIME (min)
DCM
C7
HEXAL

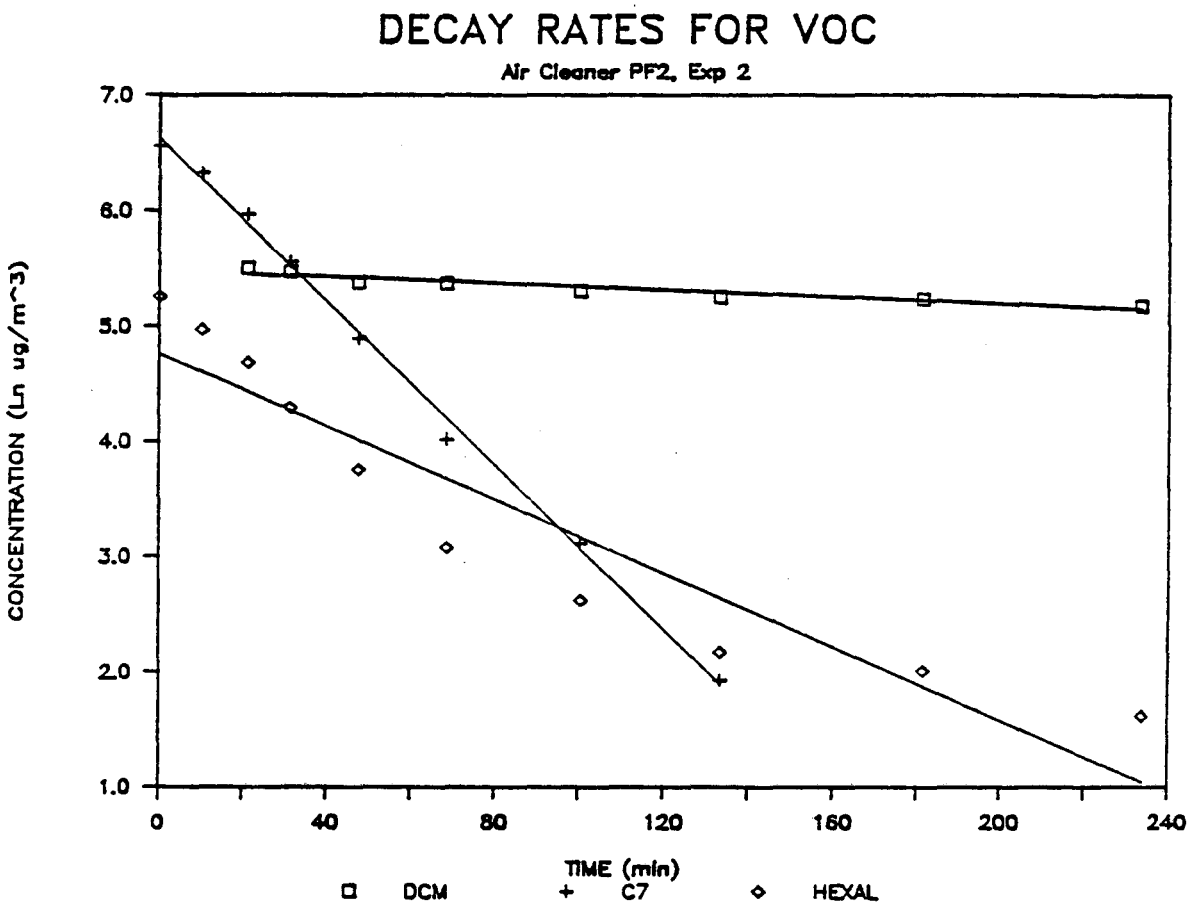

DECAY RATES FOR VOC
Background, Exp 2
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
100
200
300
400
TIME (min)
MEK
TOLU
PCE

