DEGRADATION OF CONTAMINATED AIR STREAMS CONTAINING TOLUENE, ETHYLBENZENE AND O-XYLENE BY BIOFILTRATION

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TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

NOMENCLATURE

ANOVA	analysis of variance
APC	air pollution control
APHA	American Public Health Association
AVG	average
BTEX	benzene, toluene, ethylbenzene and xylenes
BTX	benzene, toluene and xylenes
C	carbon
CAA	Clean Air Act
CFM	cubic feet per minute
COM	compost
DCA	1,2-dichloroethane
DE	diatomaceous earth
EBCT	empty bed contact time
EPA	United States Environmental Protection Agency
GAC	granular activated carbon
GC	gas chromatograph
GS	glass spheres
HC	hydrocarbon
MEK	methyl ethyl ketone

MIBK	methyl isobutyl ketone
min	minute
OSHA	Occupational Safety and Health Administration (U.S. Department of Labor)
OSL	observed significance level
OUST	Office of Underground Storage Tanks
ppm	parts per million
SAS	statistical analysis system
SD	standard deviation
SEM	scanning electron microscope
SPCs	standard population counts
SVE	soil vapor extraction
TCA	trichloroethane
TCE	trichloroethylene
TPH	total petroleum hydrocarbon
TOC	total organic carbon
USTs	underground storage tanks
VOCs	volatile organic compounds
VS	volatile solids
WBS	work breakdown structure

CHAPTER I

INTRODUCTION

Statement of the Problem

Groundwater is a valuable, limited resource that serves as a major source of water for domestic, industrial and agricultural uses. A major concern exists over the contamination of groundwater by synthetic organic compounds. The Central Plains, including Oklahoma and Kansas, are dotted with several mid-continent refineries and crisscrossed with many pipelines. Benzene, toluene, ethylbenzene and xylene (BTEX) are considered the main contaminant compounds in groundwaters and soils due to the leakage of gasoline from underground storage tanks (USTs), ruptured refined product pipelines, and spills at refineries and pipeline terminals. It was reported that there are approximately 1.4 million USTs containing gasoline in the United States, and some petroleum experts estimate that 75,000 to 100,000 of these tanks are leaking (Feliciano, 1984). According to recent information (OUST, 1990), there have been 90,000 confirmed releases reported in the last two years among about two million USTs. Gasoline and other fuels contain BTEX, which are hazardous compounds regulated by the U.S. Environmental Protection Agency (EPA, 1977). Although these aromatic hydrocarbons are relatively water-soluble, they are contained in the immiscible bulk fuel phase, which serves as a slow-release mechanism for sustained groundwater contamination (Hutchins et al., 1991).

During the cleanup of groundwaters and soils contaminated with volatile organic compounds (VOCs), air stripping or soil venting is frequently used. With both techniques, a contaminated waste gas stream is generated. In many instances this gas stream is allowed to escape untreated into the ambient air.

There are several treatment technologies which are currently used in the control of VOCs in air streams. These technologies include thermal or catalytic incineration, carbon adsorption, chlorine or ozone oxidation, and biofiltration. Compared to other widely used approaches, biofiltration can offer a cost-effective way to destroy many contaminants (Rozich, 1995). It is a clean pollution control technology, which reduces organic emissions (and some inorganics) to water, carbon dioxide and salts, rather than transferring them to another medium (Vembu and Walker, 1995). In Germany, the Netherlands and other European countries, biofiltration has been applied to air pollution control problems for more than 30 years, and more than 500 biofiltration units currently are operating with a range of applications from controlling odors at wastewater treatment plants to reducing VOCs from emissions at coating facilities (Vembu and Walker, 1995). It is still an emerging technology in the US (Griffin and Paff, 1995). Recent installations in the United States include a large system for treating ethanol at a foundry in southern California. Several major companies, including DuPont, Monsanto and American Cyanamid, are examining the technology's potential (Vembu and Walker, 1995). Apparently, biofiltration is attracting interest in the United States.

With the reauthorization of the Clean Air Act (CAA) in 1990, a new focus has been placed on limiting the discharge of toxics into the air especially from treatment processes. Obviously it is necessary to find a reasonable, practical and economical method for the treatment of contaminated air streams.

Objectives of the Project

This project was undertaken to investigate the potential of using biological filters as air pollution cleanup technology. The objectives of this study are as follows:

1) to demonstrate the feasibility of eliminating a selected mixture of BTEX compounds by biofiltration;
2) to provide the data of elimination efficiencies from biofilters for the selected mixture of BTEX compounds;
3) to compare elimination rates of the selected mixture of BTEX compounds obtained from biofilters containing two different support media;
4) to present some design criteria which can be used in a full-scale biofilter;
5) to develop a model for predicting the elimination of the selected mixture of BTEX compounds by biofiltration; and
6) to estimate the cost of eliminating the selected mixture of BTEX compounds by biofiltration.

CHAPTER II

LITERATURE REVIEW

Background of Biofiltration

Biofiltration is an air pollution control (APC) technology. As early as 1923, Bach discussed the basic concept for the control of H_2S emissions from sewage treatment plants. Reports on the application of this concept dating back to the 1950s were published in the U.S. and in West Germany. Pomeroy received U.S. Patent No. 2,793,096 in 1957 for a soil bed concept and described a successful soil bed installation in California. In the U.S., the first systematic research on biofiltration removal of H_2S was conducted by Carlson and Leiser in the early 1960s (Leson and Winer, 1991).

During the 1960s and 1970s, biofilters were successfully used in the control of odors. Since the early 1980s, a renewed interest in biofiltration as a technology to control VOCs and other air toxics emitted from industrial facilities has occurred (Leson and Winer, 1991).

The principle of biofiltration is that when a contaminated air stream containing biodegradable volatile organic compounds (VOCs) or inorganic air toxics is vented through a biologically active material. The contaminants are adsorbed to the filter medium and then biologically destroyed. The by-products in this process, if taken to completion, are carbon dioxide, water and new cells.

Since it can offer significant economic advantages over other technologies and is most effective when applied to dilute, easily biodegradable waste streams, biofiltration has been considered one of the most promising APC technologies (Ramaratnam, et al., 1993). Environmental benefits associated with this technology include low energy requirements and the avoidance of cross media transfer of pollutants (Leson and Winer, 1991).

Applications in the Control of VOCs Using Biofiltration

The following classification of gases, according to their degradability, was presented by Bahn (1992): (1) rapidly degradable VOCs, i.e. alcohols, aldehydes, ketones, etc.; (2) slowly degradable VOCs, i.e. aliphatic and aromatic hydrocarbons (xylene, toluene, benzene, and styrene), phenols and methylene chloride; and (3) very slowly degradable VOCs: i.e. halogenated hydrocarbons (trichloroethylene, trichloroethane, carbon tetrachloride, and pentachlorophenol), polyaromatic hydrocarbons, etc. In most APC situations, compounds in categories (2) and (3) are of more concern than those in category (1).

Kampbell and Wilson (1987) evaluated the removal of volatile aliphatic hydrocarbons (propane, isobutane and n-butane) from a waste air stream using a bench-scale unit and a prototype field-scale soil bioreactor. Laboratory investigations indicated first-order kinetics for the removal of total hydrocarbon vapors were followed as well as displaying the potential to degrade light aliphatic hydrocarbons and trichloroethylene, a compound ordinarily resistant to aerobic biological treatment. The predicted behavior (in terms of hydrocarbon removal) of the bioreactor, based on laboratory studies, agreed closely with the actual behavior of the field system. When the injected air contained about 2000 ppm (v/v) total hydrocarbons, and the intended flow rate was 3.0 cm^3 air per cm^2 of surface area per min, the prototype bioreactor reduced the hydrocarbon concentration in the air by at least 90 percent at a residence time of 15 minutes and a pressure drop of 85 cm of water. The bioreactor functioned well through a range of temperatures, 12 to 24 °C.

Wilson et al. (1988) performed a laboratory study using fixed-film bioreactors to biologically remediate contaminated air streams. In their work, the authors introduced vapors of trichloroethylene (TCE) and 1,1,1-trichloroethane (TCA) into bioreactors containing diatomaceous earth on which a biofilm had developed. The headspace of the columns was plumbed to receive vapors of TCE and TCA, a mixture of butane and air, and a nutrient media solution. Because TCE and TCA can be degraded by a monooxygenase enzyme which is produced by butane-oxidizing organisms, butane (8 mg butane/L air) was also introduced into the biological reactors to serve as the primary substrate. Influent TCE concentration ranged from 90 μg/L to 770 μg/L while the TCA concentration ranged from 200 μg/L to 990 μg/L. The maximum removal efficiency observed in this work was 94% for TCE and 93% for TCA. The authors did note a drop in removal efficiency for both compounds as their influent concentration increased.

Galaska et al. (1989) designed an upflow bio-airtower to degrade contaminated air originating from a gasoline service station soil venting project. High surface area inert plastic media was used to support the biofilm growth. Water containing inorganic nutrients was recirculated over the packing material in order to keep the biofilm moist and provide a working medium for biological degradation. The unit was tested at flow rates of approximately 10.4 and 17.1 cubic feet per minute (CFM). The percent removal for specific compounds such as benzene, toluene, xylene (BTX) and total petroleum hydrocarbons approximately doubled when the air flow rate through the bio-airtower was lowered. The authors concluded that the water recirculation rate and the influent concentration appeared to have very little effect on either the individual BTX or total petroleum hydrocarbons percent removal. The most important variable affecting petroleum hydrocarbon removal in this system appeared to be air flow rate. Specifically, BTX removal increased from approximately 45.2% to 74.5%, and total petroleum hydrocarbon removal increased from approximately 30.6% up to 60.8% after the flow rate was lowered from 17.1 to 10.4 CFM. The contact time between the airborne contaminants and the biomass was very limited in this type of system. Therefore, it is unreasonable to assume that a minimal air residence time would provide optimal effective treatment.

Bioreactors similar to those used by Wilson et al. (1988) were utilized in the work of Speitel and Malay (1990). However, these authors fed their system, which was packed with diatomaceous earth, a methane mixture instead of butane as the primary substrate. Nutrients and influent gas flowed co-currently in the columns. The primary objective of their work was to investigate the effect of influent contaminant concentration in the gas stream and gas flow rate on the degradation of TCE and 1,2-dichloroethane (DCA). The influent concentration of TCE ranged from 273 to 569 μg/L at an average gas flow rate of 28.9 mL/min, providing a residence time of 9.6 mins, while the surface loading rates varied only slightly from 0.160-0.335 gm TCE/m^2·hr. In the two experiments conducted using TCE, the average removals were 28 and 57%. The authors also noted reduced TCE removal at influent gas concentrations greater than 500 μg/L and speculated that elevated concentrations may have been toxic to the organisms. However, they stated that more work is needed to prove this point. The two experiments, conducted with DCA, showed an average removal of 20.4% when the average surface loading rate was 0.76 gm DCA/m^2·hr, and the influent concentration varied from 600 to 1000 µg/L at an average gas flow rate of 47.4 mL/min, which provided a residence time of 5.7 mins . However, 81% removal was obtained at an average surface loading rate of 0.45 gm DCA/m^2·hr with influent concentrations ranging from 870-1100 µg/L at an average gas flow rate of 22.7 mL/min, resulting in a residence time of 12.2 mins. Overall, the authors concluded that biofiltration is a viable process for treating gas streams containing chlorinated solvents at low concentration levels.

Douglass et al. (1991) studied the applicability of biofiltration for the treatment of contaminated streams typically created in air stripper off gas. The five packing media used in their study were native sand with chemical nutrient amendments, saw dust with chemical nutrient amendments, peat buffered with calcium carbonate to control pH, a mixture of 20% manure and 80% saw dust, and a mixture of 20% aerobically digested waste water sludge and 80% vermiculite (or saw dust). In this study, the influent concentrations of total gasoline, toluene and benzene were 61.4, 3.6 and 2.8 µg/L, respectively. Through their investigation, the authors reported that the maximum degradation rates for benzene and toluene were about 53 to 78 mg/m^3·min while for o-xylene the values ranged from 18 to 28 mg/m^3·min. Because the biological rate of degradation appeared to be the limiting factor for treatment efficiency, the chemical composition of the contaminants could be very important since rates of biodegradation varied by substrate. For the design and application of a mobile treatment system, the peat buffered with calcium carbonate medium was selected since it is the lightest, least expensive and among the best biological support media.

Hodge et al. (1991a) investigated the aerobic biodegradation of gas-phase jet fuel and diesel by microorganisms supported on four different filter media. The filter media used in this work were the following: activated carbon (GAC), diatomaceous earth (DE), a soil mixture, and a mixture of activated carbon and diatomaceous earth (50% each by volume). For the GAC and DE columns, a microbial seed culture and nutrients were completely mixed throughout the media. Individual components of the jet fuel and diesel were not determined and all the degradation rate data were reported in terms of total hydrocarbon as methane equivalents. The authors determined that the biodegradation rates ranged from 0.3-5.2 gm HC/m^3·hr (for jet fuel) and 0.2-1.3 gm HC/m^3·hr (for diesel) on the four different support matrices. The jet fuel was degraded faster than the diesel in all cases. The diatomaceous earth supported the lowest biodegradation rates, and the mixture of GAC and DE had the highest biodegradation rates. They also noted the importance of relative humidity for operational efficiency of the biofilter. The optimum water content levels were different for each filter medium. Overall, they concluded that this technology appears to be a viable method for treating hydrocarbon vapors.

Medina et al. (1992) conducted a bench-scale experiment where granular activated carbon (GAC) was used as the microorganism support medium in a biofilter to treat soil vapor extraction off-gases. In this study, gasoline vapors were introduced into the column in a downflow mode. Nutrients and microbial seed materials were vigorously mixed with the GAC medium. This material was used to fill the column. Excess solution was drained and returned to the top of the column. The excess was again drained and discarded.

Following the seeding process, no further attempt was made to add nutrients or organisms. Initial adsorption provided a high percentage of removal (>85%). However, after the adsorption capacity was saturated, the treatment efficiency dropped dramatically (down to 7-20%). Later, biological activity increased to the point where effective treatment was possible (85-95% of removal efficiency). The main obstacle to effective treatment was the slow growth of the biomass in the lower portions of the column. The average and maximum elimination capacities of the biofilter were 64 and 119 gm HC/m^3·hr, respectively. The residence time ranged from 5.9-7.0 mins, averaging 6.4 mins. Elimination rates, which ranged from 4 to 119 g HC/m^3·hr, were proportional to pollutant loadings, which varied from 0.005 to 0.238 g HC/hr. Plate counts showed that both bacterial and fungal numbers increased over time as the column operated.

Vaughn et al. (1993) carried out research on the biodegradation of vapor phase p-xylene. Two bioreactors were packed with different media, and operated in a countercurrent mode. One contained glass spheres and the other had diatomaceous earth (DE) pellets. The process parameters tested were gas and liquid flow rates and influent xylene concentration. A sterile liquid medium, which served as a nutrient source, was distributed into the columns at a rate of 5-10 mL/min. The concentration of xylene, introduced to the two columns, was 150-1500 ppm (v/v) at a gas flow rate of 600-6000 mL/min. Their results indicated that total mass degradation rates were significantly higher in the DE column (1.4-1.8 mg/min) than in the glass sphere column (0.3-0.6 mg/min). Protein levels per unit surface area were significantly higher in the DE column.

Apel et al. (1993) demonstrated the utility of a fixed-film biofilter for removal of methane, TCE, and xylene. Comparisons between the gas-phase bioreactors, conventional shaken cultures and sparged liquid bioreactors showed that the gas-phase bioreactors offer advantages over the other two systems for the degradation of methane in air. Rates of methane removal with the gas-phase bioreactors were 2.1 and 1.6 fold greater than those exhibited by the shaken cultures and sparged liquid bioreactors, respectively. The gas phase bioreactors were shown to have application for the removal of TCE vapors from air with a removal rate of approximately 2.6 mg TCE/m^3·day. Xylene vapors were also eliminated from air using gas phase bioreactors. When the gas feed stream rate was 16 mL/min with a xylene feed in the gas stream of 140 μg of xylene per minute (based on carbon), approximately 46% of the xylene was mineralized to carbon dioxide in a single pass through a bench-scale gas-phase bioreactor.

Rho et al. (1993) worked on a demonstration project to study the feasibility of biofiltration for the treatment of organic solvents (ethanol, methanol, n-propanol, 2-butanone, propyl acetate and propanol). Some microbial strains identified as being responsible for the degradation of the above VOCs were Pseudomonas sp., Bacillus sp., and Klebsiella sp.. In this study, peat was used as a packing material, and nutrients (nitrogen source only) were recirculated through the filter with a microbial suspension on a weekly basis in a countercurrent mode. The results showed that over a 7-month period, when an air flow rate was 475-675 m^3/h in an upflow direction through the biofilter, and the average inlet concentration was 1000 mg C/m^3 gas, the organic load was 100 g C/m^3 bed/h and the residence time was 18 seconds, the maximum elimination capacity was 72 g C/m^3 bed/h.

Cox et al. (1993) set up experiments to enrich styrene-degrading fungi in biofilters under conditions representative of industrial off-gas treatment. Through each biofilter 43

L/hr of a styrene/air mixture with a relative humidity of 80-85% at an initial styrene concentration of 290 mg/m^3 was passed. From the support materials tested, polyurethane and perlite proved to be most suitable for enrichment of styrene-degrading fungi. The biofilter with perlite completely degraded styrene when amounts ranging between 290 and 675 mg/m^3 in the influent gas were present. An elimination capacity of at least 70 g styrene per m^3 perlite per hour was calculated.

Gregg et al. (1993) used a bench-top bioscrubber testing unit to treat vapor phase toluene. In their work, activated carbon served as packing material. The inlet concentration of toluene was 10-20 ppm with an air flow rate of 0.5-2.0 L/min in a co-current mode. Inorganic nutrients, required for biological growth, were fed downflow to the column at a 0.1 mL/hr rate. The authors reported that the bioscrubber achieved effective removal (>95%) of low levels of toluene vapor. Column lengths ranging from 5 to 10 inches were required to confine the wavefront within the filter yielding empty bed contact times ranging from 1 to 4 seconds.

Zilli et al. (1993) evaluated biofiltration technology for removal of phenol from waste gases. The packing material, with a height of 30 cm, consisted of a mixture of peat and glass beads in a ratio of 2: 1 v/v and was supported by a sieve plate to allow a homogeneous distribution of the gas flow through the filter bed. With more than one year of continuous operation of a lab-scale unit at a gas flow rate of 40 L/min, resulting in a residence time of 54 seconds, and varying inlet phenol concentration from 50 up to 2000 mg/m^3, a phenol removal efficiency of 93.0-99.6% was achieved.

Ergas et al. (1994) performed a study on the efficiency of a compost biofiltration system degrading dichloromethane. The column consisted of four sections with an inner diameter of 15 cm and an overall height of 152 cm. Biofilters were found to be effective in degrading low concentrations of dichloromethene in the laboratory studies. Greater than 98% removal efficiency was obtained at inlet gas concentrations of 3 and 50 ppmv and superficial velocities of 1 and 1.5 $m^3/m^2 \cdot min$ corresponding to reactor residence times of 1 and 0.7 min, respectively. As a result of acidification of the column to a pH of 4.86-6.66, a decline of removal efficiency from 95% to 51% was observed in the first two sections of the column closest to the inlet when a 50 ppmv inlet concentration was used. However, the overall dichloromethane removal across the bed was still maintained at greater than 98%. A biofilm model incorporating first order biodegradation kinetics provided a good fit to observed concentration profiles, and may prove to be a useful tool for designing biofiltration systems for low inlet concentrations of VOCs.

Hodge and Devinny (1994) conducted bench-scale and continuous flow experiments to evaluate biofiltration in the treatment of waste gas streams contaminated with ethanol. The efficiency of three different packing materials (granular activated carbon, compost, and a mixture of compost and diatomaceous earth) was compared for different operating conditions. A mathematical model was developed that described the basic transport and biological processes functioning in each biofilter. For each column with an influent ethanol concentration of approximately 11,700 μg/L, the model predictions were in good agreement with experimental data for the lower loading conditions (79-154 $g/m^2 \cdot hr$). However, for the higher loading conditions (256-272 $g/m^2 \cdot hr$), possible channeling effects caused variability in terms of ethanol concentration, resulting in completely different shapes in the concentration gradient profiles.

Sorial et al. (1994) investigated three microbial attachment media, which were channelized and pelletized media as well as a compost mixture medium, in biofilters for the treatment of air contaminated with toluene. They found that at an influent toluene concentration of 500 ppmv, all the three media achieved more than 95% removal efficiencies for toluene at an organic loading of 0.725 kg COD/m^3·day with a residence time of 12 mins.

Togna and Skladany (1994) evaluated the treatment of BTEX and petroleum hydrocarbon vapors using a field-pilot-scale biofilter. In their work, a biofilter containing 30 ft^3 of packing that had been acclimated for six months to actual SVE vapors was used to evaluate the effectiveness of using biofiltration to treat air contaminated with gasoline. TPH and BTEX removal efficiencies were determined for a range of TPH concentrations up to 4500 ppmv methane equivalents at vapor contact times of 30 seconds to 6 minutes. Benzene and BTEX removal efficiencies up to 95 and 90 percent, respectively, were observed at vapor contact times as low as 1 minute. TPH removal efficiencies of 75-85 percent were observed at vapor contact times of 3-6 minutes. Higher removal efficiencies are attainable with increased vapor contact times, but may not be economically attractive.

Apel et al. (1994) developed a biofilter for the biodegradation of gasoline vapors. The overall goal of this effort was to provide information necessary for the design, construction and operation of a commercial gasoline vapor biofilter. Experimental results indicated that relatively high amounts of gasoline vapor adsorption can occur during initial exposure of the biofilter bed medium (compost) to gasoline vapors (approximately 60 μg gasoline being adsorbed per g of bed medium at a 5 g/m^3 gasoline concentration in the headspace at 40 °C). Biological removal occurred over a temperature range of 22-44 °C with removal being completely inhibited at 54 °C. At lower gasoline concentrations (100 ppm gasoline-in-air) the vapor removal rates were considerably lower than those at higher gasoline concentrations (15,000 ppm gasoline-in-air), indicating that substrate availability (i.e. transport) was limiting in the system. In addition, total BTEX removal over the operating conditions employed was 50-55%. Removal of benzene was approximately 10-15%, while removal of the other members of the BTEX group was typically greater than 80%.

Farmer et al. (1995) used a bench-scale biofiltration system to study the elimination of methyl ethyl ketone (MEK) from a waste air stream and to investigate the effects of various parameters on rate of removal. Three columns, packed with 13-mm diameter ceramic Berl saddles, were connected to allow the operation in series of desired air flow sequence. Through their study, the authors pointed out that using three columns in series instead of one column have several advantages, such as the regeneration of the column via microbial endogenous decay, and potential elimination of biofilter's plugging.

Holt and Lackey (1995) conducted a study on the feasibility of using biofiltration to treat waste gas streams containing styrene and to determine the critical design and operating parameters. In their study, four reactors packed with composted chicken litter, pine bark, peat moss, and a combination of pine bark and composted chicken litter (1:1 v/v) were used. The air stream empty bed contact time (EBCT) in each biofilter was 8 minutes, with an inlet styrene concentration of 1000 ppmv. Experimental data revealed that two of the biofilters, one containing the composted chicken litter and the second containing the combination of chicken litter and pine bark, quickly adapted to the presence of styrene and showed greater than 99% removal of the target compound. However, the removal efficiency of the peat moss and the pine bark biofilters averaged 27-34%.

Kopchynski et al. (1995) investigated the factors affecting the process performance of biofiltration in a laboratory study. In their work, MEK, xylene and hexane were selected as contaminants. Biofilm accumulation, rates of nutrient addition and chemical properties were evaluated. The air flow rate (71 L/hr) which yielded a 1 minute column residence time and the contaminant inlet concentration (1 g/L) were kept constant for all runs. The authors reported that on average, the fractional removal values for MEK, xylene and hexane were 0.68, 0.53 and 0.22, respectively. The fraction of contaminant removed decreased as Henry's law constants increased. Hence, the more volatile the compound the poorer the removal efficiency.

Cost of Degradation of VOCs by Biofiltration

In general, the total cost of the degradation of VOCs by biofiltration mainly depends on the total flow rate of waste gas to be treated, the total pollutants' concentration and the nature of the pollutants of concern. Also, there are other factors, such as the type of filter material, the regulatory requirements, the energy and manpower costs, which will affect the total cost of the degradation of VOCs by biofiltration. But, as mentioned by Leson and Winer (1991), an economic comparison of available air pollution control options should always be conducted on a case-by-case basis.

Bohn (1992) stated that, compared to the overall cost of air pollution control by several methods, biofiltration has a considerable advantage. Although the actual costs vary with each case, a situation in which biofiltration is more expensive than the other methods would be rare. The author reported that for biofiltration, the total cost per 10^6 ft^3 of air was $8, compared to $130 for incineration, $60 for chlorine or ozone oxidation, and $20 for activated carbon with regeneration. However, the author did not present more specific information about pollutants' concentration and the nature of the pollutants of concern.

Togna et al. (1994) presented the estimated capital and operating costs for the treatment of 250 cfm of air containing up to 4000 ppmv (methane equivalents) of petroleum hydrocarbon vapors using biofiltration (with a fixed bed volume of 250 ft^3), catalytic oxidation, or carbon adsorption with off-site carbon disposal/regeneration. According to two site-specific scenarios, biofiltration was the second least expensive in terms of capital cost ($34,000 versus $55,000 for catalytic oxidation and $20,000 for carbon adsorption) and had the lowest yearly operating expenses ($6,600-$7,800 versus $17,540-$23,240 for catalytic oxidation and $119,825-$174,800 for carbon adsorption with off-site disposal) of three technologies evaluated. The authors concluded that on a total project basis (considering both capital and operating costs), biofiltration offers the potential for significant cost savings, especially if the remediation efforts are expected to last for extended periods of time.

Zurlinden and Carmel (1994) performed an economic analysis on biofiltration control of VOCs and made a comparison with other air pollution alternatives (catalytic oxidation, thermal oxidation, and carbon adsorption). Cost information for biofiltration was derived from a pilot-scale study at a petroleum release site and for the other alternatives was obtained from equipment vendors or from the practical experience on the systems. In this analysis, the authors assumed that (1) flow rate of untreated soil vapor is 50 cfm, (2) average concentration of TPH in untreated soil vapor is initially 200 ppm and declines to TPH levels that do not need control in three years, (3) soil vapor is continuously extracted, (4) removal efficiency of 75 percent is required for regulatory compliance, and (5) maintenance cost of the four systems are neglected. Calculated capital cost for biofiltration, catalytic oxidation, thermal oxidation and carbon adsorption are $30,000, $45,000, $35,000, and $20,000, respectively. At the projected TPH concentration in the soil vapor, the annual operating cost for carbon adsorption was estimated to initially be $20,000 and decrease to $15,000 when controls are not needed. However, the annual operating costs for biofiltration, catalytic oxidation and thermal oxidation of $3,000, $9,000 and $17,000, respectively, are assumed to remain steady during the 3-year remediation period. Total capital and operating costs for biofiltration, catalytic oxidation, thermal oxidation and carbon adsorption are $39,000, $72,000, $86,000, and $72,500, respectively. This cost comparison, as the authors concluded, indicates that the use of a biofiltration system in the later stages of remediation may result in significant cost savings.

Modeling of the Degradation of VOCs by Biofiltration

Speitel and McLay (1990) investigated treatment of gas streams contaminated with chlorinated solvents in a biofilter. Based on their research, they estimated the microbial kinetic coefficients (pseudo-first-order rate constants) for degradation of methane and chlorinated solvents. The authors concluded that the kinetic coefficients cannot be directly measured in situ during reactor operation; performance data must be fitted with models to indirectly estimate the coefficients. Estimates of the kinetic coefficients (0.0035 L/mg VS-day for DCA; 0.0009-0.007 L/mg VS-day for TCE), which are for the chlorinated solvents, are important because they permit comparisons to other work.

Hodge et al. (1991b) developed two simple mathematical models to describe the removal of gaseous hydrocarbons by a biofiltration system. The first model was a first-order degradation model while the second one was a zero-order degradation model. Data used to test the models included that obtained when gasoline and diesel fuel vapors were fed to columns containing microorganisms supported on granular activated carbon and ethanol being fed to a column whose support matrix was garden waste compost. The ethanol/compost system was determined to be zero-order, while the gasoline and diesel fuel systems were better fitted with the first-order model. At an assumed influent concentration of 1000 mg/m^3, the degradation rates for gasoline and diesel were reported to be 3.6 gm/m^3/hr and 22 gm/m^3/hr, respectively. The authors did note that dispersion may be a significant factor in determining the performance of the biofilter; however they did not consider it in their models.