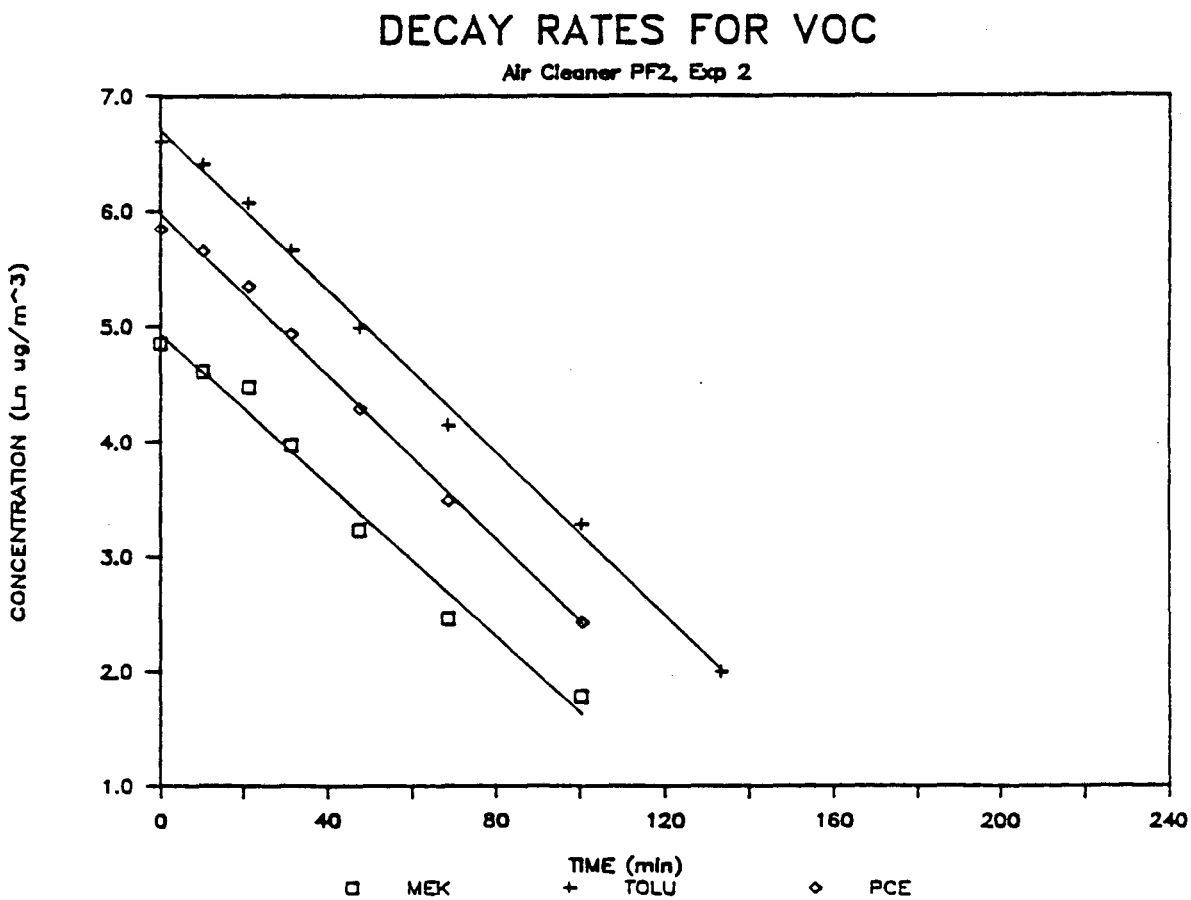

DECAY RATES FOR VOC
Air Cleaner PF1
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
40
80
120
160
200
240
TIME (min)
DCM
C7
HEXAL