Utgikar et al. (1991) developed a mathematical model to describe the biodegradation of VOCs in their biofilter experiments. Numerical solutions of a mathematical model describing the steady-state biodegradation of VOCs in the biofilter were presented. Preliminary experimental data on the removal of toluene and methylene chloride were presented. It was determined that for an inlet gas flow rate of 0.175 m^3/s (370 ft^3/min), a biofilter 3 m in diameter and 5.3 m in height is required for 90% removal of the toluene, methylene chloride and other contaminants of the leachate.

Diks and Ottengraf (1991) studied the removal of dichloromethane within the concentration range of 0-10,000 ppm from waste gases in a biological tricking filter experimentally as well as theoretically using a model. The simplified model they developed, the "Uniform-Concentration-Model", showed the predicted filter performance to be close to the numerical solutions of the model equations. The authors concluded that this model gives an analytical expression for the degree of conversion and can thus be easily applied in practice.

Ockeloen et al. (1992) presented a simulation model of a fixed-film bioscrubber that may be used to predict the applicability, removal efficiency, operational parameters, and design requirements for different gaseous waste streams. The results of the simulations with numerical methods revealed that high removal efficiencies can be obtained for reasonably soluble compounds, regardless of whether the operation of the column is co-current or countercurrent.

Hodge et al. (1992) presented the theoretical mathematical descriptions for the processes important in biofiltration. An explicit, one dimensional, numerical model was developed to predict VOC removal by biofiltration. In this model, the change of pollutant's concentration in the air phase is assumed to be the results of the processes of dispersion, advection, adsorption and biodegradation. First-order kinetics is also assumed in the biodegradation term. The model was tested on simplified problems which could be solved analytically.

Shareefdeen et al. (1993) derived a mathematical model of the biofiltration process treating methanol vapor for predictive and scale-up calculations. This model was also validated by experimental data, which closely fit those predicted by the model. The experimental results showed that a methanol removal rate of 65.1-112.8 $g/m^3 \cdot h$ was achieved at an inlet methanol concentration of 6.11-6.57 g/m^3 and a superficial velocity of

6.42-12.75 m/h. Both experimental data and model predictions suggested that the process would be limited by oxygen diffusion and methanol degradation kinetics.

Schade and Maier (1994) developed a computer model (MBIOAIR) for the treatment of methyl ethyl ketone (MEK) in a biofiltration process. The model describes rates of removal of organics as a function of rates of transport of chemicals, cell mass distribution, kinetics of biodegradation, net cell mass accumulation resulting from the combined effects of growth and endogenous metabolism, and availability of nutrients (nitrogen and phosphorus) that are essential for growth and metabolism. An important feature of the model is that it tracks the spatial distributions of biomass, nitrogen, and phosphate in the reactor train as a function of time. Biomass concentration is a critical variable. It dominates rates of biodegradation because cell mass growth is autocatalytic and results in exponentially increasing rates of biodegradation. Although the limiting substance for cell growth is usually assumed to be carbon, in a closed system such as the biofilter, it could also be nitrogen or phosphorus. For this reason the Monod equation was modified to include nitrogen and phosphorus as well as carbon as the possible limiting substrate. The model gave a reasonably good match to the trends observed in the pilot plant using microbial kinetic coefficients that had been measured independently in batch reactors and assuming an effectiveness factor of 1.0. The best match was obtained by using a very low endogenous rate coefficient. This was consistent with the observation that there was excessive accumulation of biomass to the point of partial plugging of the reactors when high mass loadings of chemicals were applied. In the pilot plant study, the test conditions included an MEK loading of 0.212 g/hr, an inlet MEK concentration of

10-320 ppmv, and an air flow rate of 54.0 $m^3/m^2 \cdot hr$, which corresponds to a residence time of 60 seconds. Overall removal of MEK was 97%.

Deshusses et al. (1995) developed a novel model for the description of gaseous waste biofiltration. The model considers the reactor to be comprised of finite sections, for each of which transient mass balances are established and solved by numerical simulation. The elimination of methyl ethyl ketone (MEK) and methyl isobutyl ketone (MIBK) vapors from air as single and mixed pollutants served as an example to illustrate both the model's response and its parametric sensitivity. With an air flow rate of 0.20-0.40 m^3/h, and a volumetric loading which varied from 44 to 88 $m^3/m^3 \cdot h$, the maximum elimination capacities were 121 $g/m^3 \cdot h$ for MEK and 30 $g/m^3 \cdot h$ for MIBK. Michaelis-Menten biodegradation kinetics were assumed to apply in the model. The model proved appropriate for describing most of the experiments undertaken and served as a basis for comprehensive understanding of biofilter operation.

Hodge and Devinny (1995) discussed in detailed the model developed by Hodge et al. (1992). Several simplifying assumptions were presented for the development of the model which can be applied to the biofiltration process. Validation tests were also performed. This included model runs in which advection, dispersion, adsorption, and biodegradation each occurred individually while the others were set to zero. Mass balances were calculated comparing contaminant input to contaminant output plus adsorption and degradation. Both model calculations and experimental column results demonstrated that adsorption was the controlling removal mechanism during start-up conditions. In later stages of operation, the contaminant removal was dominated by biodegradation. Steady-state results were approached when input concentrations were constant, packing material was saturated, and contaminant loading equaled biological degradation plus discharge.

Problems in the Control of VOCs Using Biofiltration

Although much work has been done on the control of VOCs using biofiltration, there are still some problems, listed below, which have not been attacked or addressed sufficiently:

1) For the BTEX compounds, most research has been conducted using a single BTEX compound at a time such as toluene, or xylene instead of multiple compounds (Table 1). From a practical sense, it is necessary to investigate the behavior of all the BTEX compounds and any interactions.
2) Compared to other filter media, such as GAC and DE, less research work regarding compost has been reported, especially concerning BTEX biodegradation. In fact, compost has several advantages over other filter media. For instance, it is very cheap and no nutrient addition is required.
3) There has been little research concerning the comparison of a biofilter with a nutrient addition and a biofilter without a nutrient addition in the degradation of BTEX compounds.
4) It is also not known what the key design criteria are. Nor is it known what kind of model can best be applied to a specific type of biofiltration technique for the BTEX compounds. These questions need to be answered in detail.
5) There were few research papers which provide cost estimates for the degradation of BTEX compounds for a specific type of biofiltration technique.

Table 1. Summary of Degradation of BTEX Compounds by Biofiltration

Compounds	Filter Media	Applied Loading ($mg/cm^3 \cdot day$)	Inlet Concentration (μg/L)	Residence Time (mins)	Elimination Efficiency (%)	Reference
BTX	inert plastic	not reported	75-1,850	not reported	32.6-78.6	Galaska et al. (1989)
gasoline	GAC	0.07-3.11	705-33,467	5.9-7.0	85-95	Medina et al (1992)
p-xylene	glass sphe. (GS) DE	0.55-1.29 (GS) 2.37-3.09 (DE)	651-6,510 651-6,510	5-10 (GS) 1.7-2.5 (DE)	43-75 (GS) 73-88 (DE)	Vaughn et al. (1993)
p-xylene	Pall rings	0.05	8,750	not reported	46	Apel et al. (1993)
toluene	GAC	not reported	38-76	0.02-0.07*	>95	Gregg et al. (1993)
toluene	compost channelized pelletized	not reported not reported not reported	1,888 1,507 1,884	12 12 12	>99 80 99	Sorial et al. (1994)
BTEX	not reported	0.01-1.30	20-450	0.5-6	90	Togna et al. (1994)
gasoline	compost	28.8	65,000	3.4	50-55 (BTEX)	Apel et al. (1994)

* Empty Bed Contact Time (EBCT).

The above existing questions provide a guide for the objectives of this research project. These objectives are as follows:

- to demonstrate the feasibility of eliminating a selected mixture of BTEX compounds by biofiltration,
- to provide the data of elimination efficiencies from biofilters for the selected mixture of BTEX compounds,
- to compare elimination rates of the selected mixture of BTEX compounds obtained from biofilters containing two different support media,
- to present some design criteria which can be used in a full-scale biofilter,
- to develop a model for predicting the elimination of the selected mixture of BTEX compounds by biofiltration, and
- to estimate the cost of eliminating the selected mixture of BTEX compounds by biofiltration.

CHAPTER III

MATERIALS AND METHODS

Description of the Experimental Apparatus

In this study, two columns constructed from plexiglas pipes were employed as biofilter reactors. The columns, having an inside diameter of 3.1 cm and a length of 119 cm, were packed with either compost or diatomaceous earth (DE) which served as support media for the growth of microorganisms. Seven sampling ports, spaced 18.5-22.5 cm apart, were placed along the length of each column. Two separate reservoirs, containing a mixture of three pure solvents of selected BTEX compounds (toluene, ethylbenzene, o-xylene) and distilled water, respectively, were used to create the contaminated air stream which was sent to each column. The air flow rate to each column was controlled by hosecock clamps on the air inlet, outlet and waste lines. The influent concentration to each column was adjusted using the ratio of two air flow rates from the contaminant and distilled water reservoirs. Air flow rates were monitored by four air flow meters. The seed bacterial culture, which consisted of mixed liquor from the activated sludge system of a refinery wastewater treatment plant, was mixed with the compost or diatomaceous earth when the medium was packed into each column. Schematic diagrams of these two biofilters are shown in Figures 1 and 2. It is noted that the contaminated air stream was passed through the compost column in an upflow mode (Figure 1), but in a downflow mode to the DE

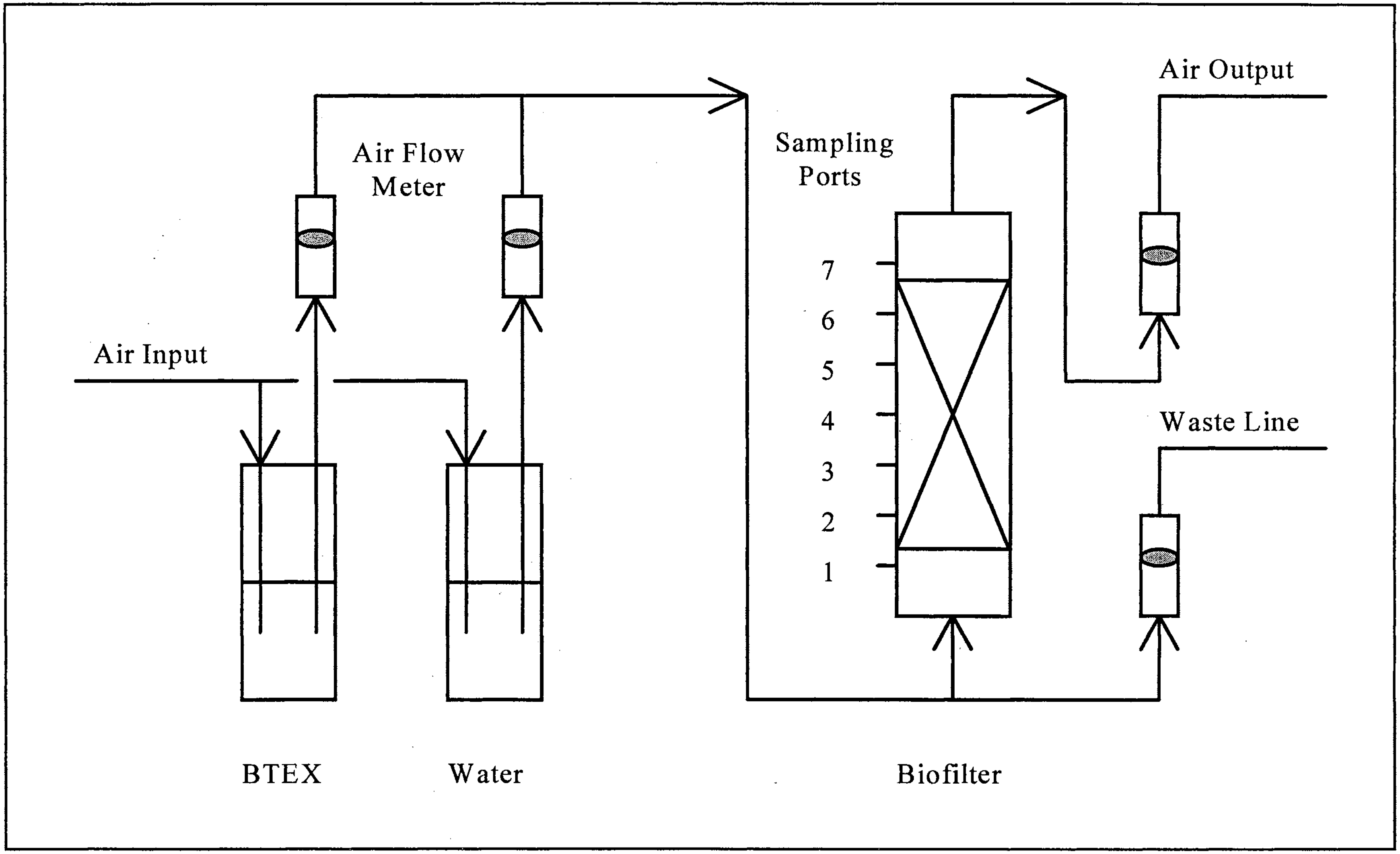

Figure 1. Schematic of the Compost Biofilter Used for Degradation of VOCs

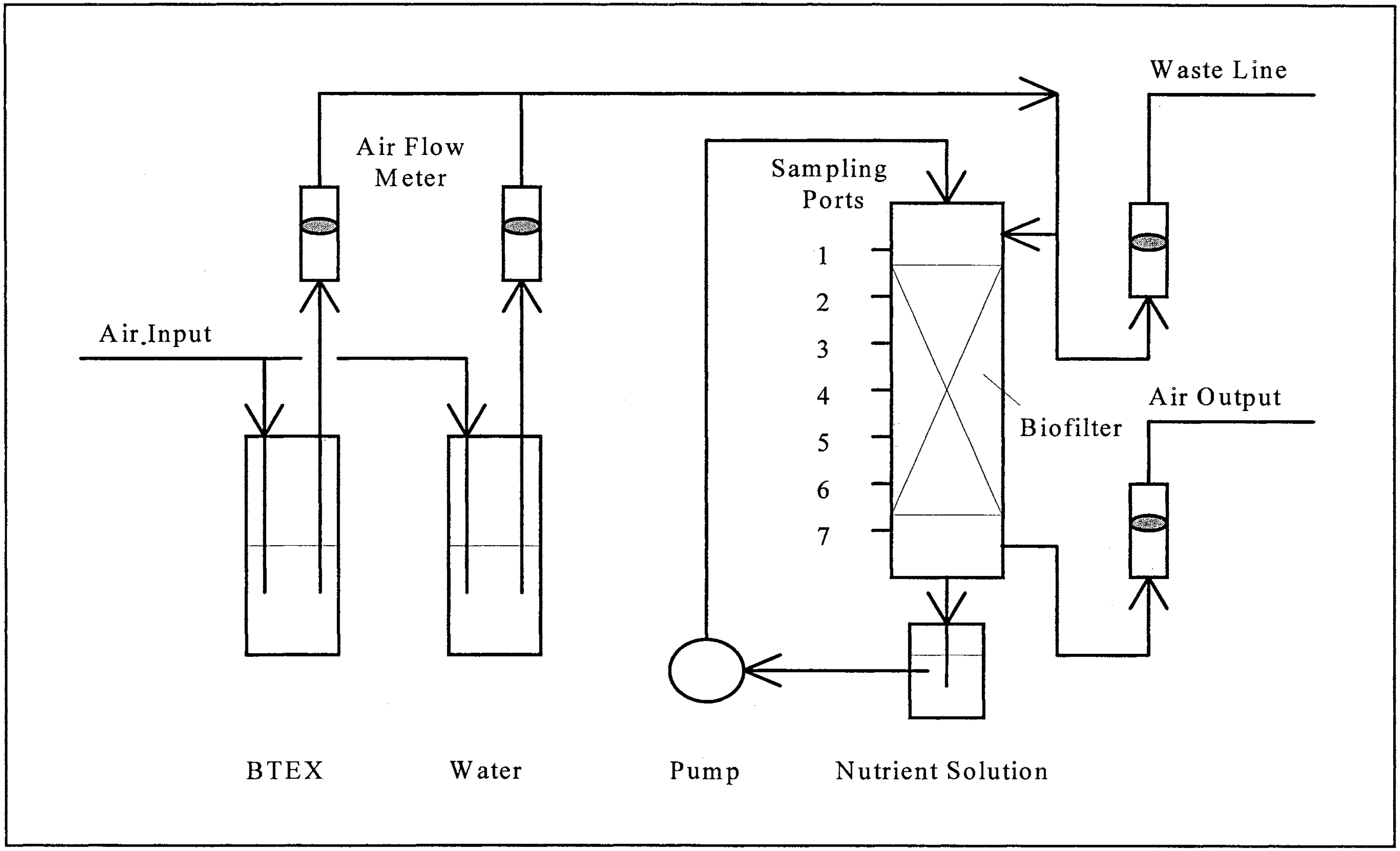

Figure 2. Schematic of the DE Biofilter Used for Degradation of VOCs

column (Figure 2). The countercurrent mode in the DE column would cause the flooding of the recirculation nutrient solution because the air flow would hold the liquid up in the DE column.

Selection of Porous Filtration Materials

In order for a biofilter to operate efficiently, the filter material must meet several requirements. First, it must provide optimum environmental conditions for the resident microbial population in order to achieve and maintain high degradation rates (Leson and Winer, 1991). Second, filter particle size distribution and pore structure should provide large reactive surfaces and low pressure drops (Leson and Winer, 1991; Douglass et al., 1991; Shareefdeen et al., 1993). Third, compaction should be kept to a minimum, reducing the need for maintenance and replacement of the filter material (Leson and Winer, 1991). Fourth, it should have the characteristics of low energy consumption (Ottengraf, 1987) and low cost as well as ready availability (Shareefdeen et al., 1993).

There are several materials which previous research has demonstrated to be suitable as filtration materials. These include granular activated carbon (GAC), compost, diatomaceous earth (DE), and soil. Since compost and DE are economical, they were selected for use in this study. The compost was obtained from a sample of backyard grass clippings, sieved (passed a #4 mesh sieve (4.75 mm), and retained on a #10 mesh sieve(2.00 mm)) and then mixed with a bulking agent (wood chips) to provide an appropriate porosity. The ratio of compost to wood chips was 85% to 15% on a volume basis. The DE was obtained from Manville Filtration and Minerals (Denver, CO). The general properties of these media are listed in Table 2.

Table 2. General Properties of Compost and Diatomaceous Earth Media

Property	Compost	Diatomaceous Earth
Particle Size (mm)	2.00 - 4.75	3.00 - 10.00
Bed Density (g/cm^3)	627	513
Porosity (%)	0.59	0.69
Total Organic Carbon (%)	0.46	
Total Nitrogen (%)	0.93	
Total Phosphorus (%)	3.7	

Notes: (1) Data of compost are from experimental measurements.

(2) Data of DE are from the manufacturer (Manville Filtration and Minerals, Denver, CO).

Selection of Contaminant Compounds

BTEX refers to benzene, toluene, ethylbenzene, and xylenes (o-xylene, m-xylene and p-xylene). Among these compounds, benzene, toluene, ethylbenzene, and o-xylene are usually considered as representatives of gasoline in terms of their mass percent (Smoley,1992). Benzene was initially selected for use in this study, however, being the most volatile of the BTEX compounds, it was difficult to keep a consistent influent concentration during preliminary experiments. Therefore, toluene, ethylbenzene, and o-xylene were selected to be used in this study. The general physical and chemical properties of the BTEX compounds are presented in Table 3.

Preparation of Two Reservoirs

To create a contaminated air stream, a 400-mL glass bottle with a plastic screw on cap was used as the contaminant reservoir. This vessel contained 50 mL each of toluene, ethylbenzene and o-xylene (reagent grade, Fisher Scientific, Fair Lawn, NJ). A 1-liter Erlenmeyer glass flask fitted with a rubber stopper was utilized as the humidification reservoir. This reservoir contained 800 mL of distilled water. These reservoirs were renewed periodically on an as-needed basis.

Acclimation of the Microbial Culture

Six liters of activated sludge from a refinery wastewater treatment plant were placed into three 4-liter glass bottles, aerated, supplied with an inorganic mineral solution, and injected with stock solutions of toluene, ethylbenzene and o-xylene on a daily basis.

Table 3. Physical and Chemical Properties of BTEX Compounds [1,2]

Property	Benzene	Toluene	Ethylbenzene	o-Xylene
Empirical Formula:	C_6H_6	C_7H_8	C_8H_{10}	C_8H_{10}
Formula Weight:	78.11	92.14	106.17	106.17
Boiling Point (°C):	80.10	92.14	136.20	144.40
Henry's Law Constant: (atm·m^3/mol, @25 °C)	0.00548	0.00674	0.00868	0.00535
Log K_{oc}:	1.69	2.05	1.98	2.11
Log K_{ow}:	2.13	2.65	3.13	2.95
Solubility in Water: (mg/L, @25 °C)	1800	524	206	204
Specific Density: (@25 °C)	0.87366	0.86233	0.86250	0.87596
Vapor Density: (g/L, @25 °C)	3.19	3.77	4.34	4.34
Vapor Pressure: (mm Hg, @25 °C)	95.2	22	10	10
Exposure Limit (ppm): (8 hour-OSHA Standard)	10	100	100	100

Source: (1) Montgomery and Welkom (1990) (2) Nielsen (1980)

The flow rate of mineral solution added was about 200 mL/day and the amount of each organic stock solution (200 μg/mL) added was 200 μg/day, resulting in a total mass loading of 600 μg/day. Before introducing the culture into the biofilters, this acclimation system was operated for at least one month.

Preparation of the Mineral Media

A mineral solution, similar to that selected by Apel et al. (1993), was used for the acclimation of the microbial culture and for the nutrient solution pumped through the DE column. The components of the mineral solution are listed in Table 4. The mineral solution was made up in tap water. All the chemicals (Fisher Scientific, Fair Lawn, NJ) were analytical grade or better.

Start-up Procedure

The compost column medium was prepared by mixing 530 grams of compost with wood chips with a size of 2-4 mm (on a 85% to 15% volume basis) and 20 mL of the acclimated bacterial culture. This mixture was placed into the column which was then connected to a contaminated air stream. The air flow rate to the column was then adjusted to the desired value. Gas phase samples were taken from the 7 sampling ports on the column after 30 minutes.

To initiate the DE column, 482 grams of the Bio-Catalyst Carrier R-635 (Manville Filtration and Minerals, Denver, CO) was mixed with 20 mL of the acclimated bacterial culture, and the mixture was then placed into the column. A mineral solution was recycled through the column for 3 days. During the 3-day period, to supply a carbon source, the

Table 4. Components of Inorganic Mineral Solution

Chemical	Concentration (mg/L)
KH_2PO_4	700
$(NH_4)_2SO_4$	600
$MgSO_4 \cdot 7H_2O$	600
$FeCl_3 \cdot 6H_2O$	1
$MnSO_4$	1

three organic stock solutions (200 μg/mL each) were injected into the top of the column with a 5-mL plastic syringe at a dose of 1 mL/day each. After this period of time, the DE column was connected to a contaminated air stream which was adjusted to the desired air flow rate. Gas phase samples from the 7 sampling ports on the column were taken after 30 minutes.

Analytical Techniques

Each analytical method discussed below was performed at the end of each experimental run (approximately every other week) unless indicated otherwise. The compost and DE samples used in all the analytical procedures were not put back to the columns.

Temperature and Humidity

Daily temperature and humidity measurements of the influent and effluent from each biofilter were performed using a Digital Thermometer/Hygrometer (Model DTH1, Davis Instruments, Baltimore, MD) that had effective ranges of -30 to 200 °F and 20 to 90% Relative Humidity (RH). There was no effort made to control these parameters over the entire experimental period.

Contaminant Concentrations

The concentrations of toluene, ethylbenzene and o-xylene from the 7 sampling ports on each column were analyzed using an HP 5890 series II gas chromatograph equipped with a flame ionization detector and a 60/80 mesh Carbopack C column (Supelco, Bellefonte, PA). The GC was connected to an HP 3396 series II integrator. Helium was selected as the carrier gas and was utilized at a flow rate of 20 mL/min. The oven temperature started at 180 °C for 9 minutes, and then increased at a rate of 15 °C/min until the final temperature of 195 °C was reached. Under these operating conditions, the retention times of toluene, ethylbenzene and o-xylene were about 4.0, 8.0 and 14.0 minutes, respectively. Each sample was injected into the GC from a 250-μL gas tight syringe (Hamilton Company, Reno, NV) using an injection volume of 200 μL. Gas standards were prepared through (1) placing 30 μL of each BTEX compound into a 40-mL vial filled with acetone (Fisher Scientific, Fair Lawn, NJ), (2) shaking the stock solution for 15 minutes at room temperature (~25 °C), (3) transferring different volumes of the stock solution to a series of 40-mL vials (standard samples) containing 20 mL of distilled water, and (4) shaking these standard samples for 2 hours at room temperature (~25 °C). Preliminary study has shown that there were no significant differences among the equilibrium times of 2, 8 and 24 hours. Henry's law constants (25 °C) of 0.00674 $\text{atm·m}^3/\text{mol}$ for toluene, 0.00868 $\text{atm·m}^3/\text{mol}$ for ethylbenzene and 0.00535 $\text{atm·m}^3/\text{mol}$ for o-xylene (Montgomery and Welkom, 1990) were used to calculate the resulting gas phase concentrations in each standard sample. The detection limits of these compounds were approximately 15 μg/L each.

Water Content

The water content of each medium (compost or DE) was measured on 1 gram of compost or 10 pieces of DE taken from each biofilter. The procedure followed was that described in section 209F of Standard Methods (APHA et al., 1985).

Pressure Drop

Pressure drop across each column was determined with an Air Velocity Meter (Model 400, Dwyer Instruments, Inc., Michigan City, IN). This meter can also function as a manometer with a range of 0-10 inches of water.

Protein Content

Protein content on the compost medium was analyzed using the Bio-Rad Protein Assay. The detailed procedure was described in the User's Manual of the Bio-Rad Protein Assay (Kit II, Bio-Rad Laboratories).

Volatile Solids

The procedure described in section 209F of Standard Methods (APHA et al., 1985) was used to determine the volatile solids content of the DE medium. For each measurement of volatile solids, 10 pieces of the DE medium was taken from the DE column.

Bacterial Population Counts

A standard plate count method presented by Benson (1967) was followed to perform the bacterial population counts on the compost medium. The sample's extraction procedure includes (1) taking about 10 grams of compost from the compost column, (2) adding 300 mL of distilled water, (3) mixing the solution in a blender for 3 minutes at a high speed (22,000 rpm), (4) settling the solution for 45 - 60 minutes, and (5) taking 1 mL of the supernatant as the sample for the standard plate count. In addition, 20-mL of nutrient agar (Difco Laboratories, Detroit, MI) was poured into each 100x15 mm sterilized-disposable plastic Petri dish (Fisher Scientific, Fair Lawn, NJ), which were incubated at a room temperature (~25 °C) for 24-48 hours.

Total Organic Carbon

The total organic carbon (TOC) of the compost medium was performed on about 0.5 gram of compost from the column, using the inexpensive titration method for TOC measurement. The analytical procedure was described by Gaudette and Flight (1974).

Kjeldahl Nitrogen

Five pieces of DE were taken from the column to determine the kjeldahl nitrogen of the DE medium. The analytical procedure was described in section 420B of Standard Methods (APHA et al., 1985). After the digestion step all five pieces of DE and the residual of the digestion reagents along with 200 mL of distilled water were poured into a distillation flask to complete the analysis.

Nitrogen and Phosphorus

Inorganic nitrogen and phosphorus in the nutrient solution recirculated through the DE column were measured utilizing the procedures described in sections 420B.4d and 424D of Standard Methods (APHA et al., 1985). In addition, total nitrogen and phosphorus of the compost were also analyzed following the same procedures.

Biofilm Appearance

A scanning electron microscope (JSM-35U, JEOL) was used to observe the biofilm's appearance on the compost and DE media. This was done at the beginning and end of the study.

Experimental Design

Adsorption Study

To separate the physical adsorption from biological elimination on each medium (compost and DE), breakthrough tests were performed using 700 cm^3 of compost or DE placed into a glass column with a diameter of 5.2 cm and a height of 33.0 cm. The column and each medium (compost or DE) were sterilized in an autoclave for 30 minutes before use. The autoclave temperature and pressure were 248 °C and 15 psi, respectively. The influent concentration of the contaminated air stream was controlled at about 1000 μg VOCs/L with an air flow rate of 42-48 mL/min, resulting in a residence time of 10 minutes. The tests were conducted until complete exhaustion of the columns occurred, that is, the point where the ratio of influent concentration to effluent concentration was 1.0.

Compost Column Study

The compost column was operated at two different influent concentrations (low and high) in an upflow mode. There was no nutrient addition to the column. At the low influent concentration, the air flow rate was varied from 25 to 200 mL/min, resulting in four residence times of 20, 10, 5 and 2.5 minutes. For the high influent concentration, the range of the air flow rates was 25-100 mL/min, corresponding to three residence times of 20, 10 and 5 minutes. No nutrients were added to the column. These experimental conditions are listed in Table 5.

Diatomaceous Earth Column Study

Most experimental conditions were the same as for the compost column (two levels of influent concentration, 1000 μg VOCs/L and 2000 μg VOCs/L, four levels of residence time, 20, 10, 5, and 2.5 minutes at each influent concentration); however, in this study, a recirculating nutrient solution at a flow rate of 5 mL/min was added to the top of the column. The contaminated air stream was introduced into the top of the column. The two flow streams entering the column operated in a co-current mode. The experimental conditions are presented in Table 6.

Tracer Study

To determine a dispersion coefficient in each biofilter, 30 mL of methane gas (99%, v/v) served as a tracer. It was injected into the inlet of each column with a 30 cc syringe (Becton, Dickinson & Co., Yale, CT). The carrier gas was clean compressed air with a flow rate of 25-100 mL/min. The outlet concentration of each column was monitored using an HP 5890 series II gas chromatograph equipped with a flame ionization detector over time until the methane was completely flushed from the column.

Table 5. Experimental Conditions for Compost Column

Experimental Run No.	1	2	3	4	5	6	7
Influent Conc. (μg VOCs/L)	1000	1000	1000	1000	2000	2000	2000
Air Flow Rate (mL/min)	25	50	100	200	25	50	100
Residence Time (mins)	20	10	5	2.5	20	10	5
Applied Loading Rate (mg VOCs/cm^3·day)	0.10	0.20	0.40	0.80	0.20	0.40	0.80

Table 6. Experimental Conditions for DE Column

Experimental Run No.	1	2	3	4	5	6	7	8
Influent Conc. (µg VOCs/L)	1000	1000	1000	1000	2000	2000	2000	2000
Air Flow Rate (mL/min)	25	50	100	200	25	50	100	200
Residence Time (mins)	20	10	5	2.5	20	10	5	2.5
Applied Loading Rate (mg VOCs/cm^3·day)	0.13	0.26	0.52	1.04	0.26	0.52	1.04	2.08

CHAPTER IV

RESULTS AND DISCUSSION

Based on the experimental design described in Chapter III, four individual experiments were conducted. These experiments are:

- adsorption study - to separate the physical adsorption capacity of a filter material (compost or diatomaceous earth) from the total elimination capacity in a biofilter, allowing the biological elimination capacity of a filter material to be determined,
- compost column study - to investigate the behavior of the compost biofilter at two levels of inlet gas concentrations (~1000 and 2000 μg VOC/L), and four levels of residence time (20, 10, 5.0 2.5 minutes),
- diatomaceous earth column study - to investigate the behavior of the diatomaceous earth biofilter at two levels of inlet gas concentrations (~1000 and 2000 μg VOC/L), and four levels of residence time (20, 10, 5.0 2.5 minutes), and
- tracer study - to determine a dispersion coefficient in each biofilter (compost and diatomaceous earth), so that a mathematical model with a dispersion term can be used for predicting the behavior of a biofilter.

In addition, based on the above experimental results, further efforts were placed on the following aspects:

- modeling - to develop a model for predicting the elimination of the selected mixture of BTEX compounds by biofiltration,
- statistical analysis - to determine the main factors on the degradation of the selected mixture of BTEX compounds by biofiltration, and
- cost analysis - to estimate the cost of eliminating the selected mixture of BTEX compounds by biofiltration.

Adsorption Study

Breakthrough Curve for Compost

The result of the breakthrough test is illustrated in Figure 3. It can be seen that C_e/C_i reached a value of 0.51 in an elapsed time of 3.3 hours, and for samples taken after 9.6 hours, the value of C_e/C_i was 1.0. Using this breakthrough curve, a physical adsorption capacity of 0.032 mg VOCs/gm compost can be determined by the integration of the area in front of curve. The raw data and calculation of the physical adsorption capacity of compost are listed in Appendix A and C, respectively.

Breakthrough Curve for Diatomaceous Earth

Figure 4 shows the breakthrough curve of the DE medium. Unlike the compost medium, the physical adsorption capacity of the DE was only 0.003 mg VOCs/gm DE after the integration of the area in front of curve. The time required before reaching breakthrough of the DE was less than 1.0 hour. This result indicates that the physical

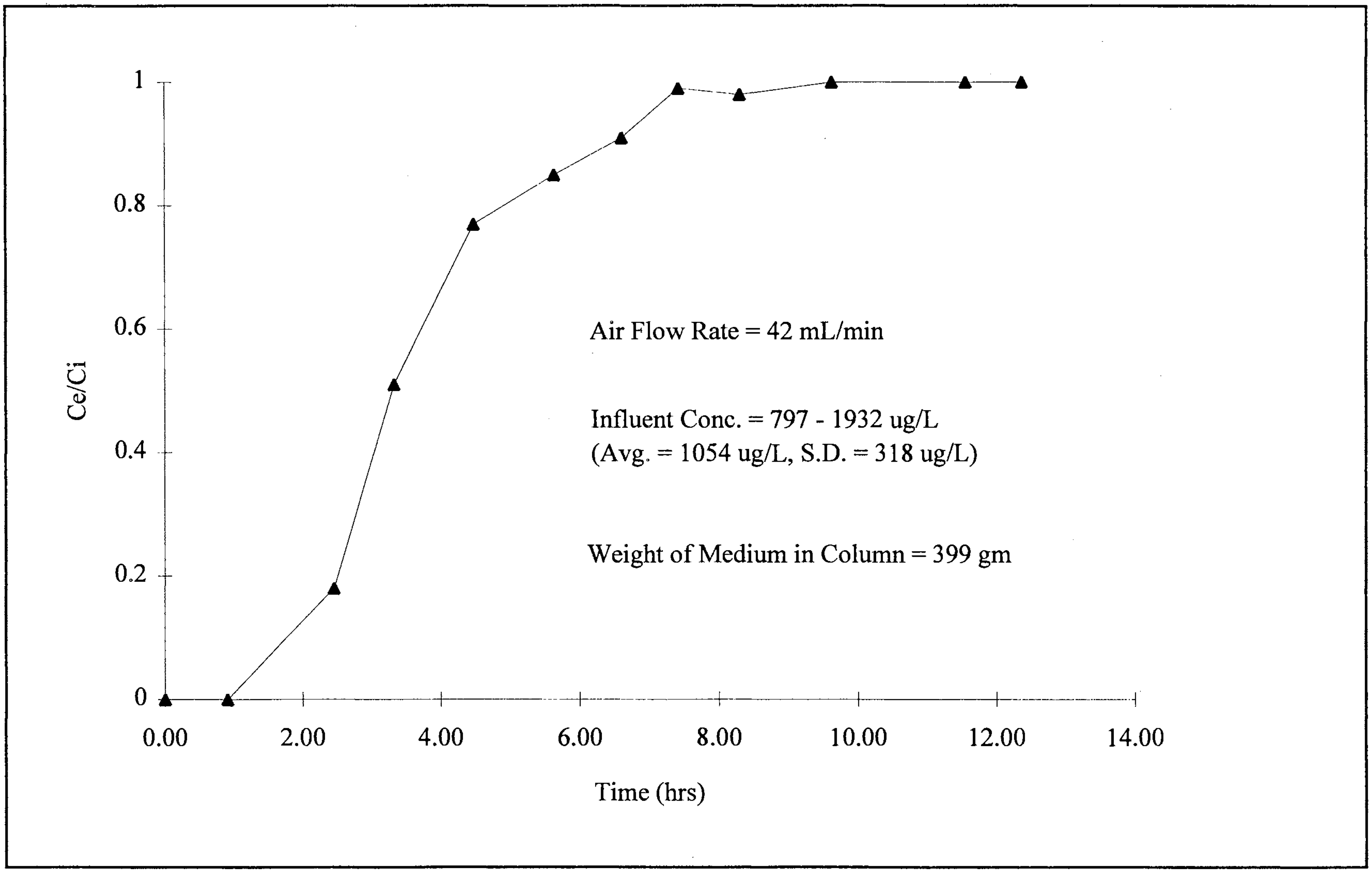

Figure 3. Breakthrough Curve for Compost

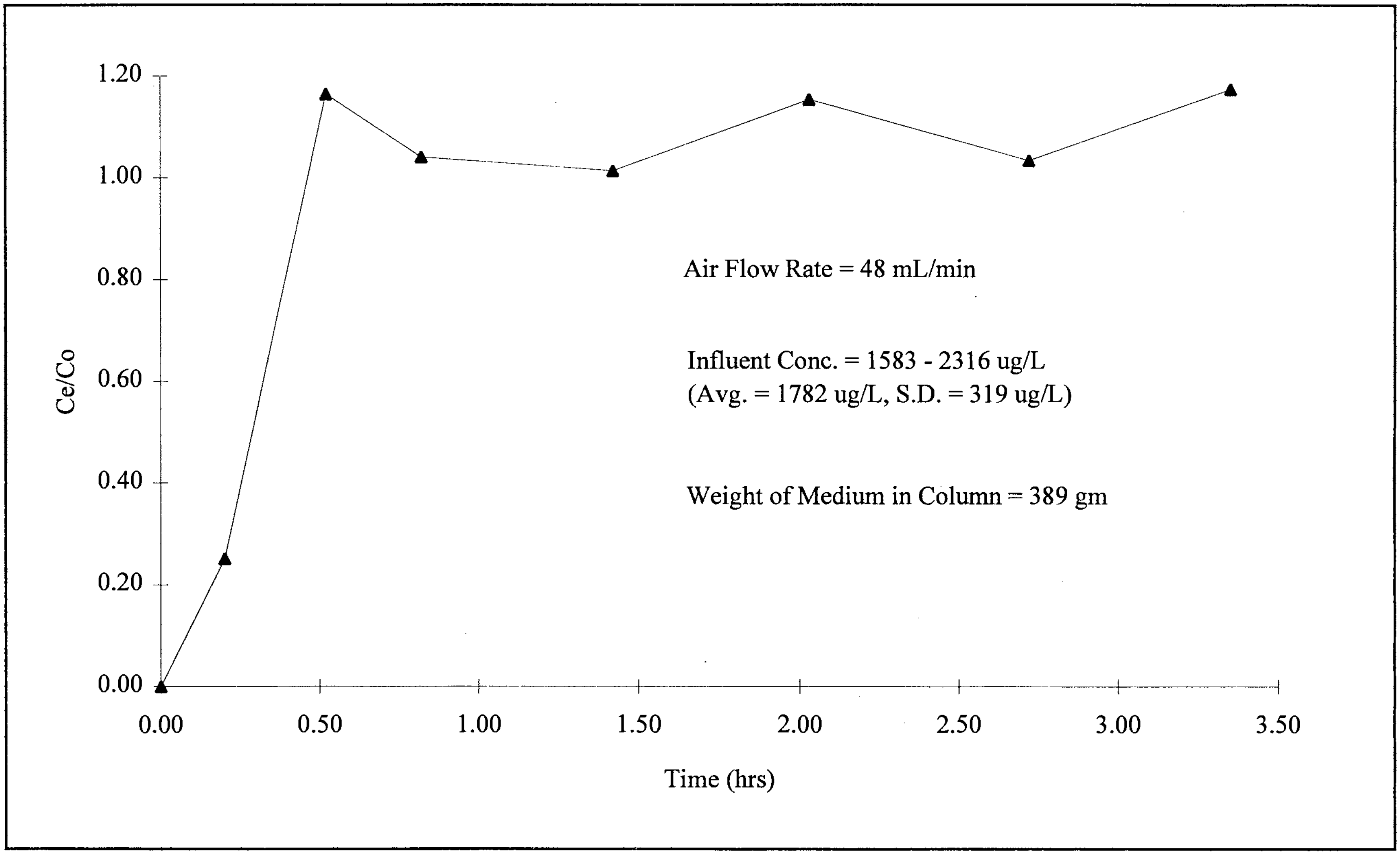

Figure 4. Breakthrough Curve for Diatomaceous Earth

adsorption capacity of the DE medium is an order of magnitude less than that of the compost medium, and the saturated time of the DE medium is also shorter than that of the compost medium. The raw data and calculation of the physical adsorption capacity of DE is shown in Appendix B and C, respectively.

Compost Column Study

Average Gas Influent and Effluent Concentrations

During the entire period of the compost column study, the influent and effluent gas concentrations from the column were monitored on a daily basis, and the air samples taken from the other sampling ports were also measured daily. The raw input air was analyzed periodically and found no VOCs present in detectable quantities. The order of the experimental runs was No. 1, 2, 3, 5, 6, 7, and 4. The average gas influent and effluent concentrations are shown in Figure 5. The low influent concentration was controlled at approximately 1000 μg VOCs/L for Runs 1 to 4 and the high influent concentration was maintained at about 2000 μg VOCs/L for Runs 5 to 7. Within each experimental run, it was difficult to control the gas influent concentration at a constant value, mainly due to the variability of the air source pressure. The daily records of gas influent and effluent concentrations are provided in Appendix D. The average contaminant concentrations from the other sampling ports are listed in Appendix E.

Records of Column Temperature and Humidity

The temperature and humidity of the column were also measured daily. Figures 6

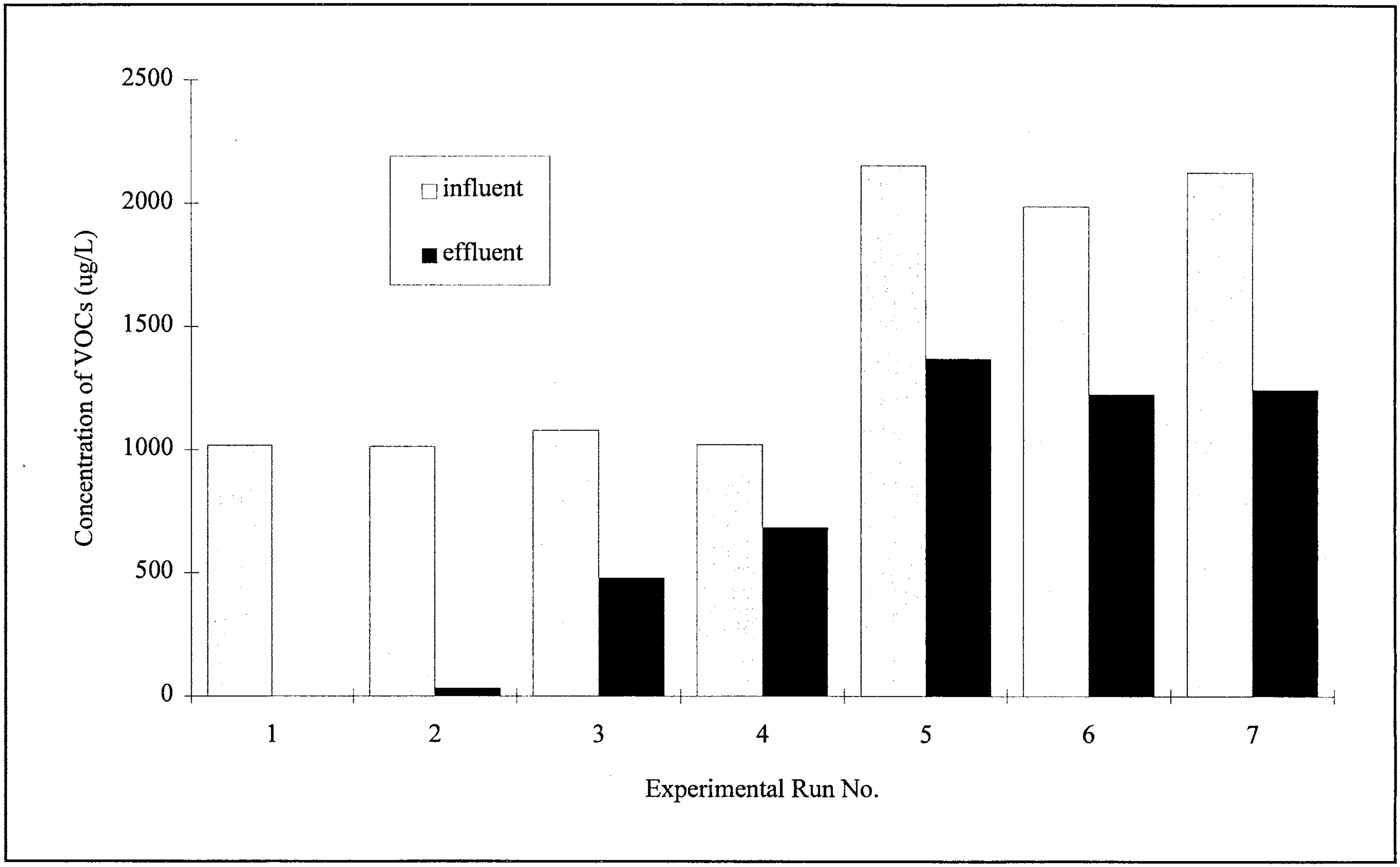

Figure 5. Average Gas Influent and Effluent Concentrations of Compost Column

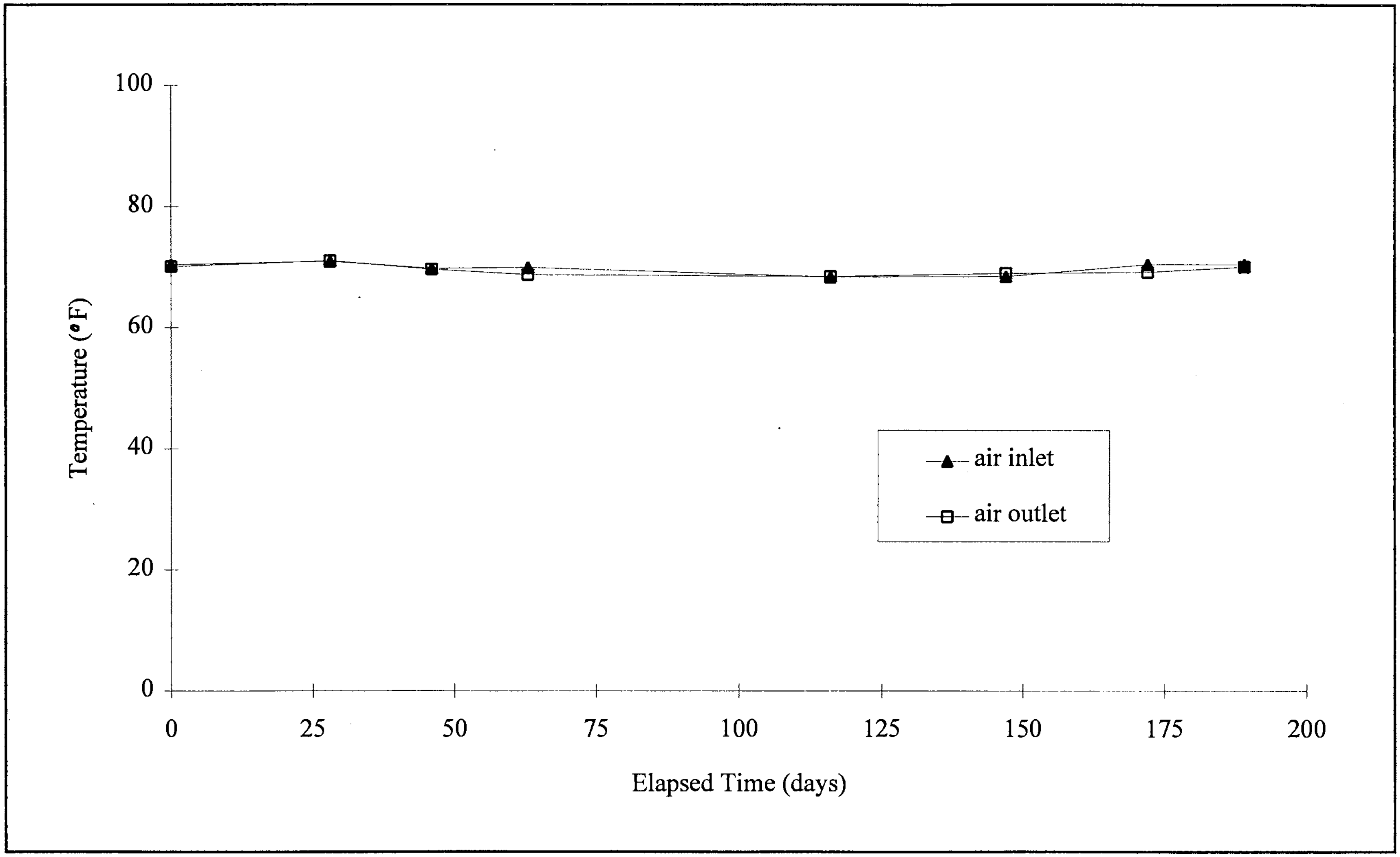

Figure 6. Record of the Compost Column's Temperature

and 7 are the records of the average temperature and humidity, respectively, of the column for the entire experimental run. For the 189-day period, the temperatures and humidities of both the influent and effluent air were close, and the average temperature of the column was about 70 °F, which is appropriate for the growth of bacteria. The average humidity, however, was about 80%, which is a little higher than the optimum range of about 50-60% given by Ottengraf (1986).

Effect of Applied Loading on Elimination Rate

The effect of applied loading on the elimination rate is illustrated in Figure 8. A 45° line was included as a point of reference. For a given applied loading, a data point which is close to the 45° line has a high elimination rate or elimination efficiency. As the applied loadings ranged from 0.11 to 0.85 mg VOCs/cm^3 compost·day with the low inlet concentration, the elimination rates were 0.11-0.28 mg VOCs/cm^3 compost·day. However, the elimination rates were 0.08-0.37 mg VOCs/cm^3 compost·day at the high inlet concentration when the applied loadings varied from 0.22 to 0.88 mg VOCs/cm^3 compost·day. It was found that the higher the inlet concentration, the lower the elimination rate, for applied loadings less than about 0.65 mg VOCs/cm^3 compost·day. The reason could be the toxicity of BTEX compounds to the bacteria. As the applied loading was raised above 0.65, however, the elimination rate obtained at the lower inlet concentration was less than that of the high inlet concentration. One possibility for this phenomenon is when running at the low inlet concentration, a larger air flow rate is needed than at the high inlet concentration to maintain the higher applied loading, resulting

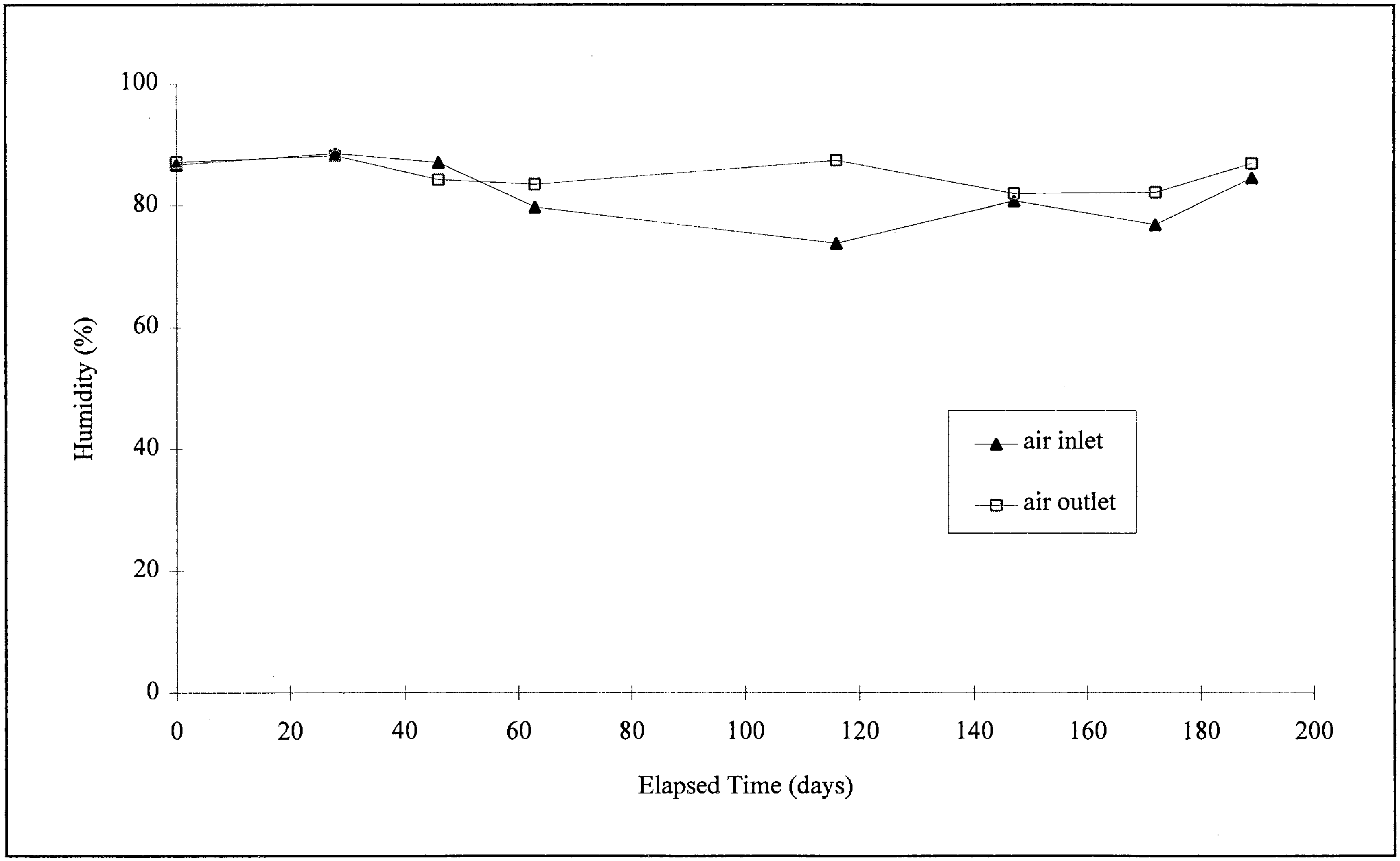

Figure 7. Record of the Compost Column's Humidity

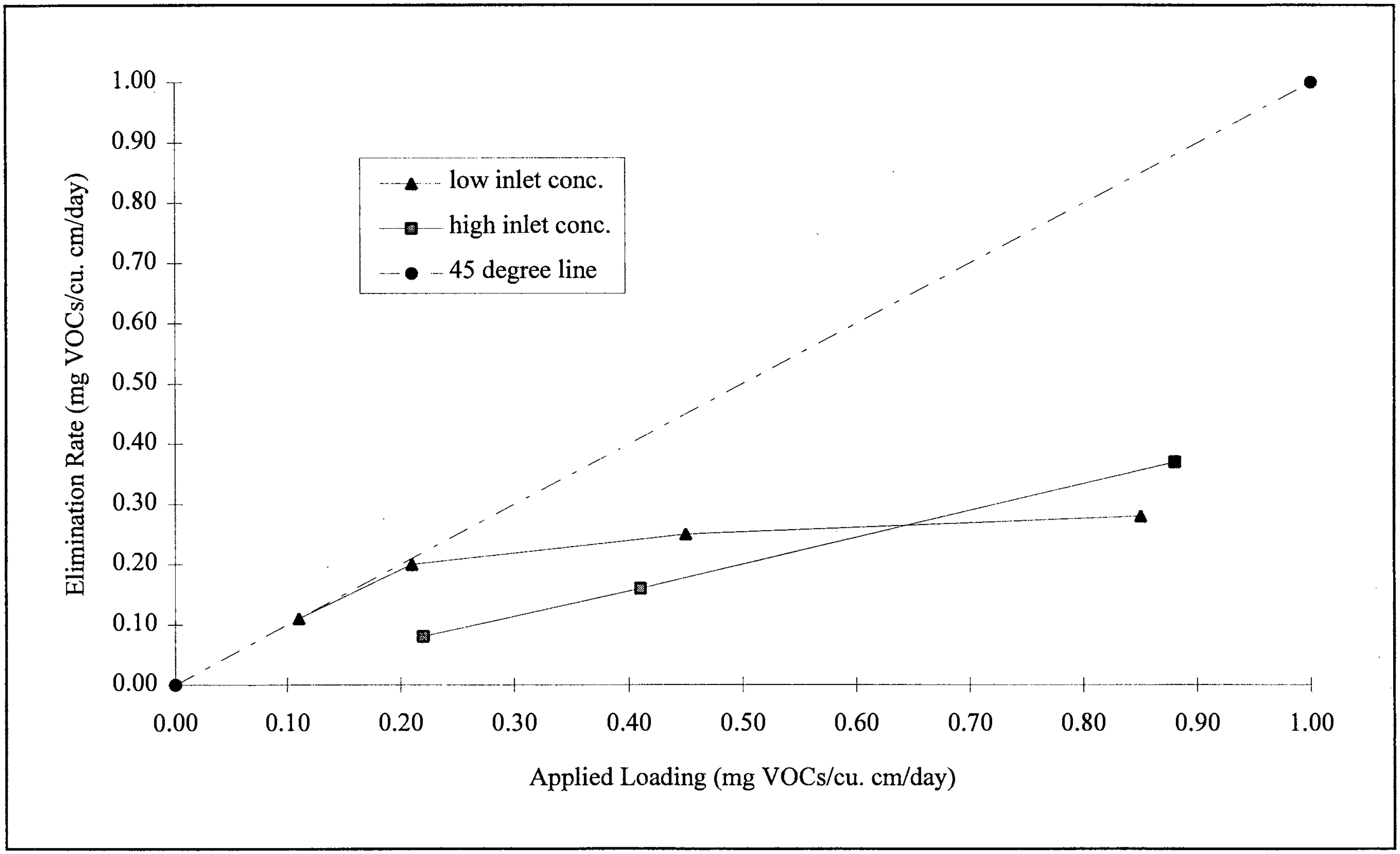

Figure 8. Applied Loading versus Elimination Rate in Compost Column

in a lower residence time for the column. In this case, the residence time (2.5 minutes) might be too low to achieve the higher elimination rate obtained using the higher inlet concentration with a residence time of 5.0 minutes. The maximum elimination rate obtained from the compost column was 0.34 mg VOCs/cm^3 compost·day, which was lower than elimination rates of 0.48-0.72 mg BTEX/cm^3 compost·day obtained by Kamarthi and Wellington (1994).