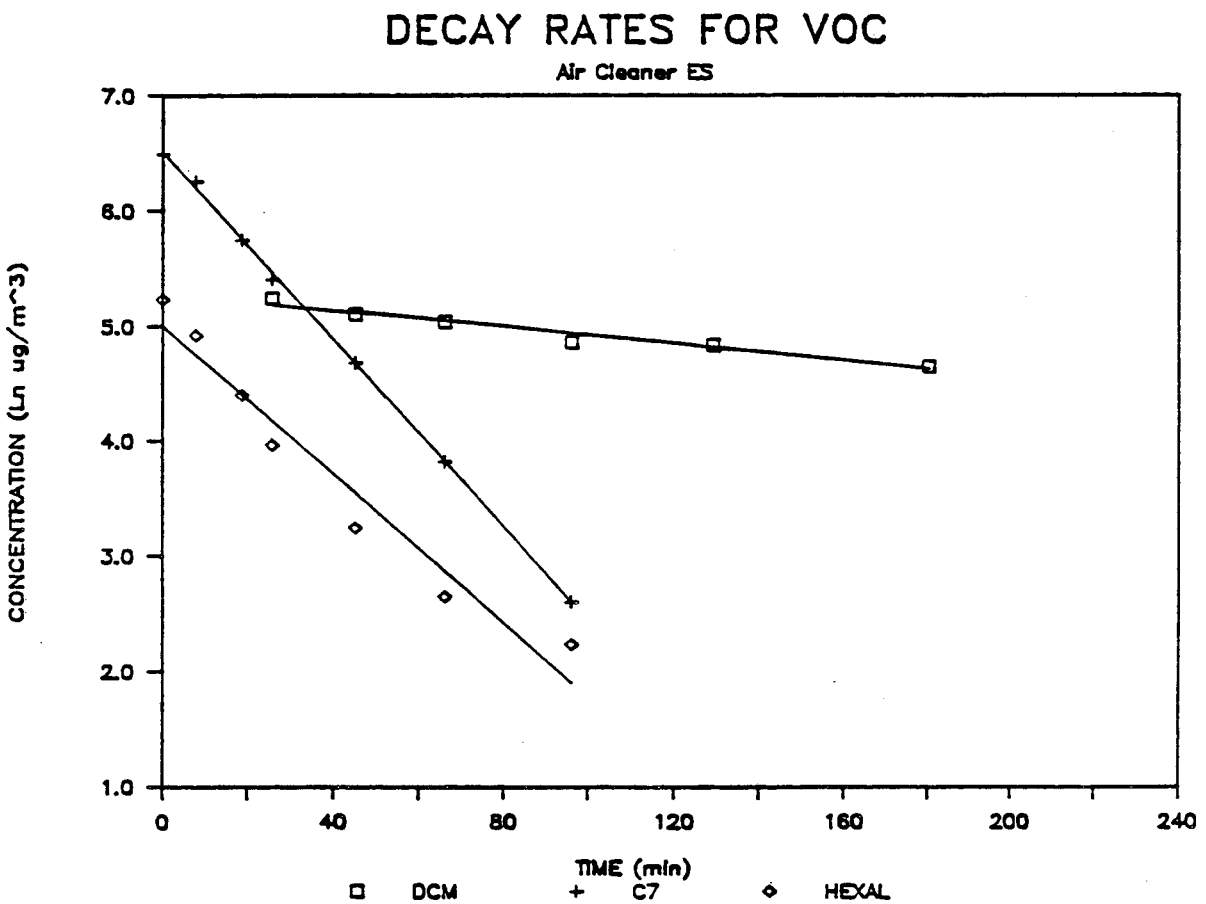

DECAY RATES FOR VOC
Air Cleaner PF1
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
40
80
120
160
200
240
TIME (min)
MEK
TOLU
PCE