Effect of Applied Loading on Elimination Efficiency

Figure 9 shows that for applied loadings of 0.11-0.85 mg VOCs/cm^3 compost·day, the elimination efficiencies of the VOCs were 100-31.4% for the low inlet concentration. But, at the applied loadings ranging from 0.22-0.88 mg VOCs/cm^3 compost·day, the efficiencies were 37.2-41.2%, respectively, when fed the high inlet concentration. This revealed that the three VOCs could be more completely removed under the condition of a low inlet concentration when the applied loading is less then about 0.70 mg VOCs/cm^3 compost·day. In addition, the error bars in this figure shows that the line depicting the low inlet concentration might be still above the line of high inlet concentration after an applied loading of 0.70 mg VOCs/cm^3. Kamarthi and Wellington (1994) reported an elimination efficiency of 70-90% (BTEX) for a compost column, but they did not present the range of the applied loading.

Comparison of Average Elimination Efficiencies of Three BTEX Compounds

Under the most experimental conditions (Runs 2-7), there were differences in the average elimination efficiencies of the three BTEX compounds in the compost column

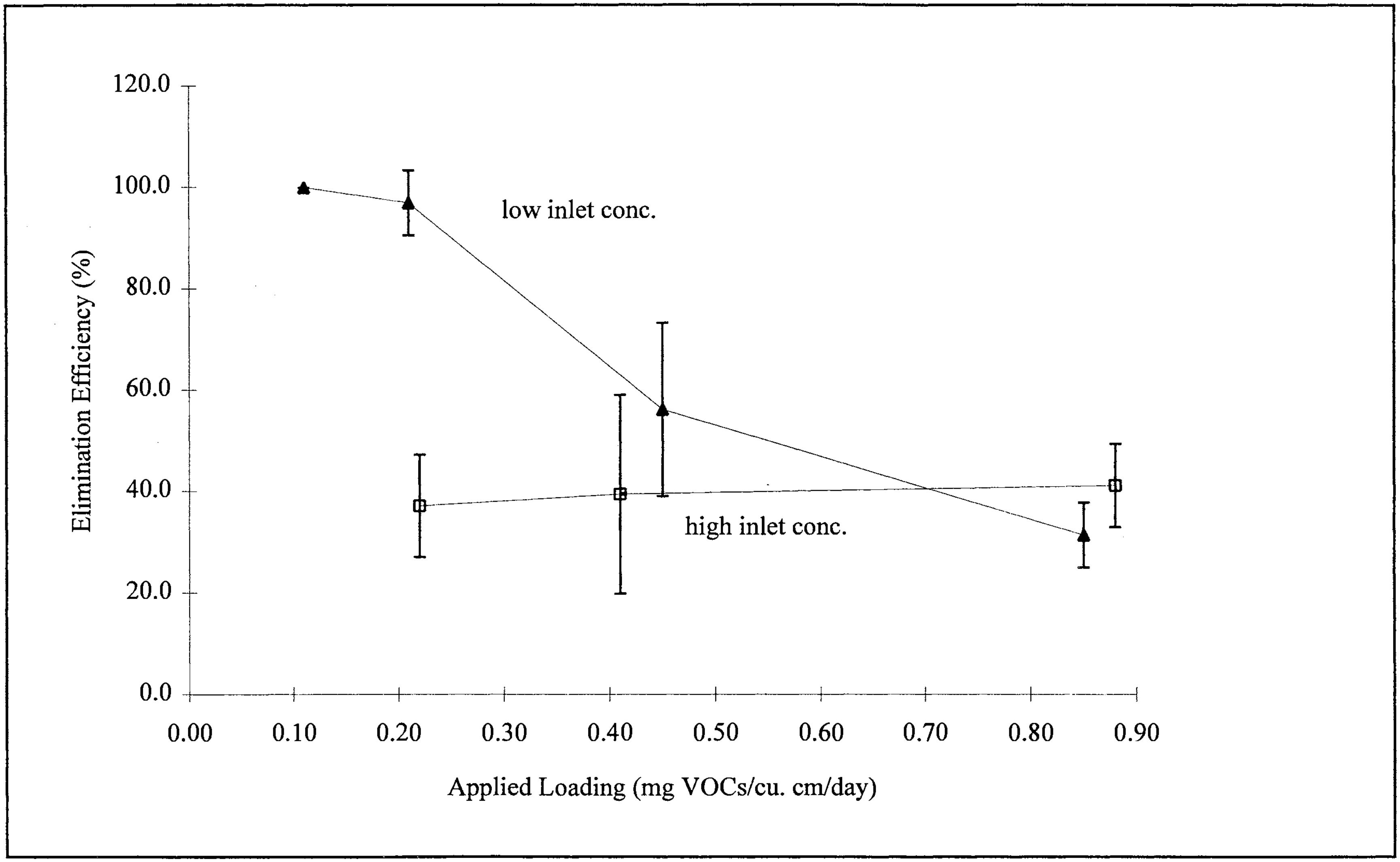

Figure 9. Applied Loading versus Elimination Efficiency in Compost Column

(Figure 10). Ethylbenzene had the highest average elimination efficiency of 47.4-100%, and o-xylene had the lowest average elimination efficiency of 12.1-93.8%. The average elimination efficiency of toluene was 31.8-96.6%.

Effect of Residence Time on Elimination Efficiency

In Figure 11, it is seen that with the residence times varying from 2.5, 5, 10 to 20 minutes, the resulting elimination efficiencies, in terms of total VOCs, were 31.4, 56.2, 97.0 and 100% at the low inlet concentration. This means the shorter the residence time, the lower the elimination efficiency. But with the high inlet concentration, the elimination efficiencies were 37.2, 39.5 and 41.2% at the residence times of 5, 10 and 20 minutes, respectively. These values actually are the same statistically. The shortest residence time used in the compost column was 2.5 minutes. Togna (1994) reported an elimination efficiency of 90% for BTEX at a residence time of 0.5-6.0 minutes. A BTEX removal of 70-90% was found by Kamarthi and Wellington (1994) at a 1.2-min residence time.

Effect of Air Flow Rate on Pressure Drop

The effect of air flow rate on the pressure drop through the column is presented in Figure 12. At air flow rates of 25, 50 and 100 mL/min, the pressure drops were 0.05, 0.09 and 0.11 in. H_2O, respectively. It is apparent that under the condition of the high inlet concentration, the smaller the air flow rate the lower the pressure drop. From a view of energy costs, the lower the air pressure the better the system. A filter material with a large porosity is usually considered to have the characteristic of low pressure drop.

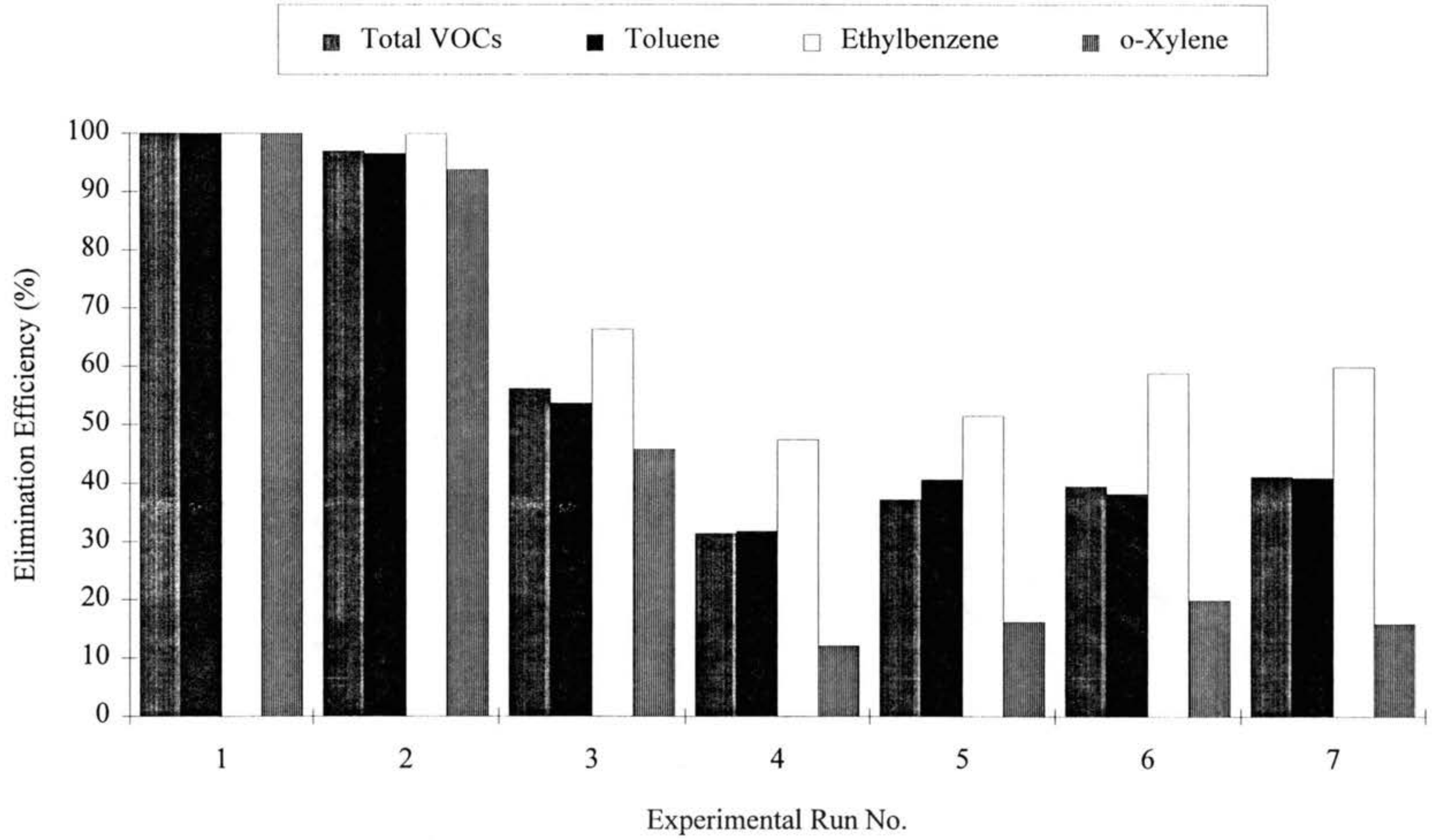

Figure 10. Comparison of Average Elimination Efficiencies of Three BTEX Compounds in Compost Column

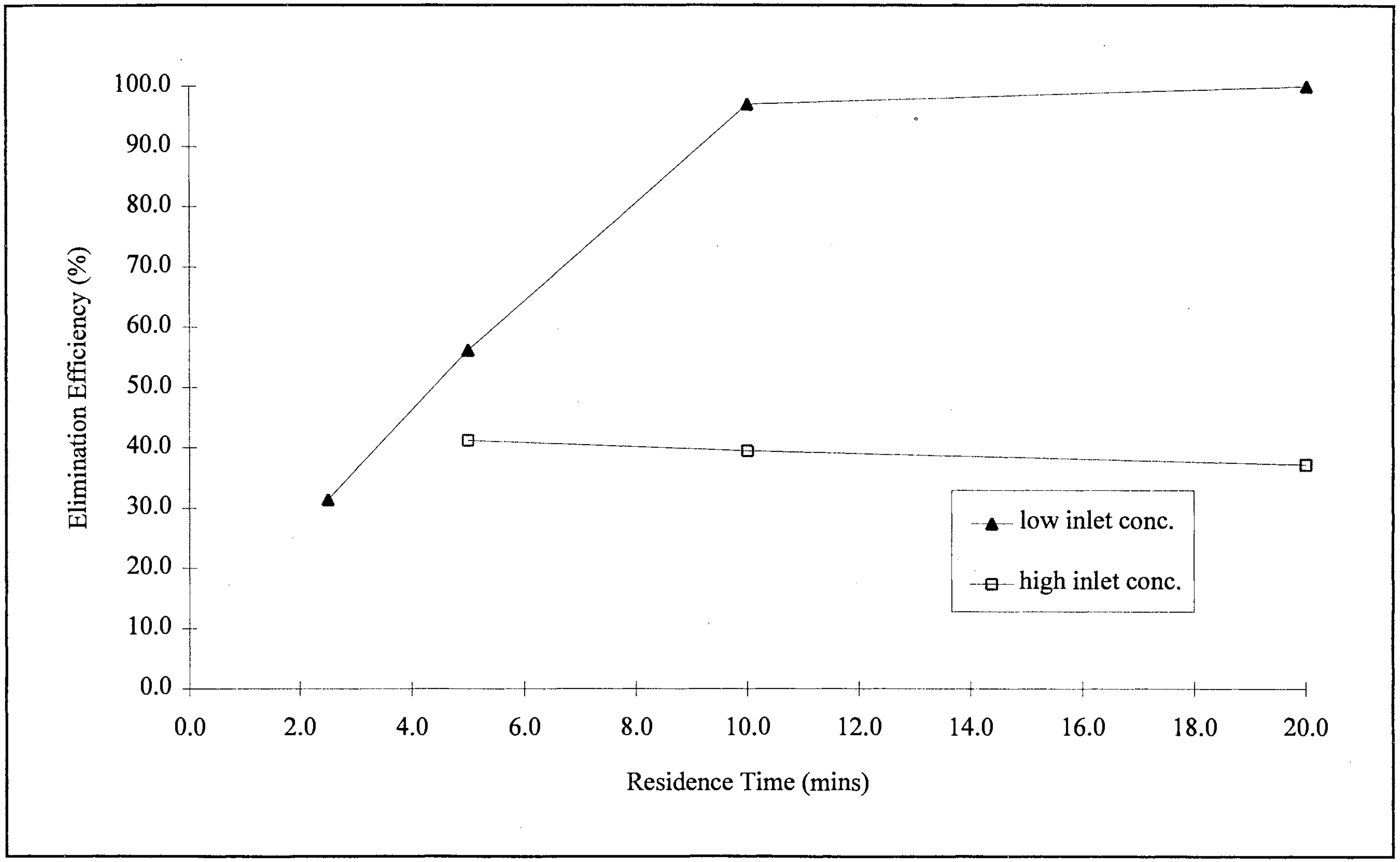

Figure 11. Residence Time versus Elimination Efficiency in Compost Column

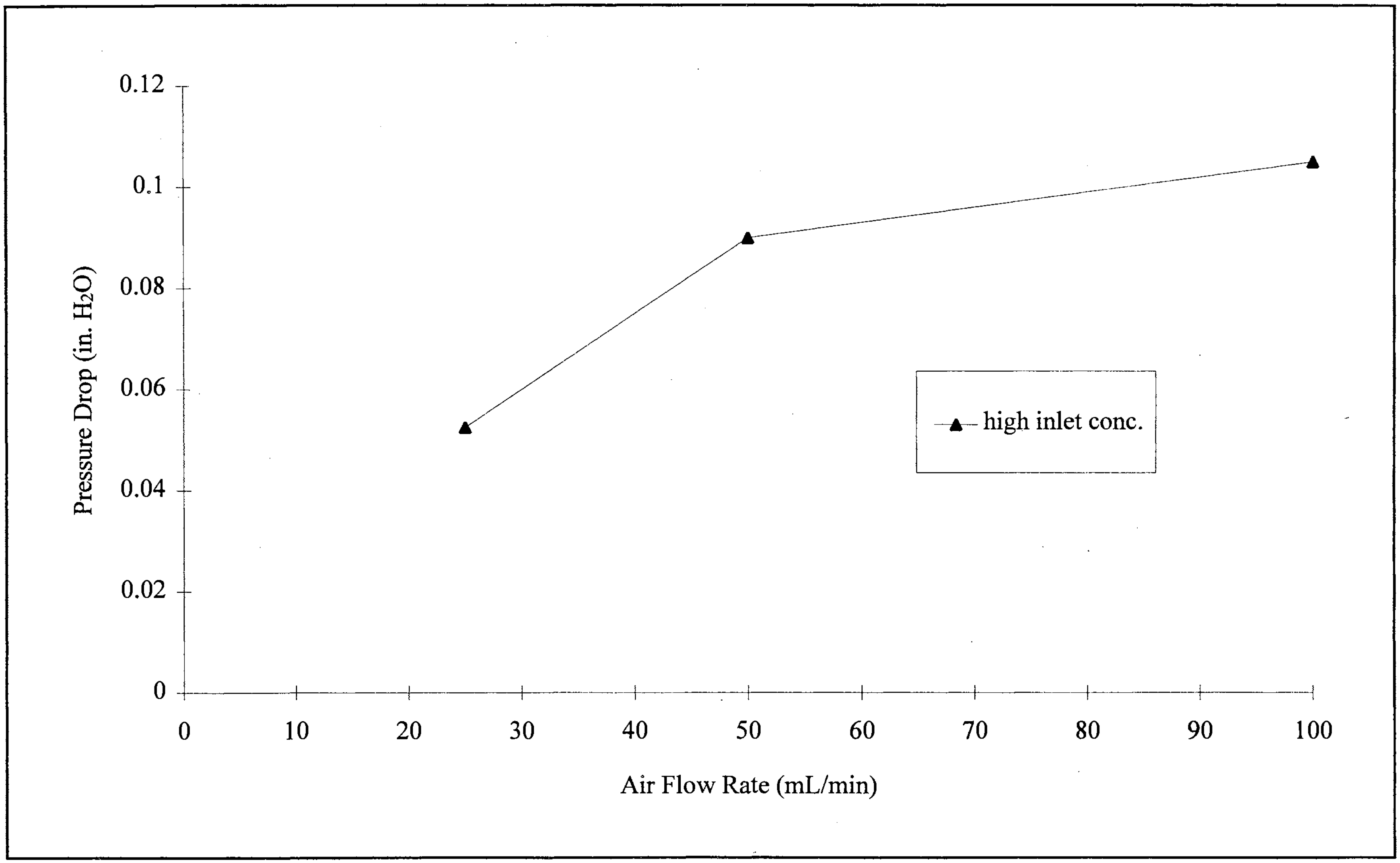

Figure 12. Air Flow Rate versus Pressure Drop in Compost Column

Water Content of Compost Column

The values of the average water content of the compost column are shown in Figure 13. For the column, the water content of the top portion were higher than those of the bottom portion over time. This was because the column was operated in an upflow mode, and water was one of the end products in the degradation process. During the first 28 days, the difference in water content between the top and the bottom of the column, operated in an upflow mode, was small. However, from day 46 on, the difference gradually increased until day 116. After that , the difference seemed to be constant.

Total Organic Carbon of Compost

Figure 14 presents the total organic carbon content of the compost medium. During the first 28 days, the total organic carbon (TOC) values from both the top and bottom of the column were small, and there was little difference between them. This implied that the formation of biofilm was small along the length of the column during this period. After day 46, there was a significant increase on the TOC for both the top and bottom. This indicated that there was more biofilm formed in the column. Since the column was operated in an upflow mode, the bottom portion of the column got more substrates than the top portion; therefore the TOC contents (or quantities of biofilm) in the bottom portion were larger than those in the top portion. On day 147, the TOC difference between the top and the bottom reached its maximum.

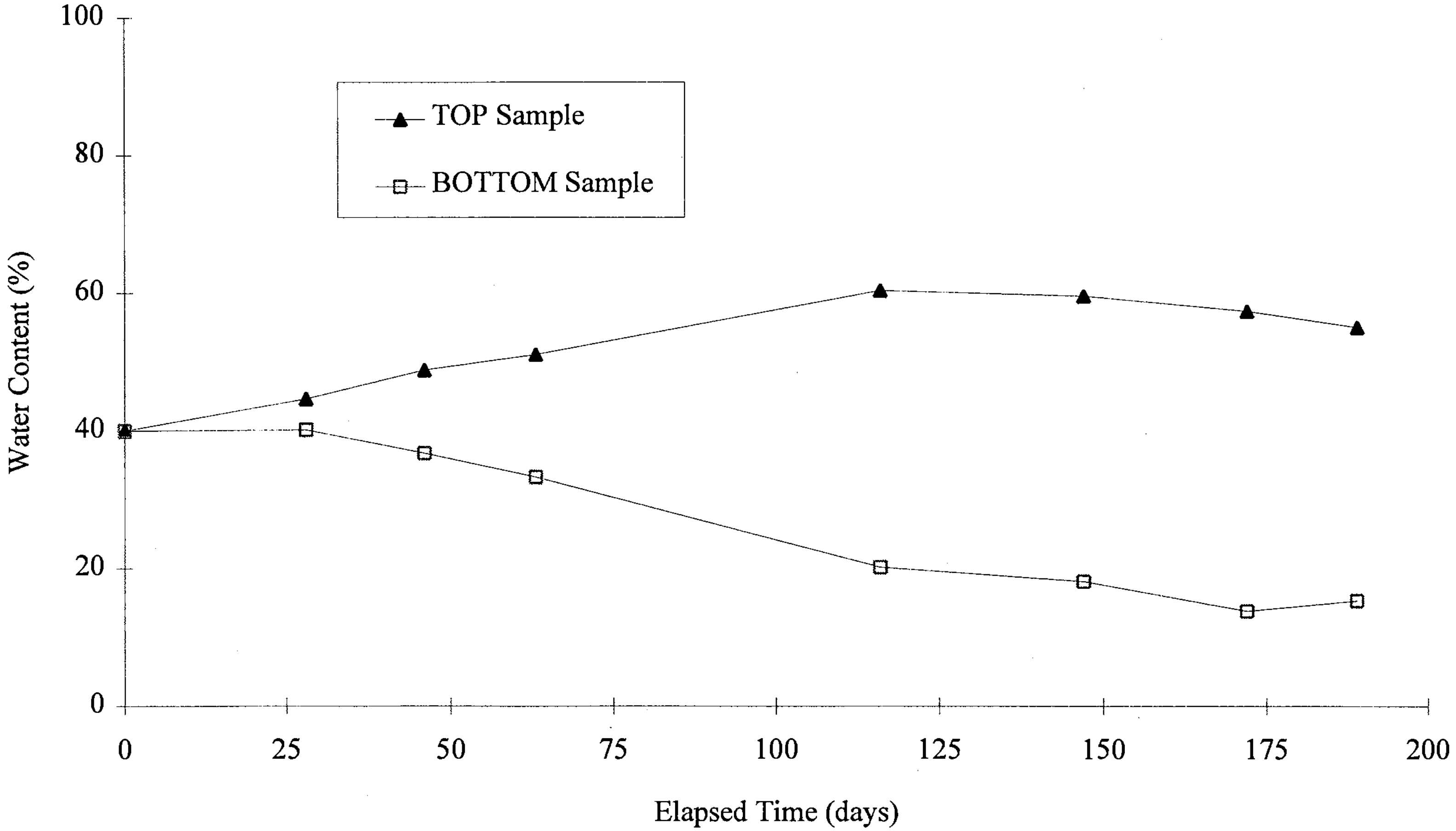

Figure 13. Water Content of Compost Column

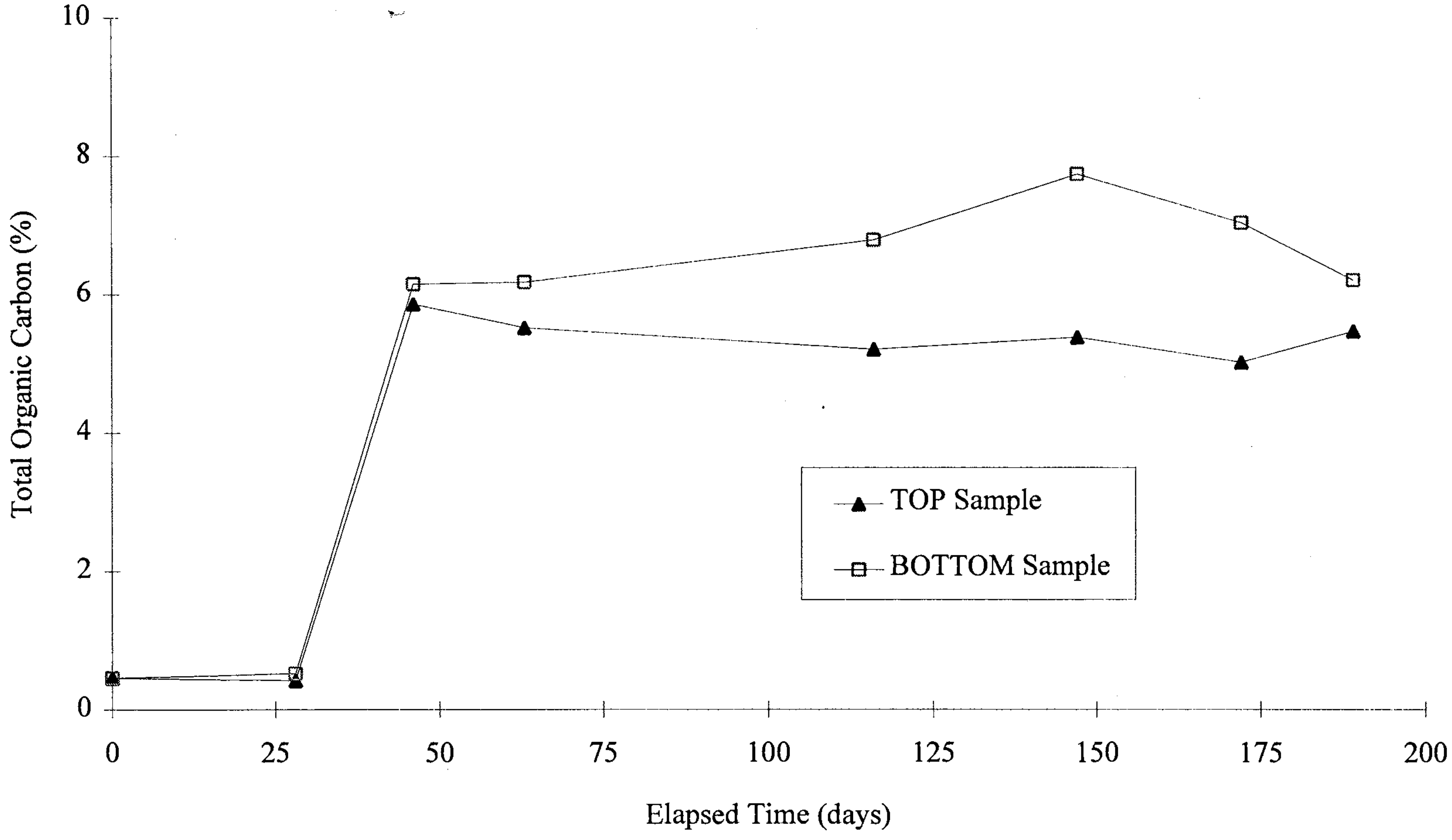

Figure 14. Total Organic Carbon of Compost

Protein Content of Compost

The protein content of the compost medium is provided in Figure 15. In general, the greater the protein content, the greater the biofilm in the column. For the bottom portion of the column, the protein content increased with time. For the top portion of the column, however, the protein content did not increase significantly until day 46, and after day 63, it begun to decrease until day 172, and then remained constant. Like the TOC content, the protein content also revealed the fact that for the compost column there was more biofilm in the bottom portion than in the top portion.

Bacterial Population Counts of Compost

The results of the bacterial population counts of the compost medium are plotted in Figure 16. During the first 63-day period, the Standard Population Counts (SPCs) from the bottom portion of the column were less than those from the top portion. One possibility was that the concentration of VOCs in the bottom was higher than that in the top, which might inhibit the growth of the bacteria in the bottom portion. However, from day 116 through day 189, the SPCs from the bottom were larger than those from the top. The explanation might be that during this period, the bacteria in the bottom portion had been acclimated, and were able to obtain more substrates than the top portion, which was beneficial to the growth of the bacteria.

Column Weight Loss During Experiment

It was found that the column weight decreased over the experimental period

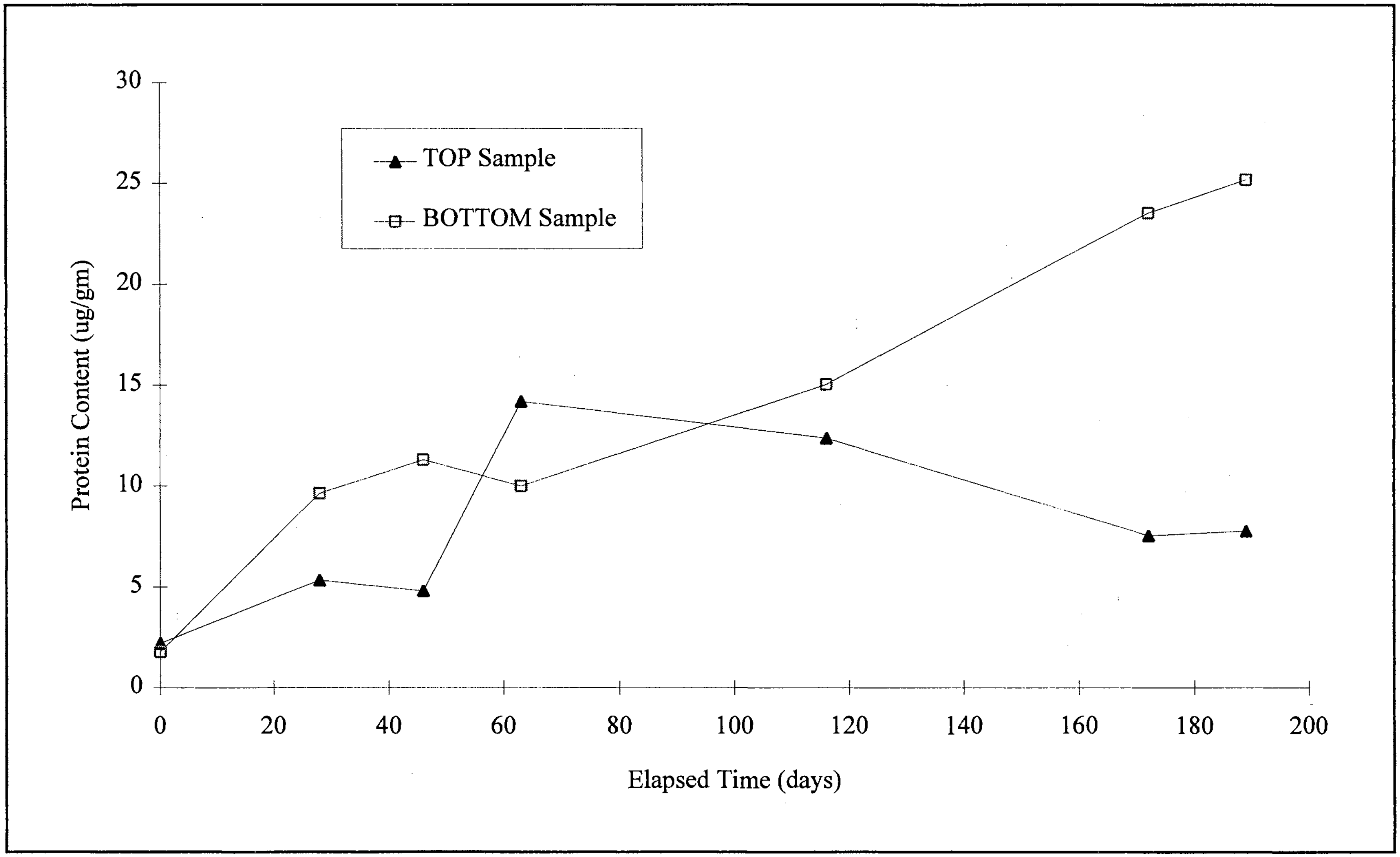

Figure 15. Protein Content of Compost

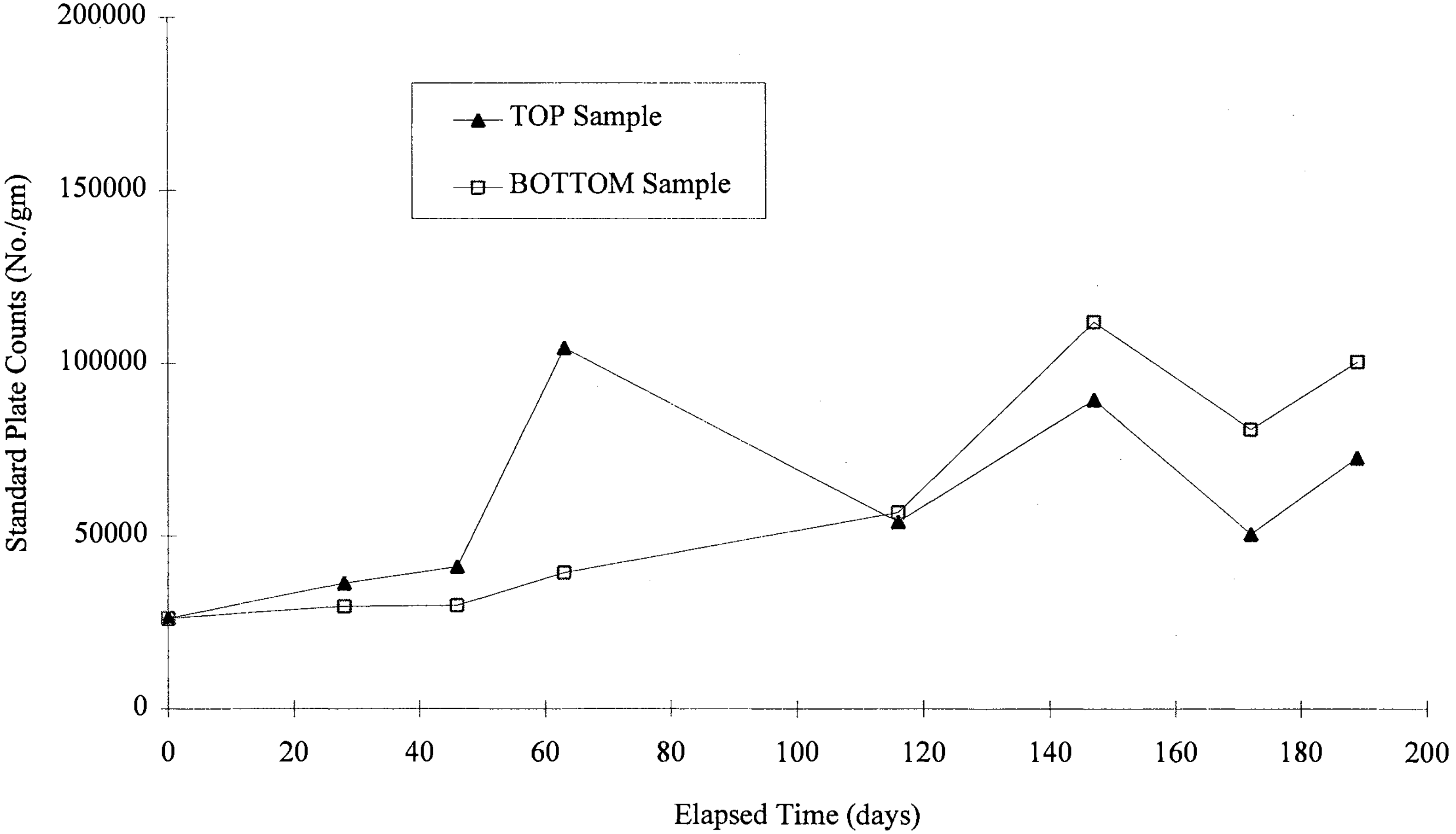

Figure 16. Bacterial Population Counts of Compost

(Figure 17). For each experimental run, the value of the weight loss varied from 2 to 16 gm. The reason for the weight loss might be that in the loss rate of CO_2 and H_2O, produced in the degradation of the contaminants in the compost biofilter, was higher than that of the gain rate of biofilm.

Separation of Physical Adsorption and Biological Degradation

Figure 18 shows the separation of the physical adsorption and biological elimination capacities of the compost. During the acclimation period (Run No. 0), the total elimination capacity was 6.977 mg VOCs/gm·compost, while the physical adsorption capacity was only 0.032 mg VOCs/gm compost (based on data from adsorption study). Therefore, the biological elimination capacity could be considered the most significant portion (6.945 mg VOCs/gm compost) in this period. Throughout Runs 1-3 and 5-7, it was assumed that if contaminants were physically adsorbed to the compost medium, they would finally be degraded by the microorganisms. Thus, the maximum physical adsorption capacity in each of these periods was 0.032 mg VOCs/gm compost, and the total elimination capacity can be attributed to the biological elimination capacity during subsequent runs on the compost column.

Biofilm Appearance of Compost

Figures 19-21 show the electron micrographs of the biofilm's appearance in the compost. There were no significant differences among the raw compost, the compost from the top portion of the column and that from the bottom of the column.

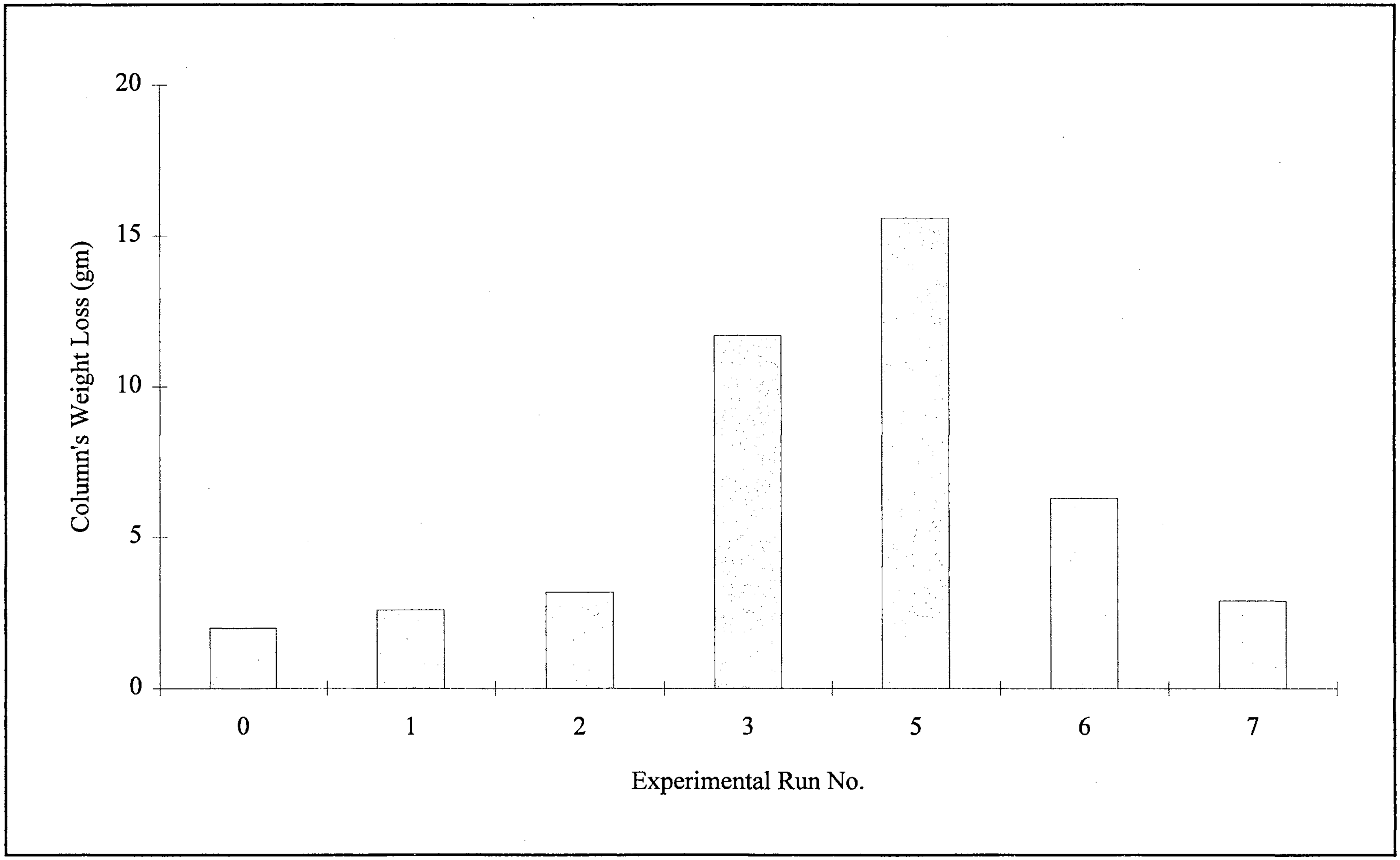

Figure 17. Compost Column's Weight Loss During Experiment

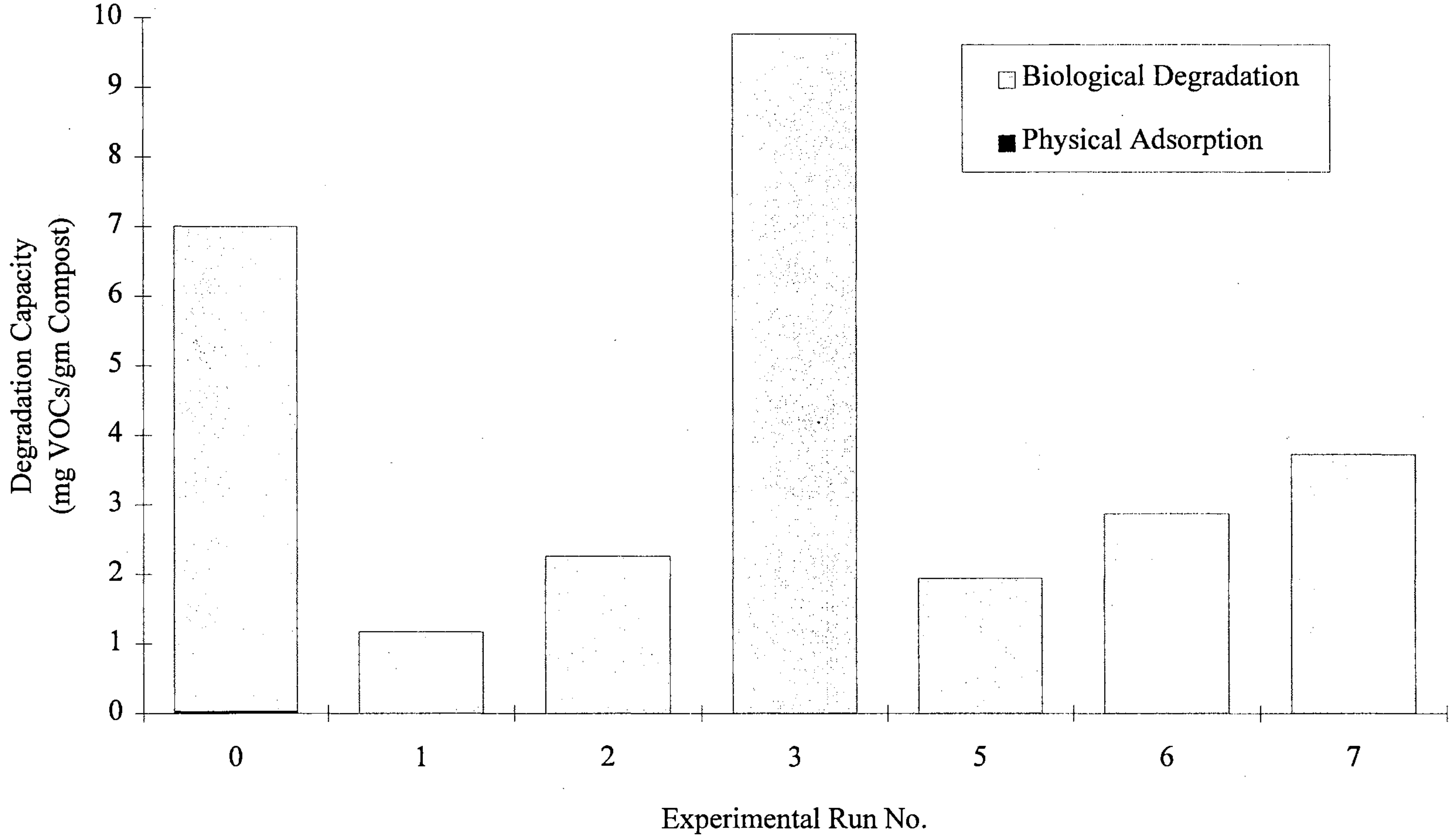

Figure 18. Separation of Physical Adsorption and Biological Degradation

Figure 19. Scanning Electron Micrograph of Compost (Raw Medium)

Figure 20. Scanning Electron Micrograph of Compost (Sample from Column's Top Portion)

Figure 21. Scanning Electron Micrograph of Compost (Sample from Column's Bottom Portion)

Diatomaceous Earth Column Study

Average Gas Influent and Effluent Concentrations

As with the compost column, during the period of the DE column study, the influent and effluent gas concentrations from the column were monitored daily, and the air samples taken from the other sampling ports were also measured on a daily basis. The order of the experimental runs was 1, 2, 3, 5, 6, 7, 4, and 8. The average gas influent and effluent concentrations are shown in Figure 22. In this portion of the study, the low influent concentration was controlled at approximately 1300 μg VOCs/L for Runs 1 to 4 and the high influent concentration was maintained at about 2200 μg VOCs/L for Runs 5 to 8. It was difficult to control the gas influent concentration at a constant value through each experimental period, mainly due to the variability of the air source pressure. This was similar to a problem encountered during the compost system experiments. The daily records of the influent and effluent gas concentrations throughout the experimental period for the DE system are presented in Appendix F. The average contaminant concentrations from the other sampling ports are provided in Appendix G.

Records of Column Temperature and Humidity

The temperature and humidity of the column were also measured on a daily basis. Figures 23 and 24 are the records of the average temperature and humidity of the column for each run. For the entire 97-day period, the temperatures and humidities of both the influent and effluent air were fairly close except those on day 62 (for temperature) and day 18 (for humidity). The average temperature of the column fell within a range of 50-72 °F,

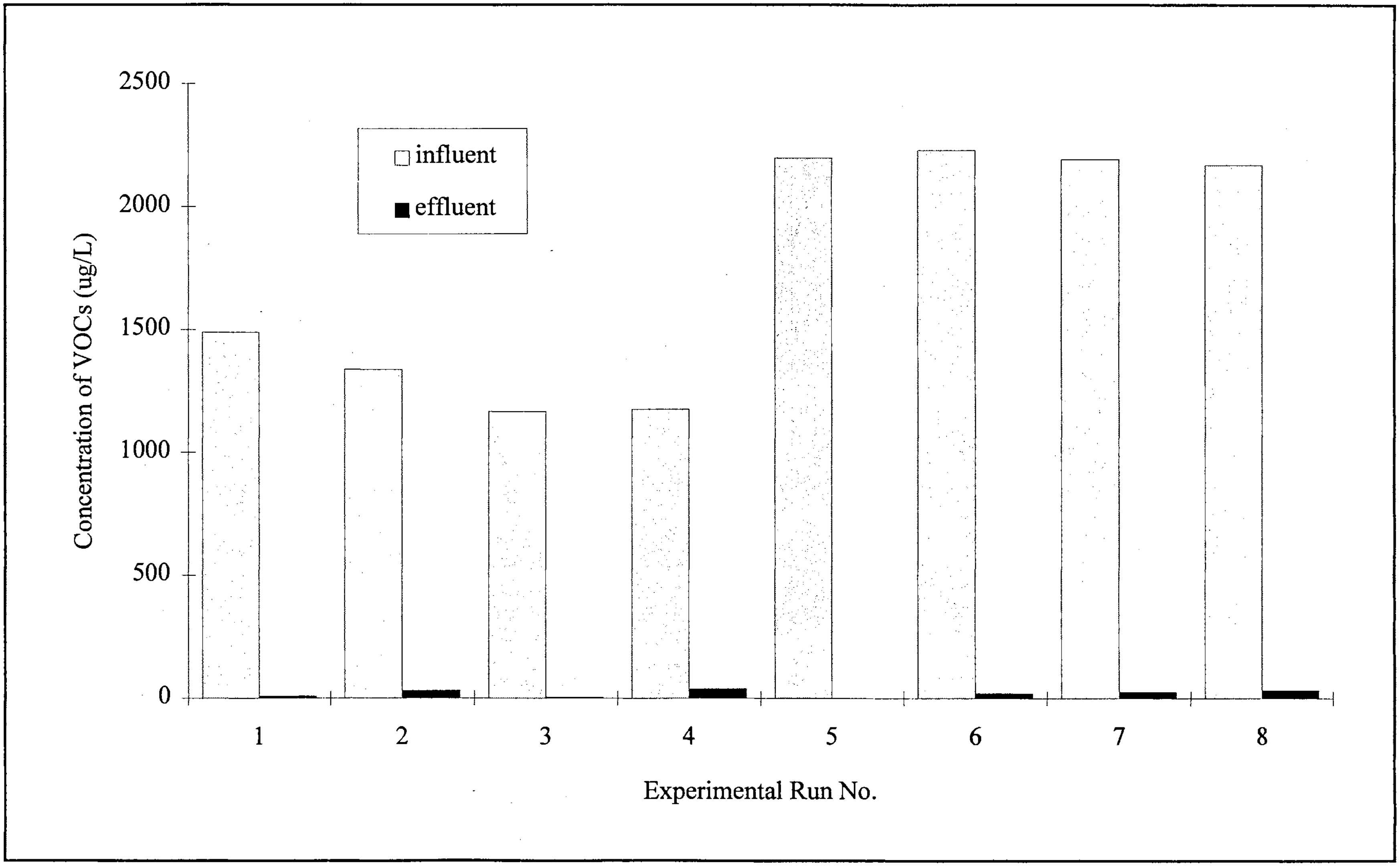

Figure 22. Average Gas Influent and Effluent Concentrations of Diatomaceous Earth Column

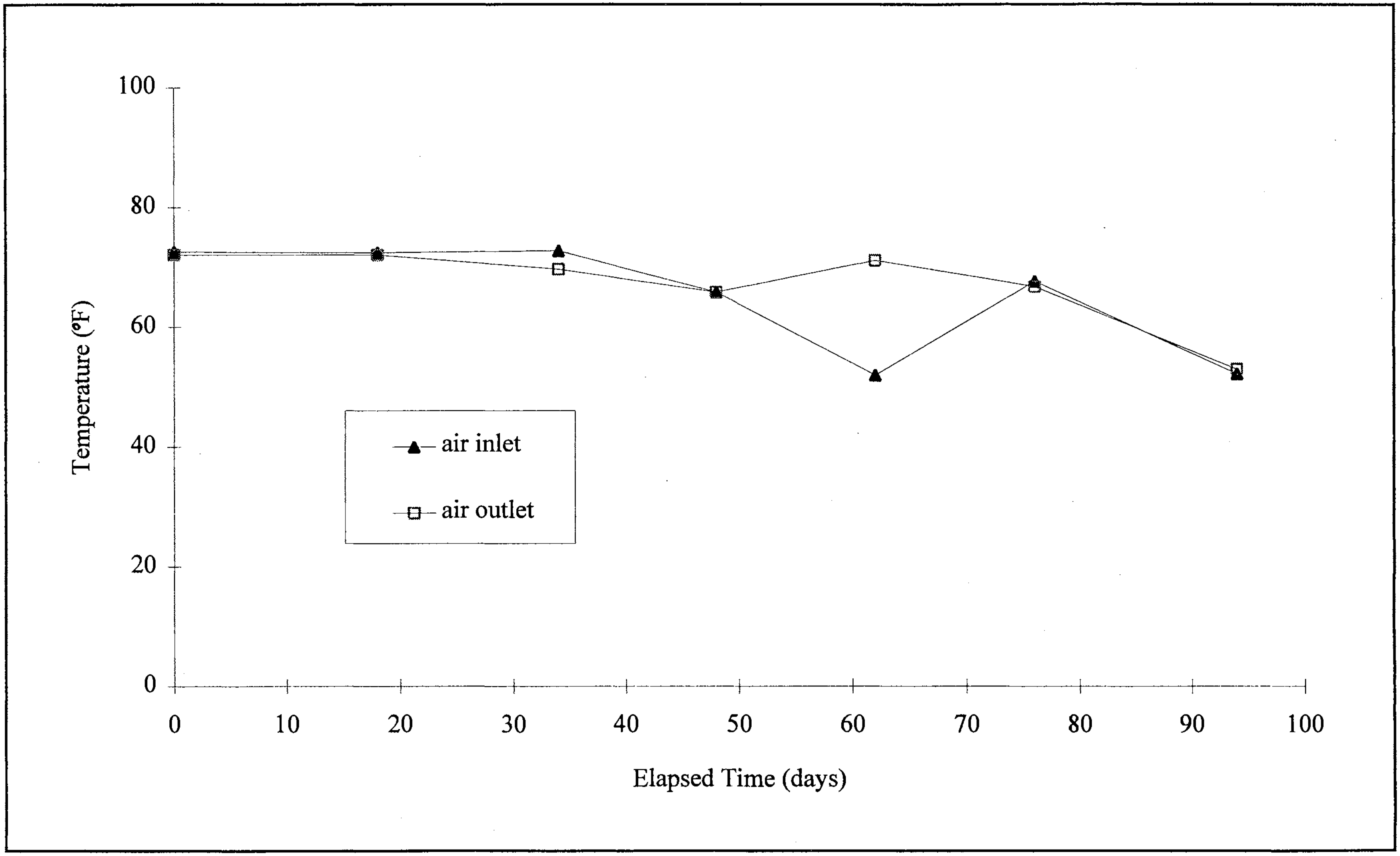

Figure 23. Record of the Diatomaceous Earth Column's Temperature

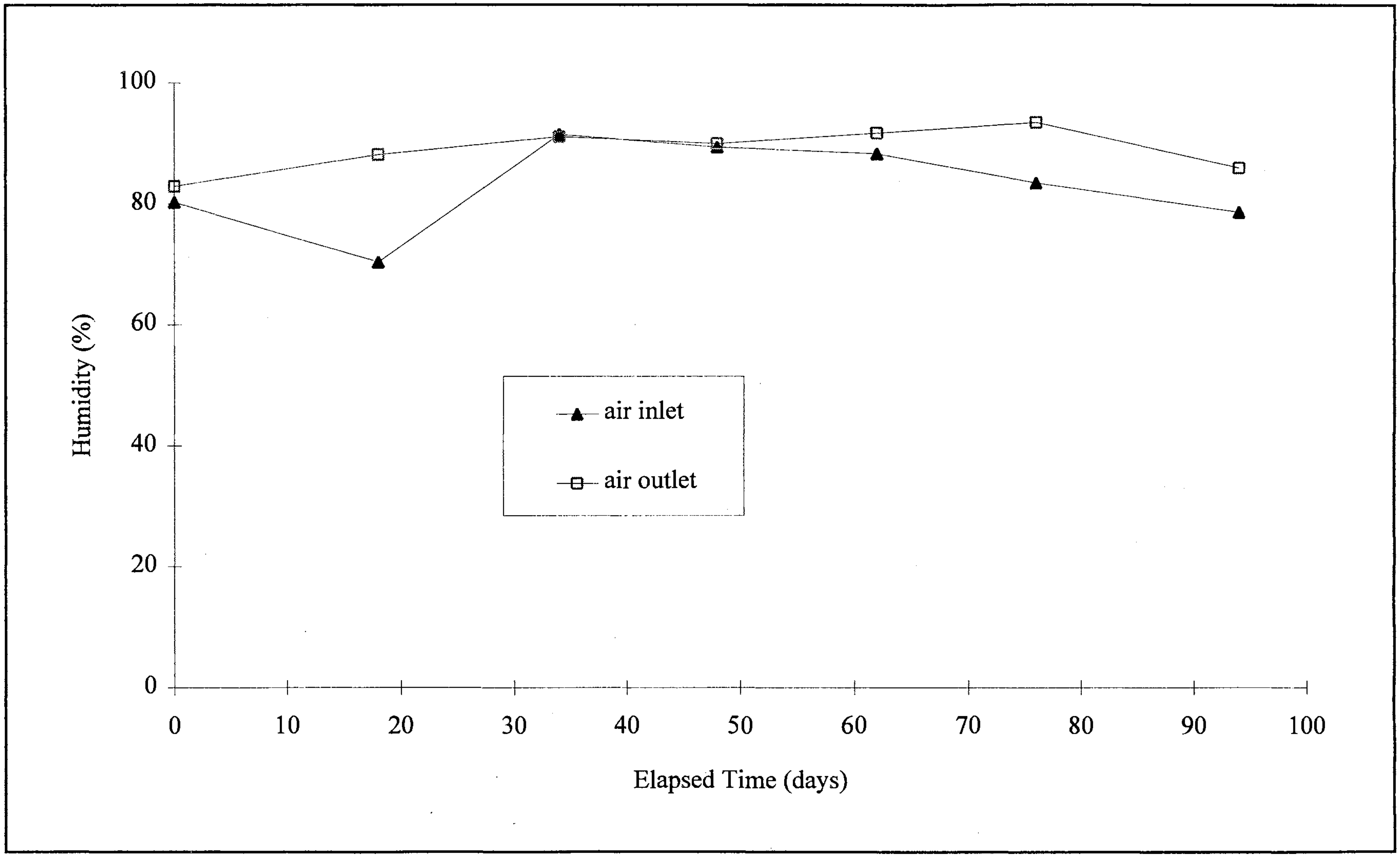

Figure 24. Record of the Diatomaceous Earth Column's Humidity

which is appropriate for the growth of bacteria. It was noted that the temperature was gradually decreased from 72 to 50 °F over time due to the seasonal effect on lab temperatures. The average humidity of the column was about 80%. In addition, since the DE column was run in a co-current, downflow mode, and because there was a water-seal in the bottom of the column for the nutrient recirculation, the values of the humidity in the air outlet (bottom part) were higher than those in the air inlet (top part) over the experimental period.