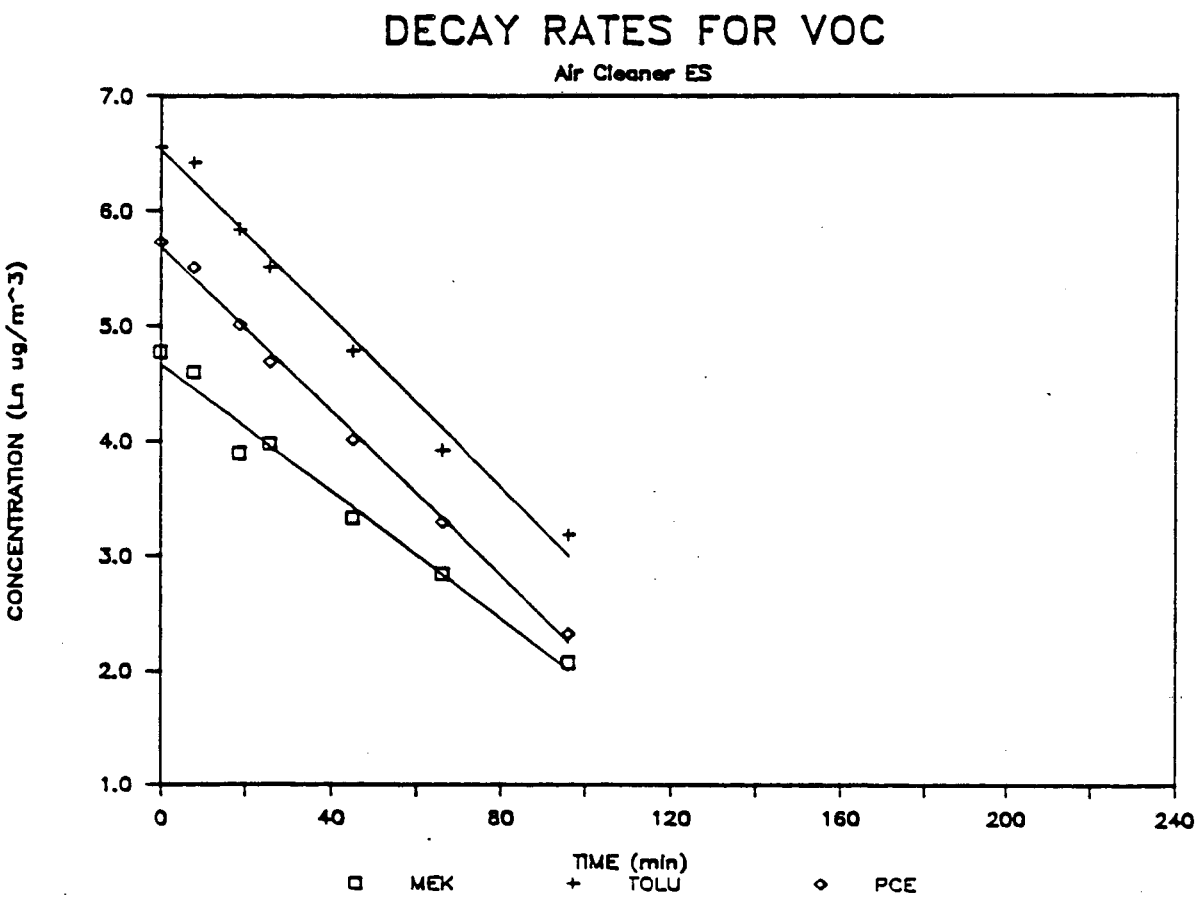

DECAY RATES FOR VOC
Air Cleaner PF2, Exp 1
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
40
80
120
160
200
240
TIME (min)
DCM
C7
HEXAL


DECAY RATES FOR VOC
Air Cleaner PF2, Exp 1
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
40
80
120
160
200
240
TIME (min)
MEK
TOLU
PCE


DECAY RATES FOR VOC
Air Cleaner PF2, Exp 2
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
40
80
120
160
200
240
TIME (min)
DCM
C7
HEXAL


DECAY RATES FOR VOC
Air Cleaner PF2, Exp 2
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
40
80
120
160
200
240
TIME (min)
MEK
TOLU
PCE