Effect of Applied Loading on Elimination Rate

The effect of applied organic loading on the elimination rate is shown in Figure 25. As the applied loadings varied from 0.20 to 1.29 mg VOCs/cm^3 DE·day at the low inlet concentration, the elimination rates were 0.20-1.25 mg VOCs/cm^3 DE·day. The elimination rates ranged 0.30-2.35 mg VOCs/cm^3 DE·day under the high inlet concentration when the applied loadings varied from 0.30 to 2.39 mg VOCs/cm^3 DE·day. At any fixed applied loading, there was very little difference in the elimination rates between the low inlet concentration and a high inlet concentration. It should be noted that the maximum elimination rate obtained in the DE column study was 2.35 mg VOCs/cm^3 DE·day at an applied loading of 2.39 mg VOCs/cm^3 DE·day. Vaughn et al. (1993) reported that an elimination rate of 1.73-2.72 mg p-xylene/cm^3 DE·day was achieved at an applied loading of 2.37-3.09 mg p-xylene/cm^3 DE·day.

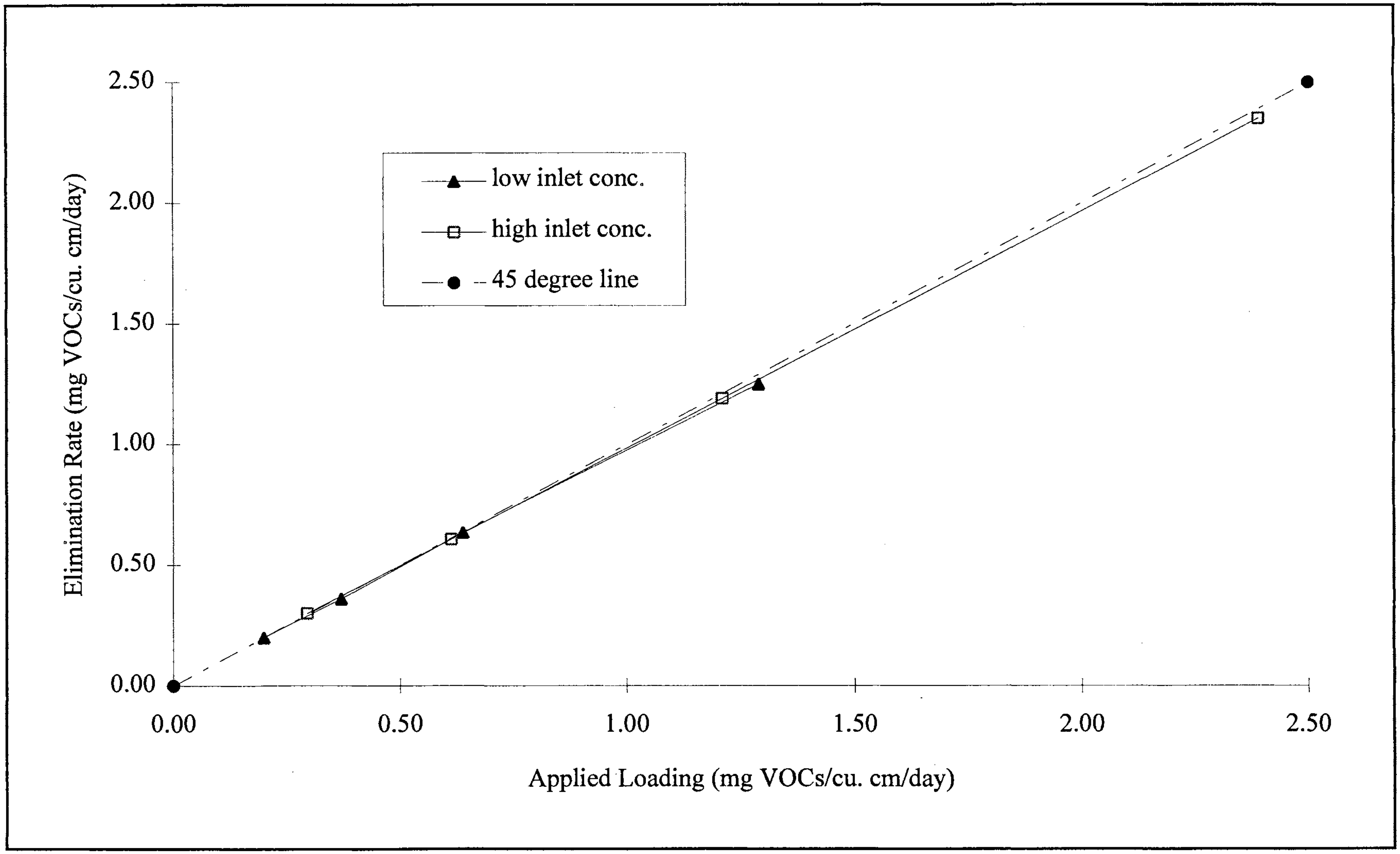

Figure 25. Applied Loading versus Elimination Rate in Diatomaceous Earth Column

Effect of Applied Loading on Elimination Efficiency

Figure 26 shows that for the applied organic loadings of 0.20-1.29 mg VOCs/cm^3 DE·day, the elimination efficiencies of the VOCs varied from 99.6 to 96.7% while operating with the low inlet feed concentration. As the applied loadings increased to 0.30-2.39 mg VOCs/cm^3 DE·day (high inlet concentration), the elimination efficiencies ranged from 100 to 98.6%. As can seen in Figure 25, all of the error bars are very small, and the values of elimination efficiency, no matter if at low or high inlet concentration, are the same statistically. An elimination efficiency of 73-88% for p-xylene was obtained at an applied loading of 2.37-3.09 mg p-xylene/cm^3 DE·day (Vaughn et al., 1993).

Comparison of Average Elimination Efficiencies of Three BTEX Compounds

There are no significant differences in the average elimination efficiencies of the three BTEX compounds in the DE column (Figure 27). From Run 1 through Run 8, the elimination efficiencies of toluene were always 100%, and ethylbenzene had a relatively lower elimination efficiencies (88.2-100%), and the range of elimination efficiencies for o-xylene was 92.5-100%.

Effect of Residence Time on Elimination Efficiency

In Figure 28, it can be seen that with the residence times of 20, 10, 5 and 2.5 minutes, the resulting elimination efficiencies were 99.6, 97.8, 99.7, and 96.7% at the low inlet concentration and 100, 99.0, 99.0, and 98.6%, respectively, with the high inlet concentration. As seen in this figure, a greater than 95% elimination efficiency can still be

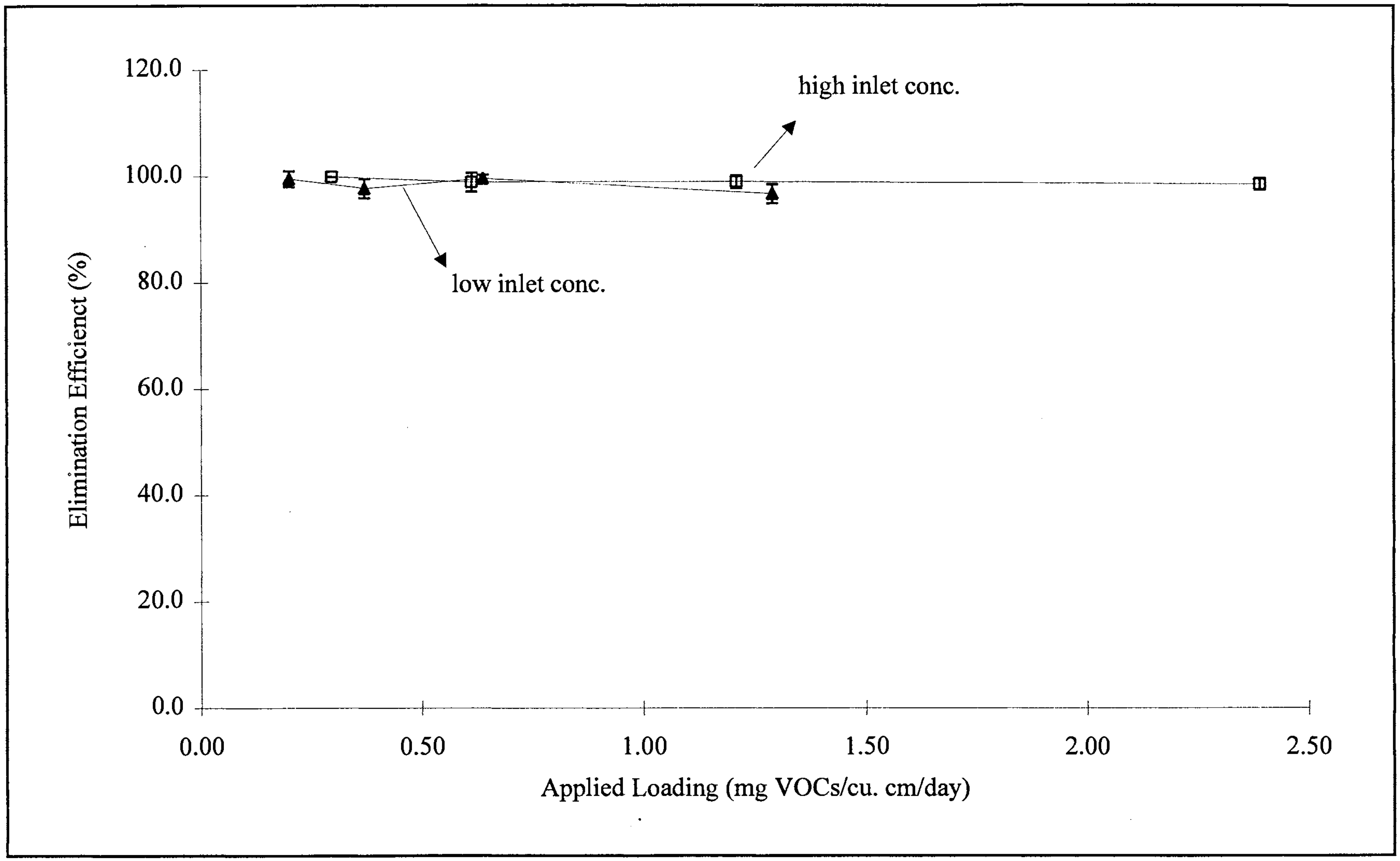

Figure 26. Applied Loading versus Elimination Efficiency in Diatomaceous Earth Column

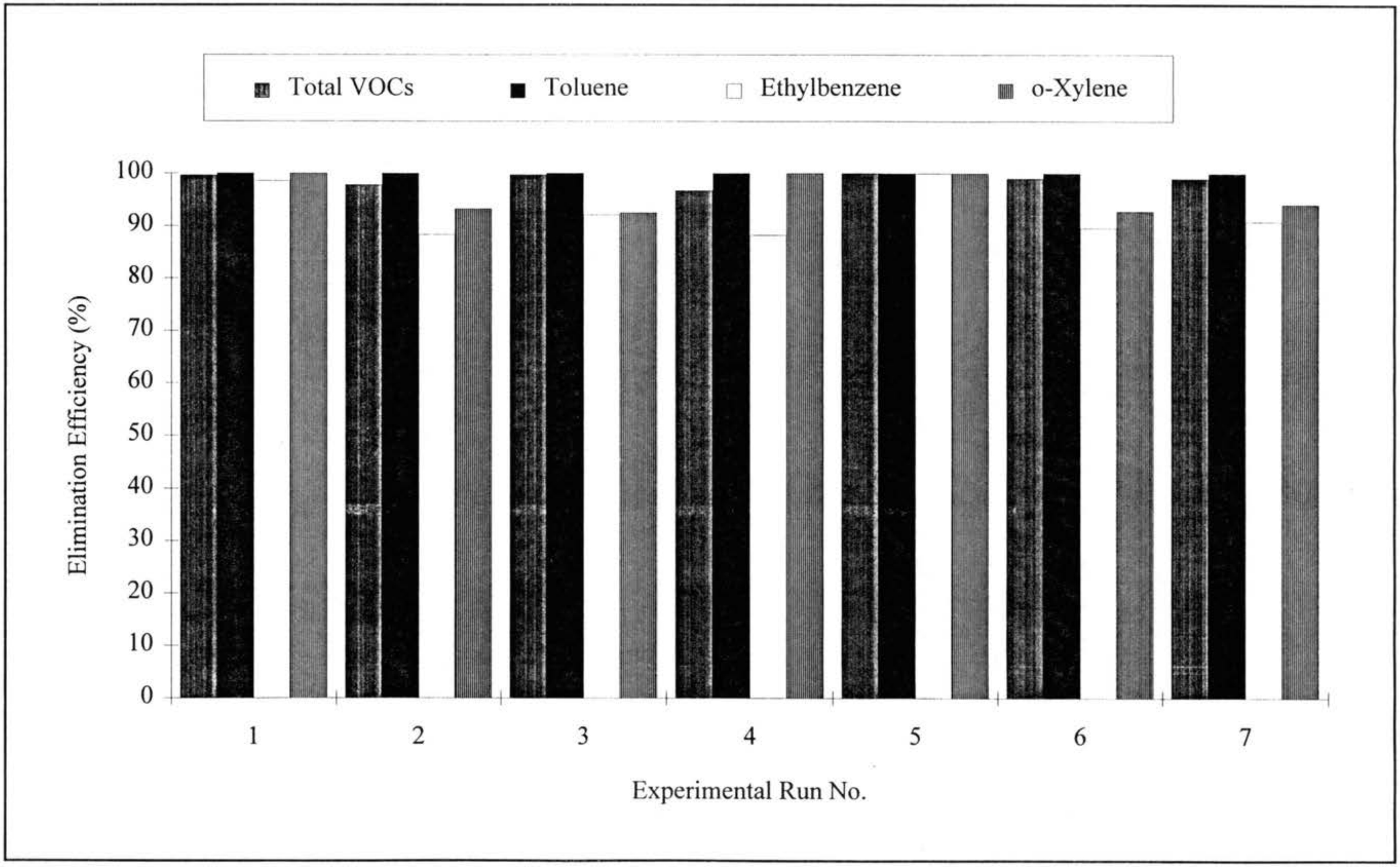

Figure 27. Comparison of Average Elimination Efficiencies of Three BTEX Compounds in Diatomaceous Earth Column

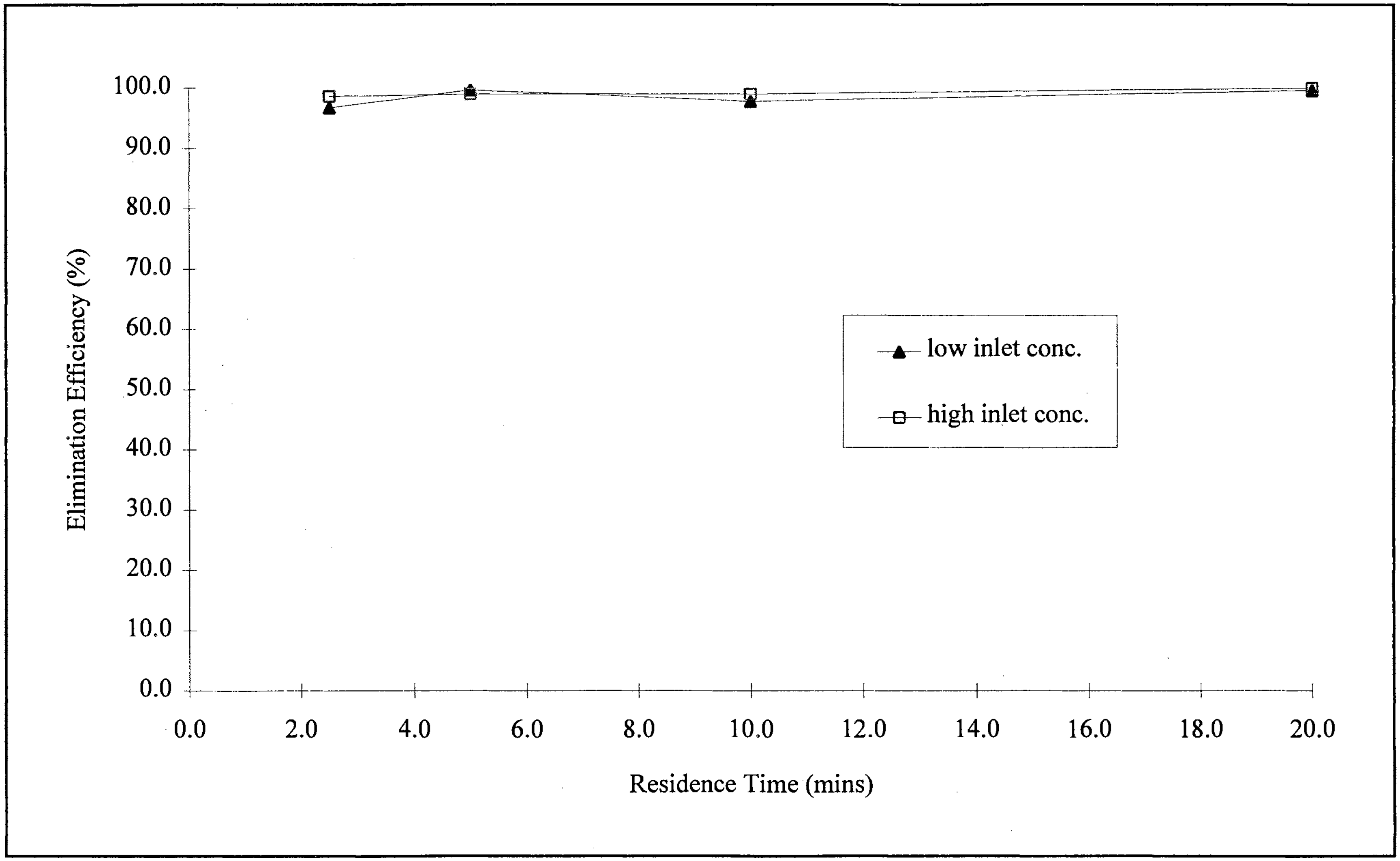

Figure 28. Residence Time versus Elimination Efficiency in Diatomaceous Earth Column

obtained at a fairly low residence time of 2.5 minutes. According to the data given by Vaughn et al. (1993), an elimination efficiency of 73-88% for p-xylene was obtained at a residence time of 1.7-2.5 minutes.

Effect of Air Flow Rate on Pressure Drop

The effect of air flow rate on the pressure drop across the column is presented in Figure 29. While holding the air flow rate at 25, 50 and 100 mL/min, the pressure drops were 0.02, 0.03 and 0.30 in. H_2O at the low inlet concentration, and 0.80, 4.5 and 3.0 in. H_2O at the high inlet concentration, respectively. However, the pressure drops in the compost column were 0.05, 0.09, and 0.11 in. H_2O at the high inlet concentration. This indicates that the DE medium has a higher pressure drop compared to the compost medium. Most of these values in Figure 29 indicated that the larger the air flow rate, the higher the pressure drop. On the other hand, a pressure drop across the column might also be increased over the elapsed time due to accumulation of the biomass on the medium.

Water Content of Diatomaceous Earth Column

The values of the average water content at the top and bottom of the column are shown in Figure 30. During the 94 day experimentation period, the differences in water content between the top and bottom of the column gradually increased since one of the end products of biodegradation is water. The values from the top samples were higher that those from the bottom samples. This was because the DE column was operated in a co-current mode, where the nutrients solution was introduced onto the top of the column. In addition, the recycle solution provided a better environment (more water content in the

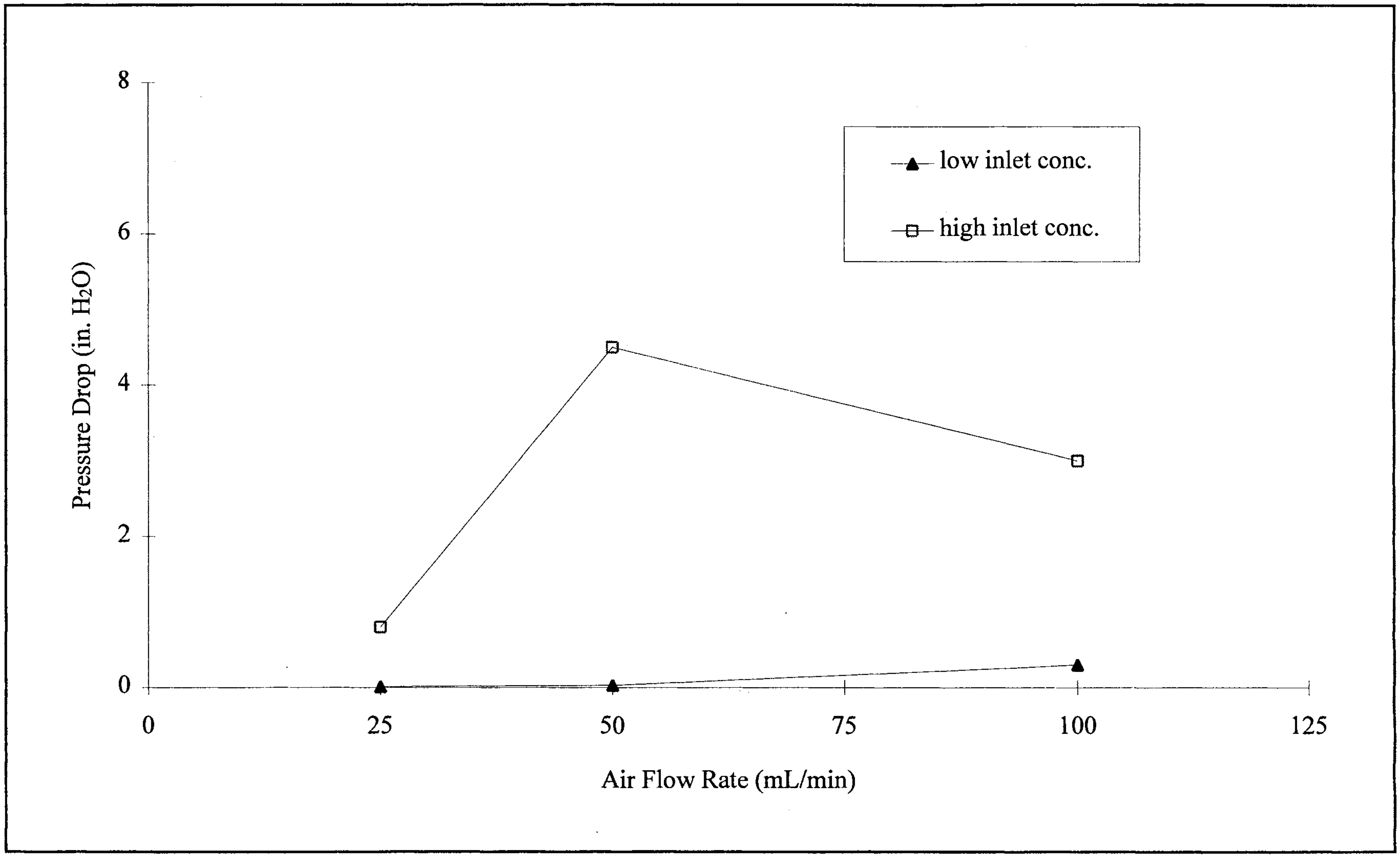

Figure 29. Air Flow Rate versus Pressure Drop in Diatomaceous Earth Column

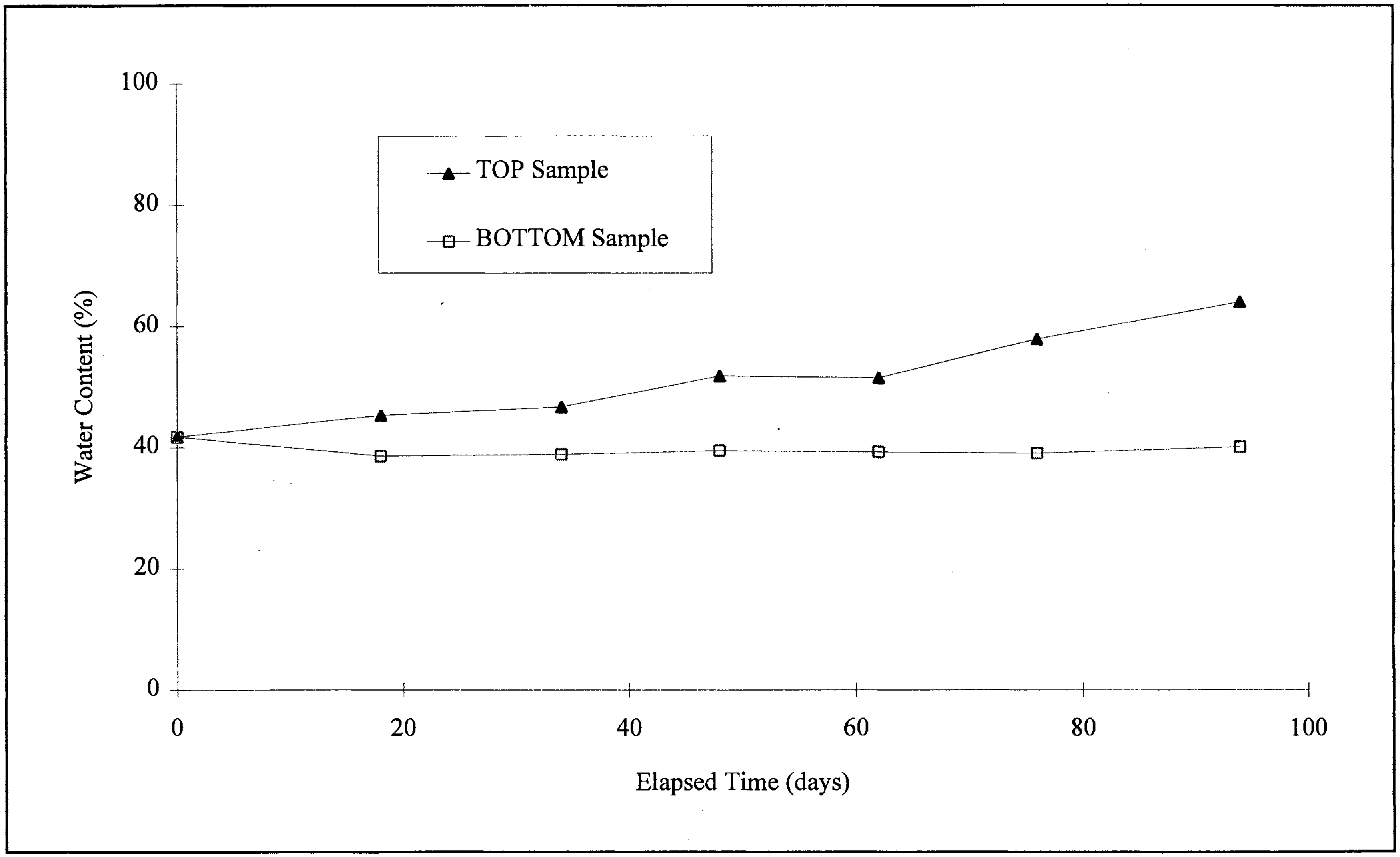

Figure 30. Water Content of Diatomaceous Earth Column

bottom portion of the DE column than that in the compost column) for the transport of the contaminants. This may be one of the causes that the DE column had a higher elimination efficiency than that of the compost column.

Biomass on Diatomaceous Earth

The values of the biomass (as VS) on the DE medium are provided in Figure 31. Throughout the experimental period of 96 days, there was only a small increase in biomass in the bottom portion of the column; however a general trend of increasing biomass in the top portion of the column was observed. The primary reason was that the bacteria in the top portion of the column were able to get more substrates and inorganic nutrients than those in the bottom portion of the column due to the downflow and co-current flow mode of operation. Therefore the majority of the biofilm formed in the top of the column.

Kjeldahl Nitrogen Content of Diatomaceous Earth

The kjeldahl nitrogen content of the DE medium is plotted in Figure 32. There was a significant increase of the kjeldahl nitrogen content in the top portion of the column during the first 18 days, and after that, the kjeldahl nitrogen content gradually decreased with elapsed time. Like the biomass content, there was a little increase in kjeldahl nitrogen in the bottom portion of the column during the whole 96 day period.

Column Weight Gain During Experiment

The column weight gain, using the DE medium, is shown in Figure 33. After each experimental run, the column was weighed using a balance. The column weight gain was

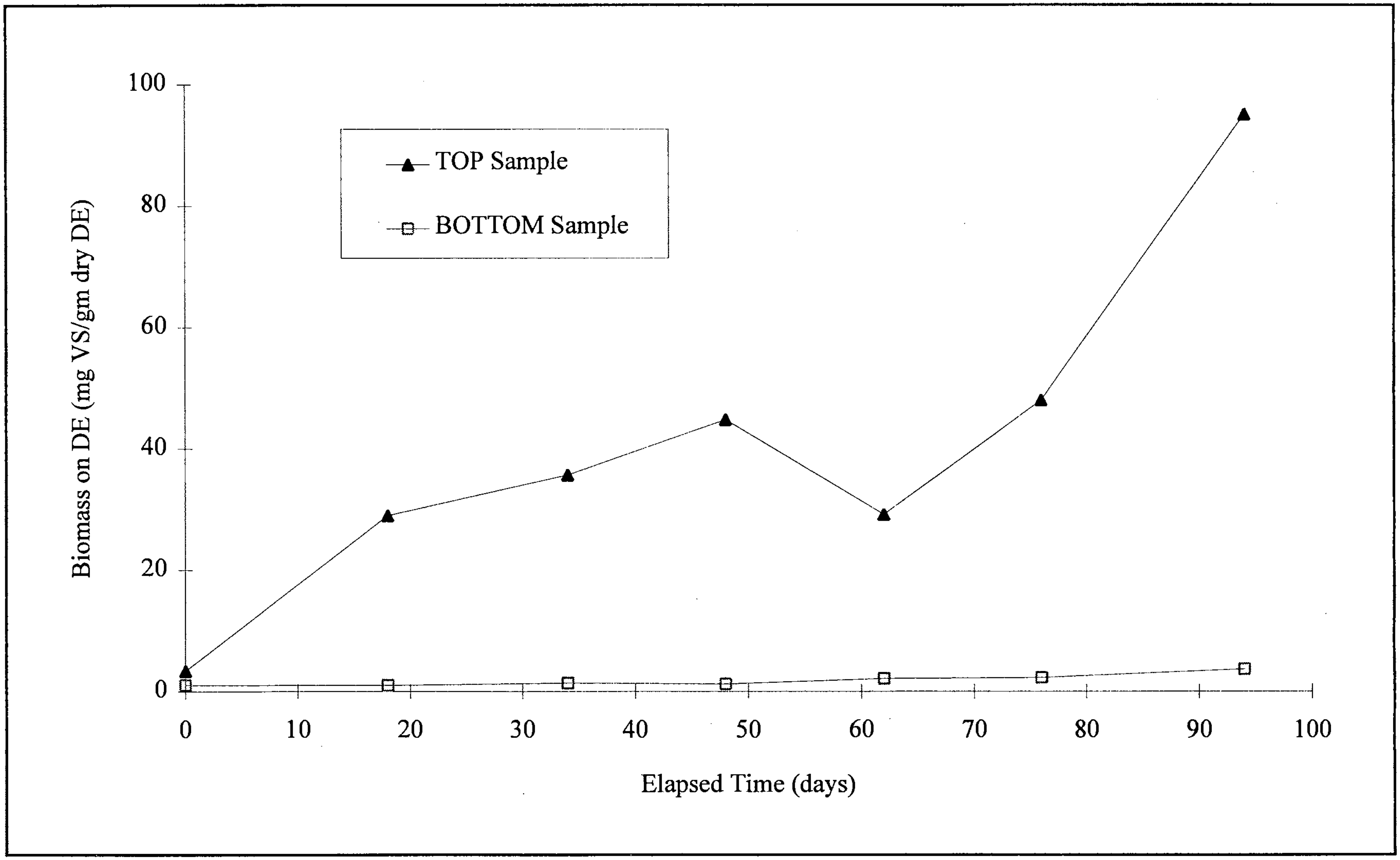

Figure 31. Biomass on Diatomaceous Earth

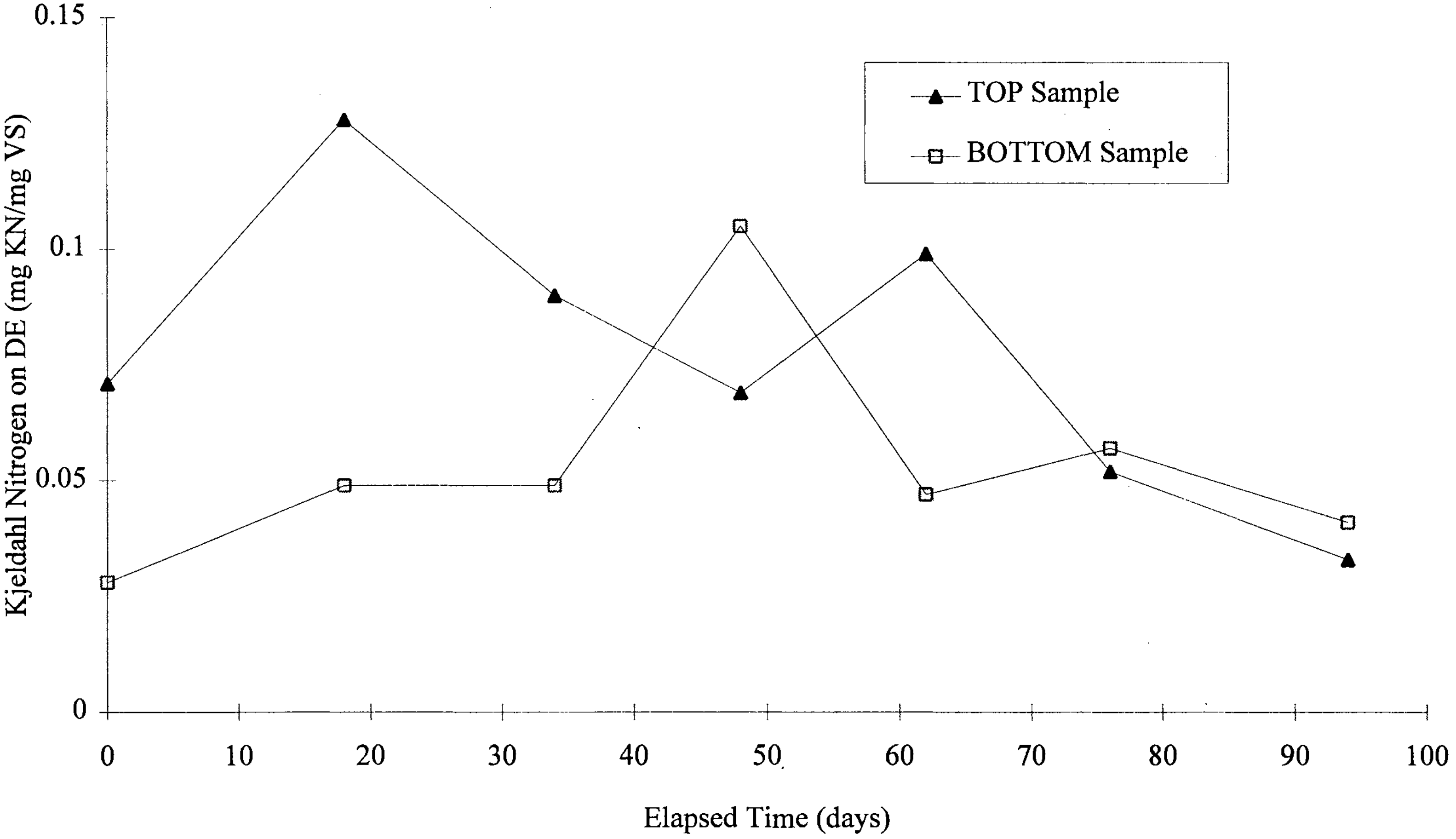

Figure 32. Kjeldahl Nitrogen Content of Diatomaceous Earth

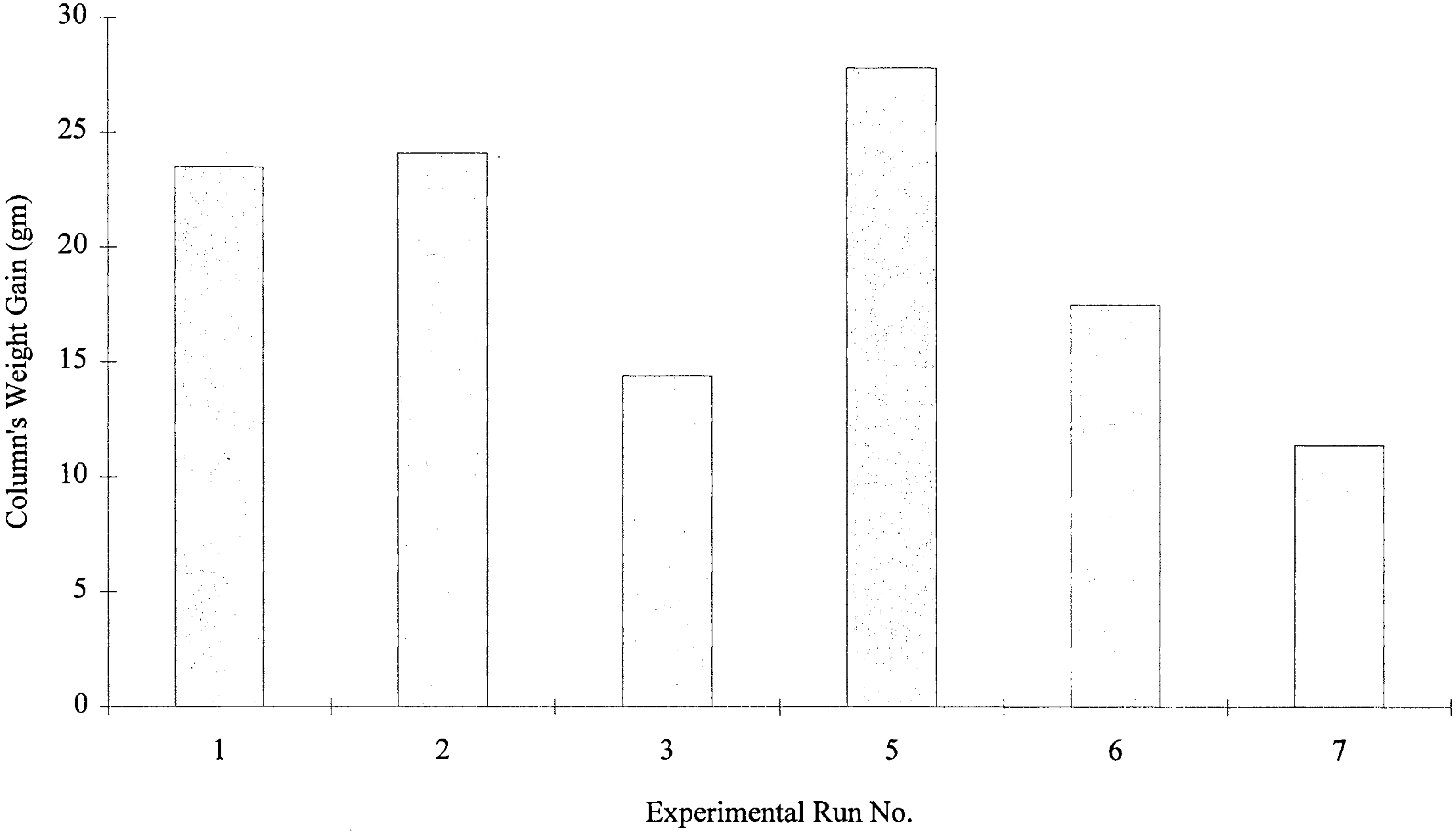

Figure 33. Diatomaceous Earth Column's Weight Gain During Experiment

assumed to be caused by a biomass gain on the DE medium. A large weight gain was measured following Runs 1, 2 and 5, however, a relatively small weight gain from Runs 3, 6 and 7 was recorded.

Average Consumption Rates of Nitrogen and Phosphorus

Figure 34 presents the average consumption rate of nutrients (nitrogen and phosphorus) in the recirculation solution. During the entire 96 day experiment, there was a higher average consumption rate of total inorganic nitrogen than that of total inorganic phosphorus. This revealed that more inorganic nitrogen was required than inorganic phosphorus in the degradation process.

Replacement of Nutrient Solution

The nutrient solution to the DE column was replaced in a weekly basis. None of these three BTEX compounds was measured in the used nutrient solution. In addition, no major increases in the removal of total VOCs were seen on the day after replacing the nutrient solution.

Biofilm Appearance of Diatomaceous Earth

Figures 35-37 show the SEM photographs of biofilm's appearance on the diatomaceous earth. There was more biofilm on the sample from the top portion of the column than that on the sample from the bottom portion of the column. There was no significant different between the raw DE medium and the sample from the bottom of the column.

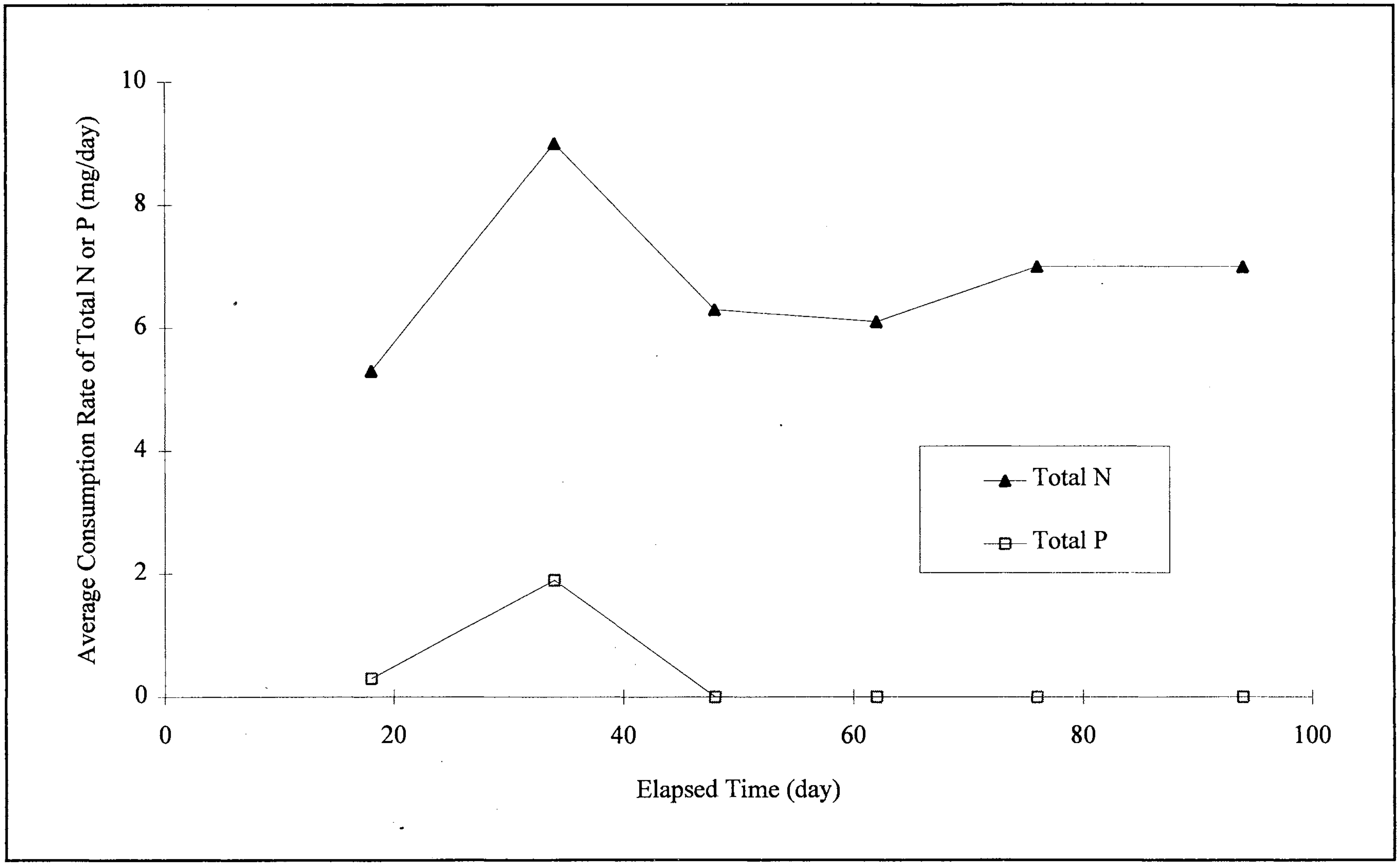

Figure 34 Average Consumption Rate of Nutrients in Diatomaceous Earth Column

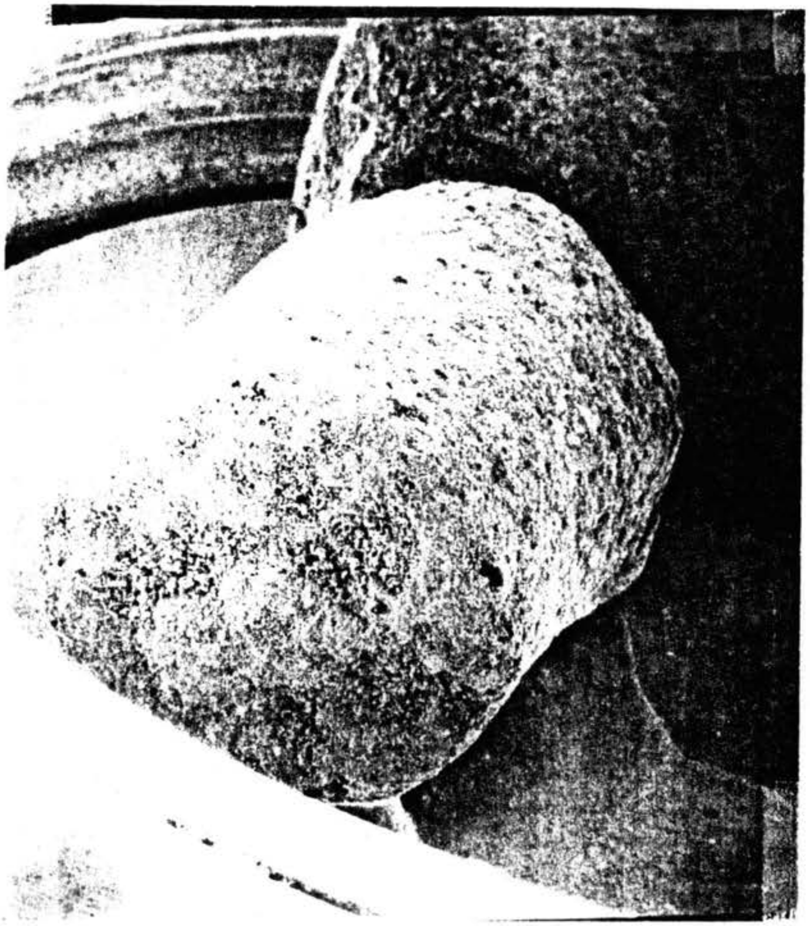

Figure 35. Scanning Electron Micrograph of Diatomaceous Earth (Raw Medium)

Figure 36. Scanning Electron Micrograph of Diatomaceous Earth (Sample from Column's Top Portion)

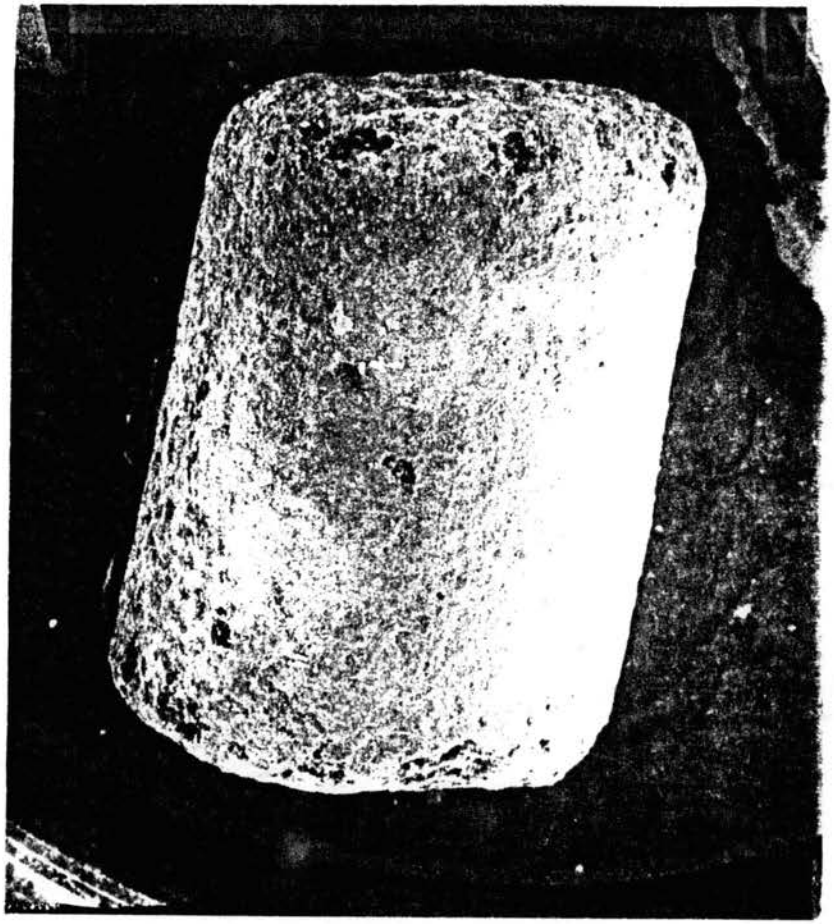

Figure 37. Scanning Electron Micrograph of Diatomaceous Earth (Sample from Column's Bottom Portion)

Tracer Study

Dispersion Coefficient of the Compost Column

As shown in Figure 38, when the air flow rate were 25, 50 and 100 mL/min, the maximum concentration of methane at the outlet was detected at the 14, 10, and 7 minutes, respectively. The raw data are presented in Appendix H. Based on these curves, the dispersion coefficients of the compost column, shown in Table 7, can be determined. The detailed calculation procedure is listed in Appendix J.

Dispersion Coefficient of the Diatomaceous Earth Column

From Figure 39, it can been seen that when the air flow rates were 25, 50 and 100 mL/min, the maximum concentration of methane at the outlet was detected at 9, 7, and 5 minutes, respectively. The raw data are listed in Appendix I. Similar to the compost system, the dispersion coefficients (Table 8) of the DE column can be obtained following the detailed calculation procedure shown in Appendix J.

Recovery Efficiency of Tracer

To determine the recovery efficiencies of the tracer (methane) in the tracer studies, mass balances were performed. The results of the mass balances are listed in Table 9. The average recovery efficiencies of methane for the compost and DE columns are 61.0% and 40.2%, respectively. This reveals that methane is not a completely inert tracer. This may call into question the absolute values of the dispersion coefficients calculated in this work. Thus, in order to obtain a more accurate value of dispersion coefficient, further effort with a completely inert tracer (i.e. argon) is necessary.

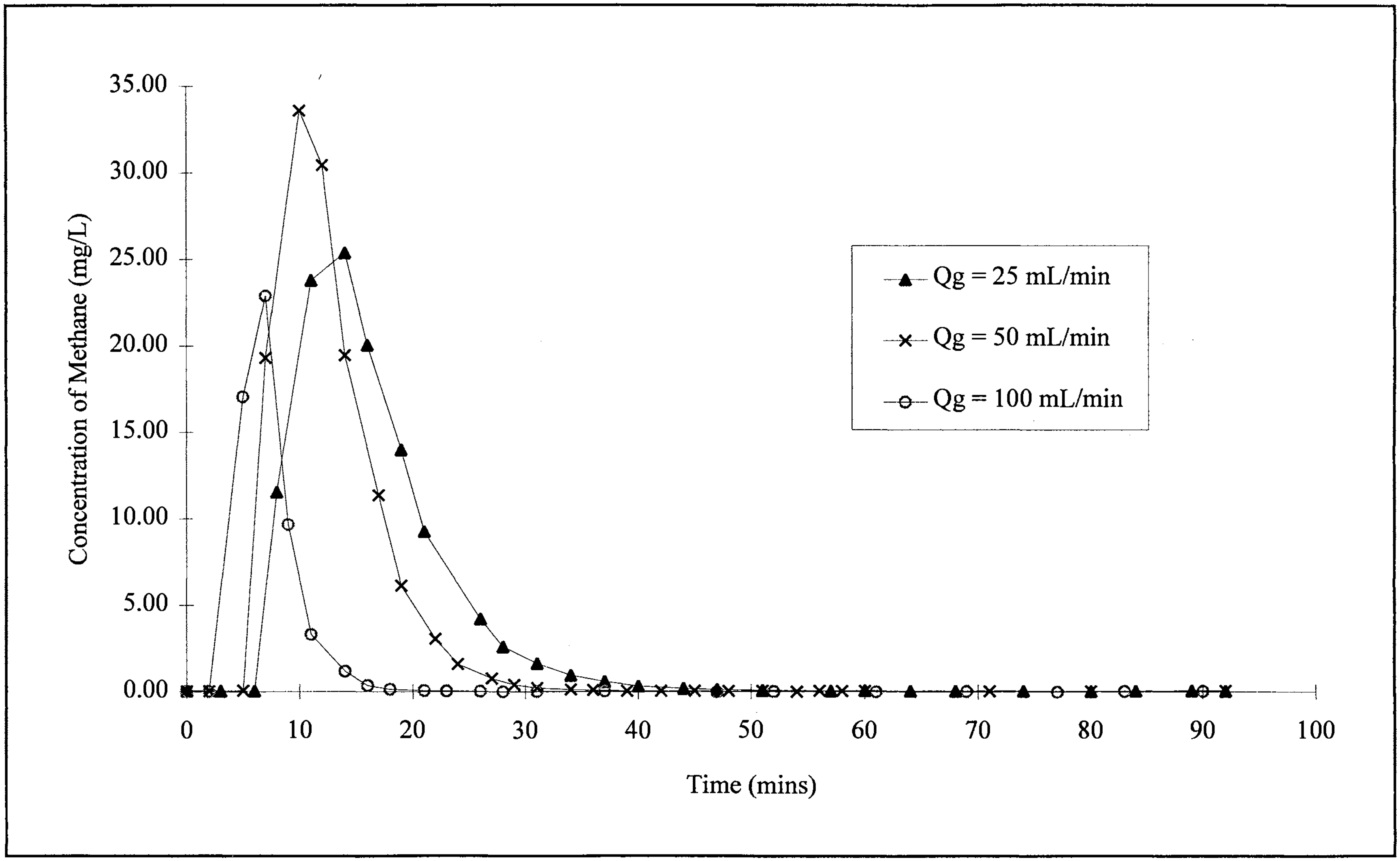

Figure 38. Tracer Study for Compost Column

Table 7. Dispersion Coefficient of the Compost Column

Air Flow Rate (mL/min)	Residence Time (mins)	Dispersion Coefficient (cm^2/sec)
25	20	1.47
50	10	2.08
100	5	7.37

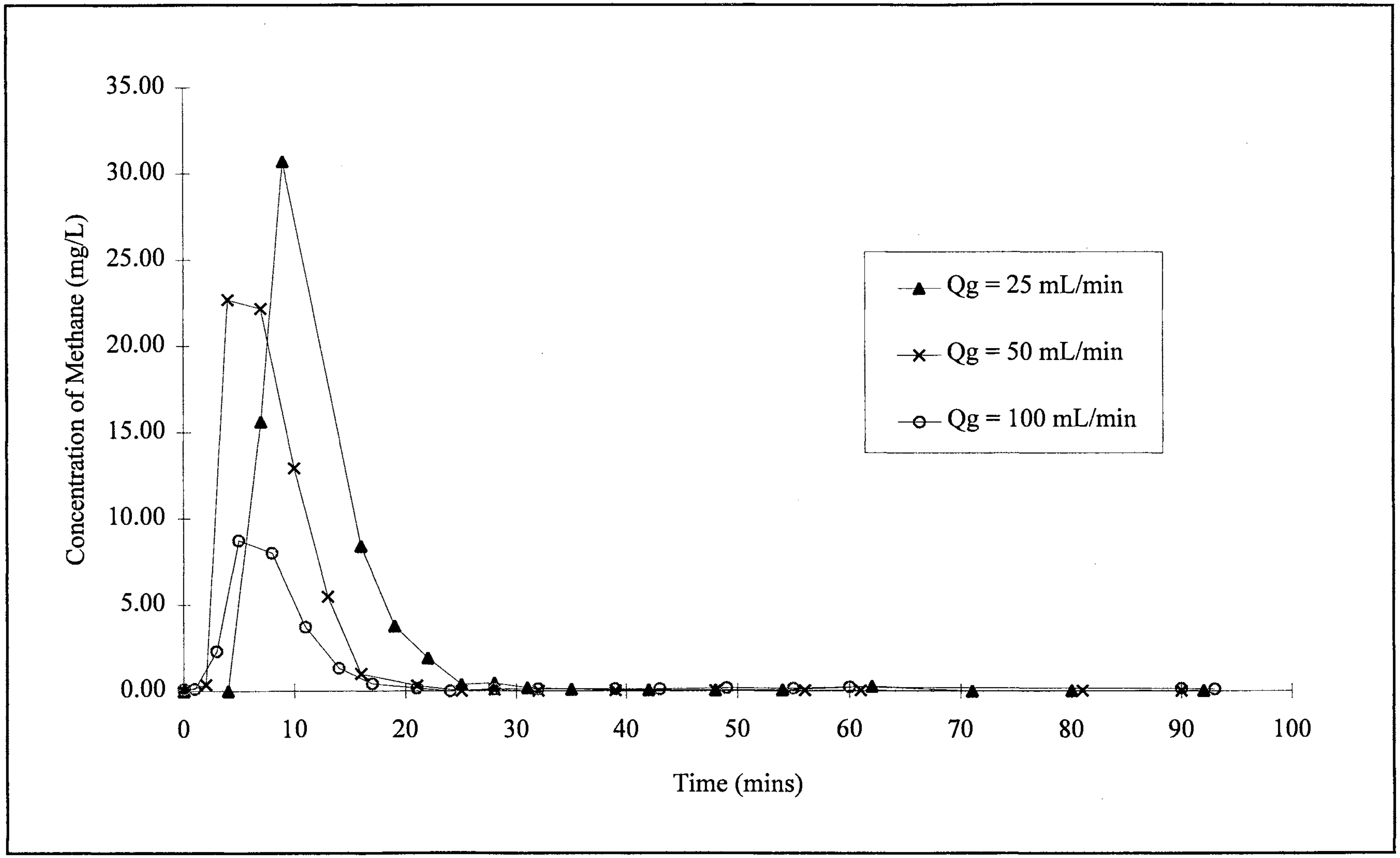

Figure 39. Tracer Study for Diatomaceous Earth Column

Table 8. Dispersion Coefficient of the DE Column

Air Flow Rate (mL/min)	Residence Time (mins)	Dispersion Coefficient (cm^2/sec)
25	20	3.85
50	10	7.22
100	5	10.92

Table 9. Recovery Efficiency of Tracer

Biofilter:	Compost			DE		
Air Flow Rate: (mL/min)	25	50	100	25	50	100
Input (mg CH_4)	19.31	19.31	19.31	19.31	19.31	19.31
Output (mg CH_4)	7.94	15.21	12.17	6.10	9.33	7.87
Recovery (%)	41.1	78.8	63.0	31.6	48.3	40.8

Modeling

Development of Models

To develop a model to simulate the transport and fate of the selected BTEX compounds in a biofiltration system, the following assumptions were made:

- Flow of the waste stream is one-dimensional and steady-state;
- The porous medium in each biofilter is homogeneous, saturated and isotropic;
- There is no interaction among the three selected BTEX compounds, and;
- There is no contaminant in the water effluent in a diatomaceous earth biofilter.