DECAY RATES FOR VOC
Air Cleaner ES
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
40
80
120
160
200
240
TIME (min)
DCM
C7
HEXAL


DECAY RATES FOR VOC
Air Cleaner ES
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
40
80
120
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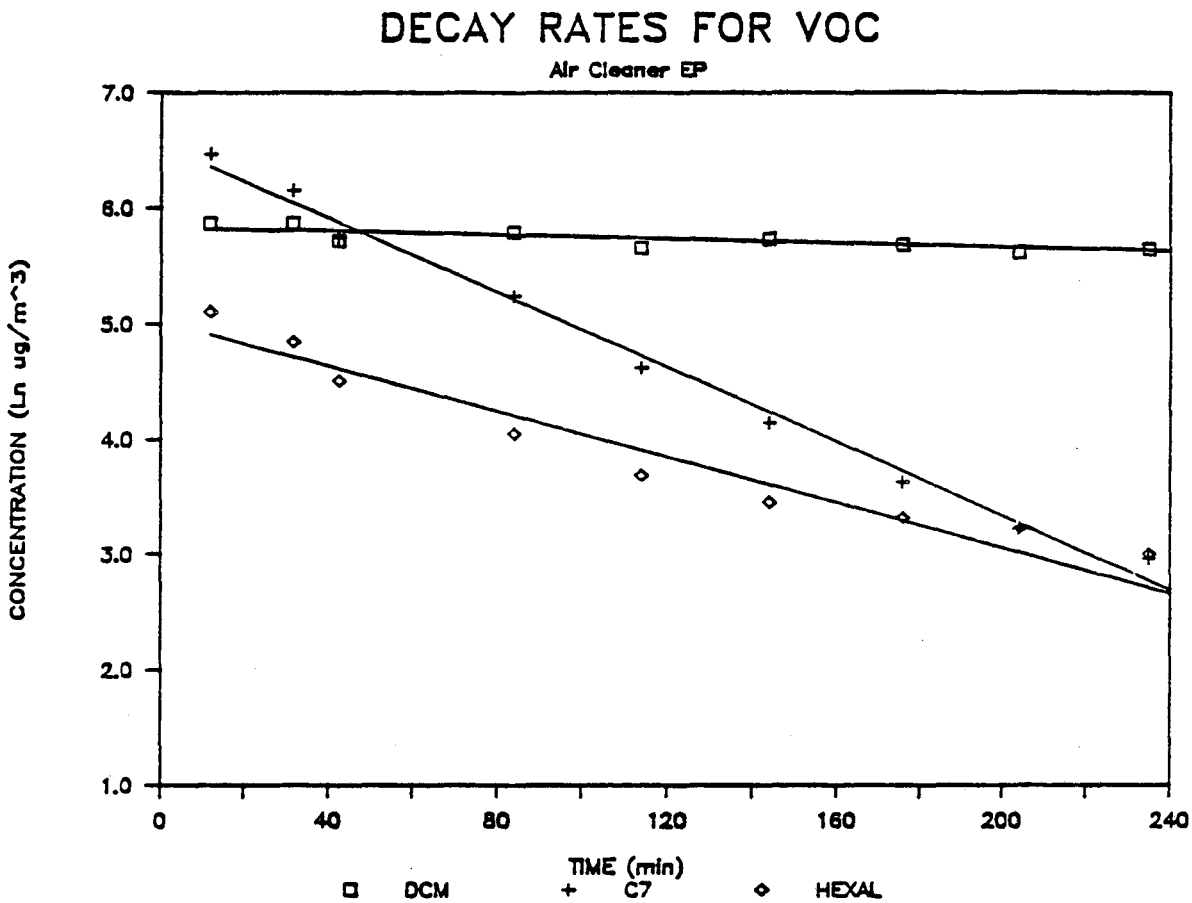
200
240
TIME (min)
MEK
TOLU
PCE


DECAY RATES FOR VOC
Air Cleaner EP
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
40
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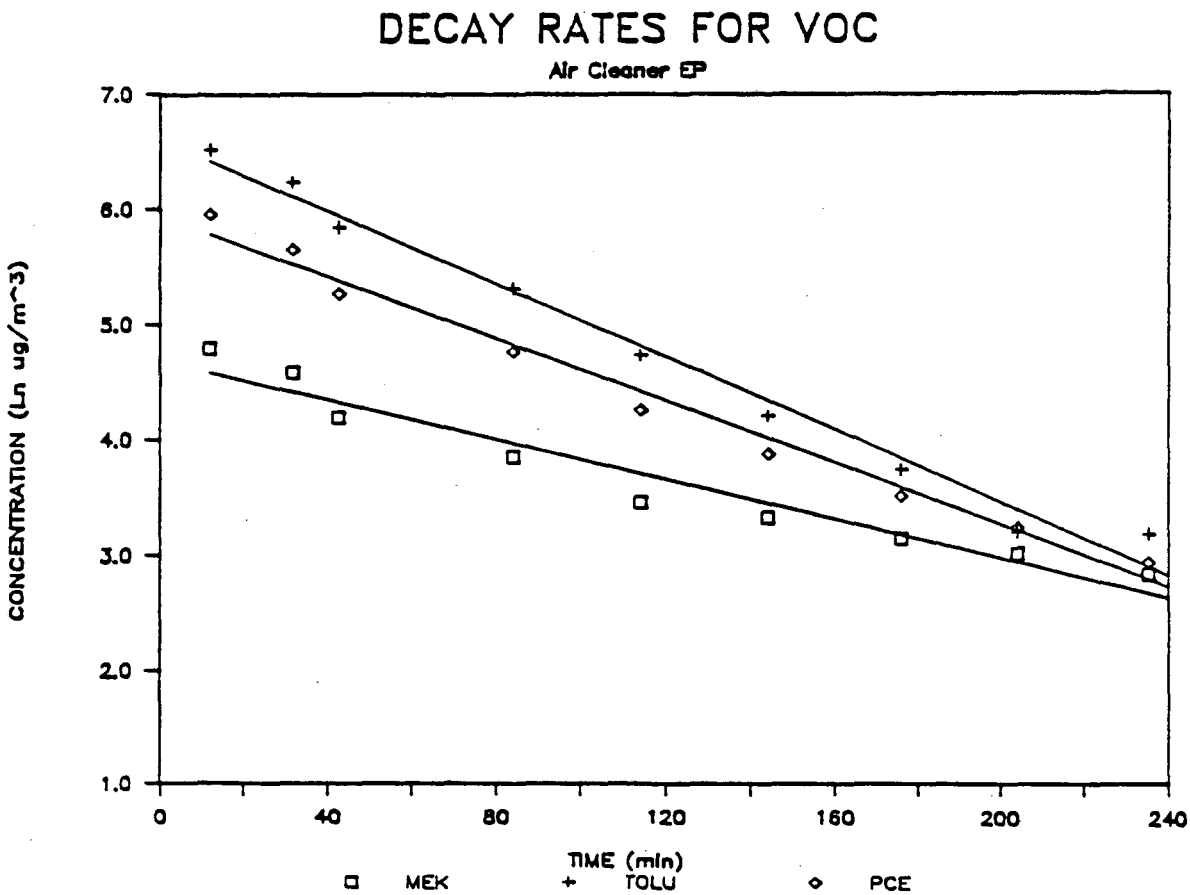
120
160
200
240
TIME (min)
DCM
C7
HEXAL


DECAY RATES FOR VOC
Air Cleaner EP
CONCENTRATION (Ln ug/m^3)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
40
80
120
160
200
240
TIME (min)
MEK
TOLU
PCE

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