Figure 40 represents the distribution of the total concentration of VOCs in a biofilter as part of a mass balance. A conservation of mass statement for an elemental volume is:

$$\begin{bmatrix}\text{mass accumulation}\\ \text{rate in a segment}\end{bmatrix} = \begin{bmatrix}\text{mass gain rate due to flux}\\ \text{coming in to a segment}\end{bmatrix} - \begin{bmatrix}\text{mass loss rate due to}\\ \text{flux leaving a segment}\end{bmatrix}$$
$$- \begin{bmatrix}\text{mass loss rate due to}\\ \text{adsorption in a segment}\end{bmatrix} - \begin{bmatrix}\text{mass loss rate due to}\\ \text{biodecay in a segment}\end{bmatrix}$$

The above statement can also be expressed as:

$$R_a = R_{in} - R_{out} - R_{ads} - R_{bio} \tag{1}$$

where,

R_a = mass accumulation rate of total VOCs in a segment, $[\mathrm{M\ T^{-1}}]$

$$R_a = \varepsilon S \Delta z \frac{\partial C}{\partial t} \tag{2}$$

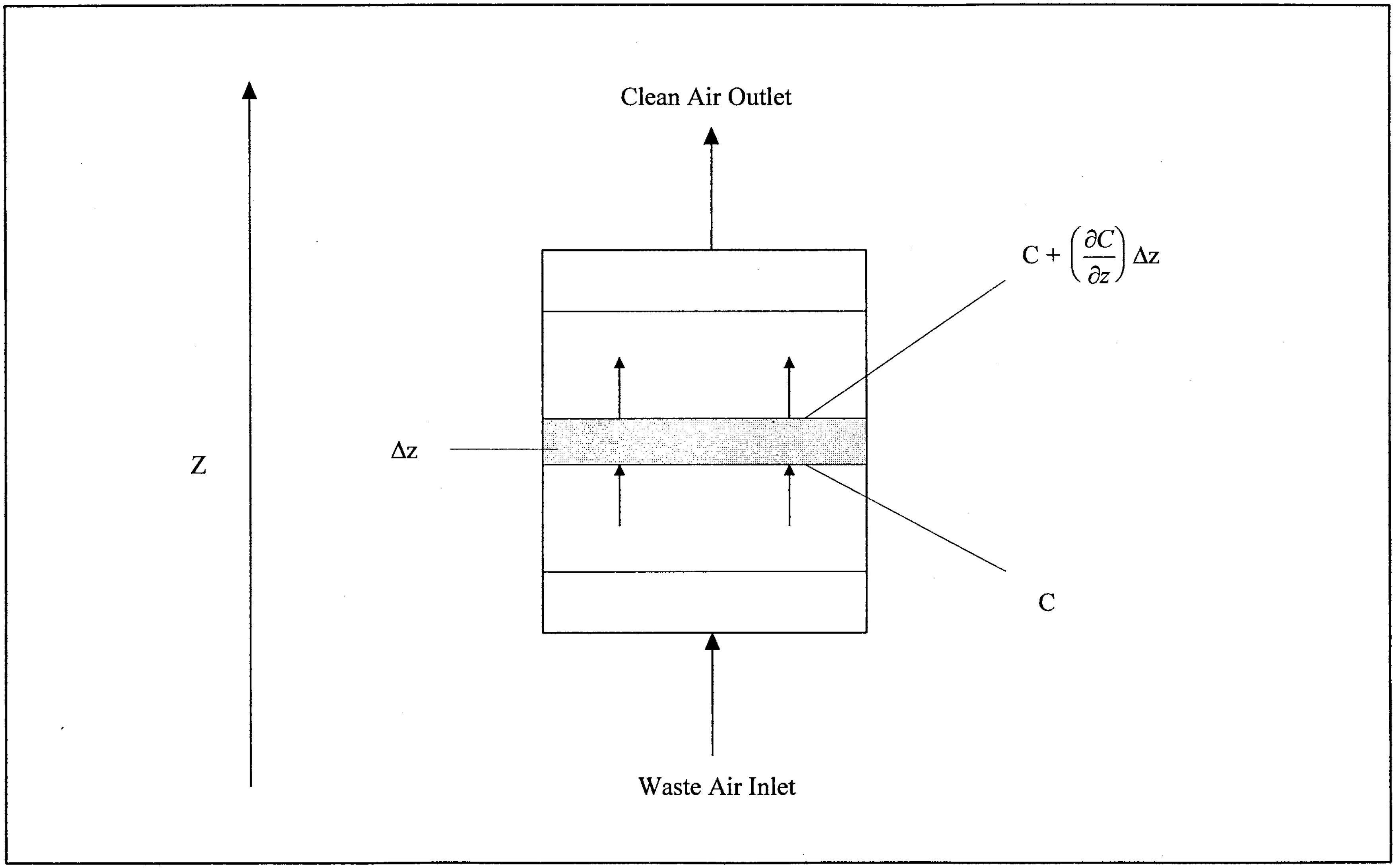

Figure 40. Distribution of Total VOCs in a Biofilter for Mass Balance

ε = porosity of the filter material, dimensionless

S = cross-sectional area of the column, $[L^2]$

z = distance in the air flow direction, [L]

C = total gas-phase concentration of VOCs, $[M\ L^{-3}]$

t = time, [T]

R_{in} = mass gain rate of total VOCs due to the flux coming to a segment, $[M\ T^{-1}]$

$$R_{in} = \varepsilon SUC - \varepsilon SD\frac{\partial C}{\partial t} \tag{3}$$

U = interstitial gas velocity, $[L\ T^{-1}]$

D = dispersion coefficient for total VOCs, $[L^2\ T^{-1}]$

R_{out} = mass loss rate of total VOCs due to the flux leaving a segment, $[M\ T^{-1}]$

$$R_{out} = \varepsilon SU\left(C + \Delta z\frac{\partial C}{\partial z}\right) - \varepsilon SD\frac{\partial\left(C + \Delta z\frac{\partial C}{\partial z}\right)}{\partial z}$$

$$= \varepsilon SU\left(C + \Delta z\frac{\partial C}{\partial z}\right) - \varepsilon SD\left(\frac{\partial C}{\partial z} + \Delta z\frac{\partial^2 C}{\partial z^2}\right) \tag{4}$$

R_{ads} = mass loss rate of total VOCs due to the adsorption in a segment, $[M\ T^{-1}]$

$$R_{ads} = (1-\varepsilon)S\Delta z\left(\frac{\partial C_s}{\partial t}\right)_{ads} \tag{5}$$

C_s = total solid-phase concentration of VOCs, $[M\ L^{-3}]$; $C_s = \rho_b q$

The adsorption term, $\left(\frac{\partial C_s}{\partial t}\right)_{ads}$, has the following three expressions:

$$\left(\frac{\partial C_s}{\partial t}\right)_{ads} = \left(\frac{\partial(\rho_b q)}{\partial C}\right)\left(\frac{\partial C}{\partial t}\right) = \rho_b K_d\left(\frac{\partial C}{\partial t}\right) \tag{5a}$$

or $$\left(\frac{\partial C_s}{\partial t}\right)_{ads} = \left(\frac{\partial(\rho_b q)}{\partial C}\right)\left(\frac{\partial C}{\partial t}\right) = \rho_b\left(\frac{1}{n}KC^{\left(\frac{1}{n}-1\right)}\right)\left(\frac{\partial C}{\partial t}\right) \tag{5b}$$

or $$\left(\frac{\partial C_s}{\partial t}\right)_{ads} = \left(\frac{\partial(\rho_b q)}{\partial C}\right)\left(\frac{\partial C}{\partial t}\right) = \rho_b\left(\frac{Q_o b}{(1+bC)^2}\right)\left(\frac{\partial C}{\partial t}\right) \tag{5c}$$

ρ_b = bulk density of the filter material, [M L^{-3}]

q = total solid-phase concentration of VOCs, dimensionless

K_d = linear adsorption coefficient

n, K = Freundlich adsorption coefficients

Q_o, b = Langmuir adsorption coefficients

A preliminary isotherm study showed that the Langmuir adsorption kinetics was the best for the compost medium.

R_{bio} = mass loss rate of total VOCs due to the biodecay in a segment, [M T^{-1}]

$$R_{bio} = (1-\varepsilon)S\Delta z\left(\frac{\partial C_s}{\partial t}\right)_{bio} \tag{6}$$

The biodecay term, $\left(\frac{\partial C_s}{\partial t}\right)_{bio}$, has the following three expressions:

$$\left(\frac{\partial C_s}{\partial t}\right)_{bio} = k_o \qquad \text{(Zero-order Model)} \tag{6a}$$

or $$\left(\frac{\partial C_s}{\partial t}\right)_{bio} = k_1 C_s \qquad \text{(First-order Model)} \tag{6b}$$

or $$\left(\frac{\partial C_s}{\partial t}\right)_{bio} = \frac{k_m C_s}{K_s + C_s} \qquad \text{(Monod Model)} \tag{6c}$$

k_o = zero-order reaction rate constant

k_1 = first-order reaction rate constant

k_m, K_s = Monod rate constants

Substituting Eqs. (2)-(6) into Eq. (1), and rearranging:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - U\frac{\partial C}{\partial z} - \left(\frac{1-\varepsilon}{\varepsilon}\right)\left[\left(\frac{\partial C_s}{\partial t}\right)_{ads} + \left(\frac{\partial C_s}{\partial t}\right)_{bio}\right] \tag{7}$$

At steady-state, $\frac{\partial C}{\partial t} = 0$ and $\left(\frac{\partial C_s}{\partial t}\right)_{ads} = 0$, so Eq. (7) becomes:

$$D\frac{\partial^2 C}{\partial z^2} - U\frac{\partial C}{\partial z} - \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{\partial C_s}{\partial t}\right)_{bio} = 0 \tag{8}$$

As mentioned above, the biodecay term, $\left(\frac{\partial C_s}{\partial t}\right)_{bio}$, has three possible expressions, and for each case, the dispersion coefficient, D, may be considered or ignored. Therefore, for Eq. (8), the following three cases are further developed:

(1) When the biodecay term follows the zero-order kinetics, Eq. (8) becomes:

$$D\frac{\partial^2 C}{\partial z^2} - U\frac{\partial C}{\partial z} - \left(\frac{1-\varepsilon}{\varepsilon}\right)k_O = 0 \tag{9}$$

- If D = 0, then

$$\frac{\partial C}{\partial z} = -\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_o}{U}\right) \tag{10}$$

$$C = C_o - \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_o}{U}\right)z \tag{11}$$

where,

C_o = total influent gas-phase concentration of VOCs, $[M\ L^{-3}]$

- If $D \neq 0$, then

$$\frac{\partial^2 C}{\partial z^2} - \left(\frac{U}{D}\right)\frac{\partial C}{\partial z} - \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_o}{D}\right) = 0 \tag{12}$$

$$C = C_o - \left(\frac{Q}{P}\right)z + \left(\frac{C_e + (Qh/P) - C_o}{e^{Ph} - 1}\right)(e^{pz} - 1) \quad (13)$$

where,

$Q = \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_o}{D}\right)$

$P = \left(\frac{U}{D}\right)$

C_e = total effluent gas-phase concentration of VOCs, [M L^{-3}]

h = height of biofilter, [L]

(2) When the biodecay term follows the first-order kinetics, Eq. (8) becomes:

$$D\frac{\partial^2 C}{\partial z^2} - U\frac{\partial C}{\partial z} - \left(\frac{1-\varepsilon}{\varepsilon}\right)k_1 C_s = 0 \quad (14)$$

Assume: $C_s = k_p C$

where,

k_p = partition coefficient of total VOCs between solid-phase and gas-phase

thus

$$D\frac{\partial^2 C}{\partial z^2} - U\frac{\partial C}{\partial z} - \left(\frac{1-\varepsilon}{\varepsilon}\right)k_1^{'} C = 0 \quad (15)$$

where,

$k_1^{'} = k_1 k_p$

- If D = 0, then

$$\frac{\partial C}{\partial z} = -\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_1^{'}}{U}\right)C \quad (16)$$

$$C = C_0 e^{-\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_1'}{U}\right)z} \tag{17}$$

- If D ≠ 0, then

$$\frac{\partial^2 C}{\partial z^2} - \left(\frac{U}{D}\right)\frac{\partial C}{\partial z} - \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_1'}{D}\right)C = 0 \tag{18}$$

$$C = A_1 e^{r_1 z} + A_2 e^{r_2 z} \tag{19}$$

where,

$$r_1 = \frac{-u+\sqrt{u^2-4*v}}{2}$$

$$r_2 = \frac{-u-\sqrt{u^2-4*v}}{2}$$

$$u = -\left(\frac{U}{D}\right)$$

$$v = -\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_1'}{D}\right)$$

A_1 and A_2 = constants

To determine the values of A_1 and A_2, the following two boundary conditions are considered:

- $z = 0$, $C = Co = A_1 + A_2$
- $z = h$, $C = Ce = A_1 e^{r_1 h} + A_2 e^{r_2 h}$

(3) When the biodecay term follows Monod kinetics, Eq. (8) becomes:

$$D\frac{\partial^2 C}{\partial z^2} - U\frac{\partial C}{\partial z} - \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_m C_s}{K_s + C_s}\right) = 0 \tag{20}$$

- If D = 0, then

$$\frac{\partial C}{\partial z} = -\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_m k_p}{U}\right)\left(\frac{C}{K_s + k_p C}\right) \tag{21}$$

or
$$\frac{\partial C}{\partial z} = -\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_m}{U}\right)\left(\frac{C}{K_s' + C}\right) \tag{22}$$

where,

$$K_s' = \frac{K_S}{k_p}$$

$$\left(\frac{K_s' + C}{C}\right) dC = -\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_m}{U}\right) dz$$

$$\int_{C_o}^{C} \frac{K_s'}{C} dC + \int_{C_o}^{C} dC = -\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_m}{U}\right) \int_o^z dz$$

$$C + K_s' \ln C = C_O + K_s' \ln C_O - \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_m}{U}\right) z \tag{23}$$

- If D≠ 0, then

$$\frac{\partial^2 C}{\partial z^2} - \left(\frac{U}{D}\right)\frac{\partial C}{\partial z} - \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_m}{D}\right)\left(\frac{C}{K_s' + C}\right) = 0 \tag{24}$$

Because of the complexity of Eqs. (23) and (24), it was difficult to find analytical solutions. The solutions of the remaining four equations, Eqs (11), (13), (17), and (19), derived from the above development of models are summarized in Table 10.

Prediction of Experimental Results

To test and utilize the models shown in Table 10 for the prediction of experimental results, the same procedure, reported by Hodge et al. (1991b), was followed. These authors determined the degradation rate constants (k_o and k_1') by using all their

Table 10. Mathematical Models of Biofiltration

Reaction Order	Dispersion Coef.	Mathematical Model
Zero	$D = 0$	$C = C_o - \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_o}{U}\right) z$
Zero	$D \neq 0$	$C = C_o - \left(\frac{Q}{P}\right) z + \left(\frac{C_e + (Qh/P) - C_o}{e^{Ph} - 1}\right)(e^{pz} - 1)$
First	$D = 0$	$C = C_0 e^{-\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_1'}{U}\right) z}$
First	$D \neq 0$	$C = A_1 e^{r_1 z} + A_2 e^{r_2 z}$

experimental data. They then reapplied these constants to the models to fit the data. For the compost column, the average value of k_o is 2.1349 µg/L·sec (zero-order kinetics) and the average value of k_1' is 0.0037 sec^{-1} (first-order kinetics), while for the DE column these values become 4.8157 µg/L·sec (zero-order kinetics) and 0.0203 sec^{-1} (first-order kinetics). A complete list of k_o and k_1' is presented in Appendix K. Similarly, the values of coefficients, P, Q, r_1, r_2, A_1, and A_2, summarized in Table 11, were also determined with all the experimental data, and then tested with the models using the same experimental data. A complete list of the coefficients developed considering dispersion is provided in Appendix L.

Thus, the above four equations can be used to predict the experimental results. The experimental data and predicted values from the equations are listed in Appendix M. Plots of these results are provided in Figures 41-52.

It is necessary to point out that some of the plots shown in Figures 44-45 are not reasonable. In these cases, those models with a dispersion coefficient are hard to accept, where the predicted values go up at the point of 112-cm distance in the compost biofilter. Since the two boundary conditions of each column were considered for the development of the model (Eq. 13) and determination of A_1 and A_2 (Eq. 19), which might be the cause of the unreasonable prediction. Another possibility is that the values of dispersion coefficient are not accurate due to a poor recovery efficiency of tracer so that the models in these experimental conditions do not work.

Table 11. Summary of Mathematical Model's Coefficients*

Biofilter	Run No.	Zero-Order Kinetics		First-Order Kinetic			
		P	Q	r1	r2	A1	A2
Compost:							
	1	0.0639	1.0092	0.0846	-0.0207	-0.0077	1018
	2	0.0899	0.7133	0.1020	-0.0121	-0.0025	1013
	3	0.0507	0.2013	0.0569	-0.0061	-0.1094	1079
	5	0.0639	1.0092	0.0846	-0.0207	0.0886	2155
	6	0.0899	0.7133	0.1020	-0.0121	0.0078	1989
	7	0.0507	0.2013	0.0569	-0.0061	0.2995	2127
DE:							
	1	0.0208	0.5620	0.0602	-0.0394	-0.0120	1489
	2	0.0222	0.2997	0.0483	-0.0262	-0.1812	1338
	3	0.0293	0.1981	0.0471	-0.0178	-0.8022	1168
	5	0.0208	0.5620	0.0602	-0.0394	-0.0317	2199
	6	0.0222	0.2997	0.0483	-0.0262	-0.4436	2230
	7	0.0293	0.1981	0.0471	-0.0178	-1.4130	2195

* Considering the effect of the dispersion coefficient ($D \neq 0$).

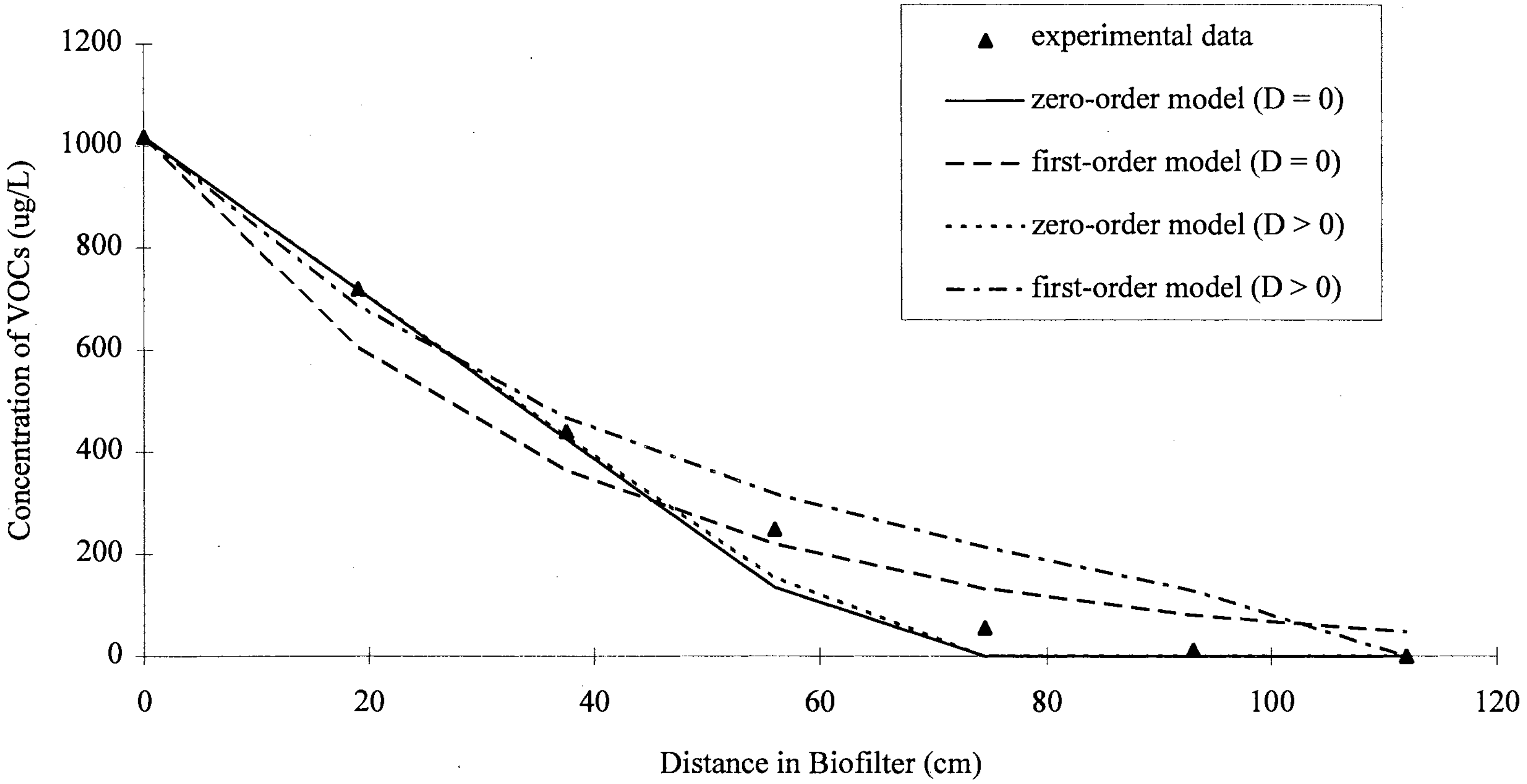

Figure 41. Modeling of Compost Column (Run 1, Air Inlet Conc. = ~1000 ug/L, Residence Time = 20 mins)

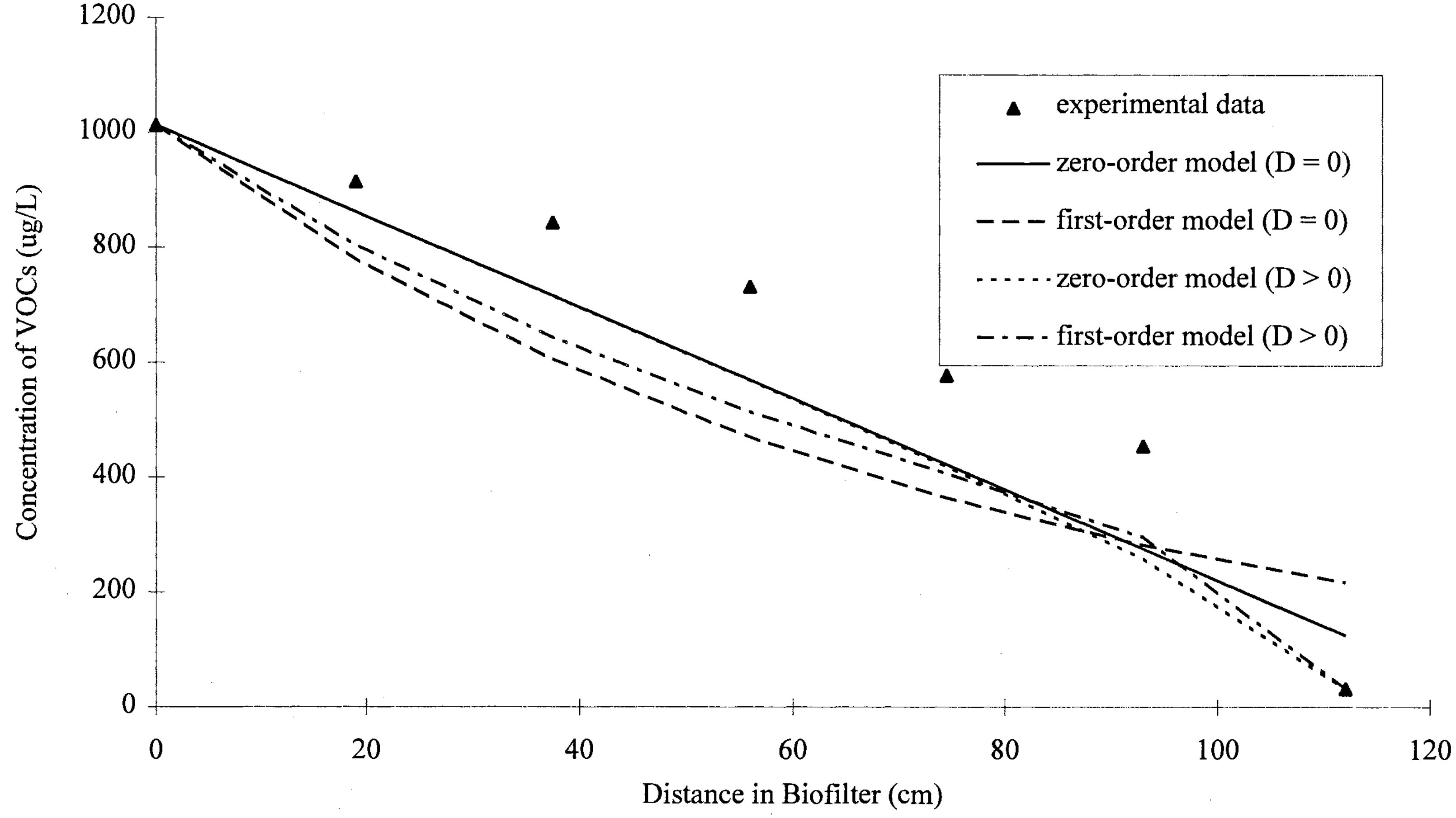

Figure 42. Modeling of Compost Column (Run 2, Air Inlet Conc. = ~1000 ug/L, Residence Time = 10 mins)

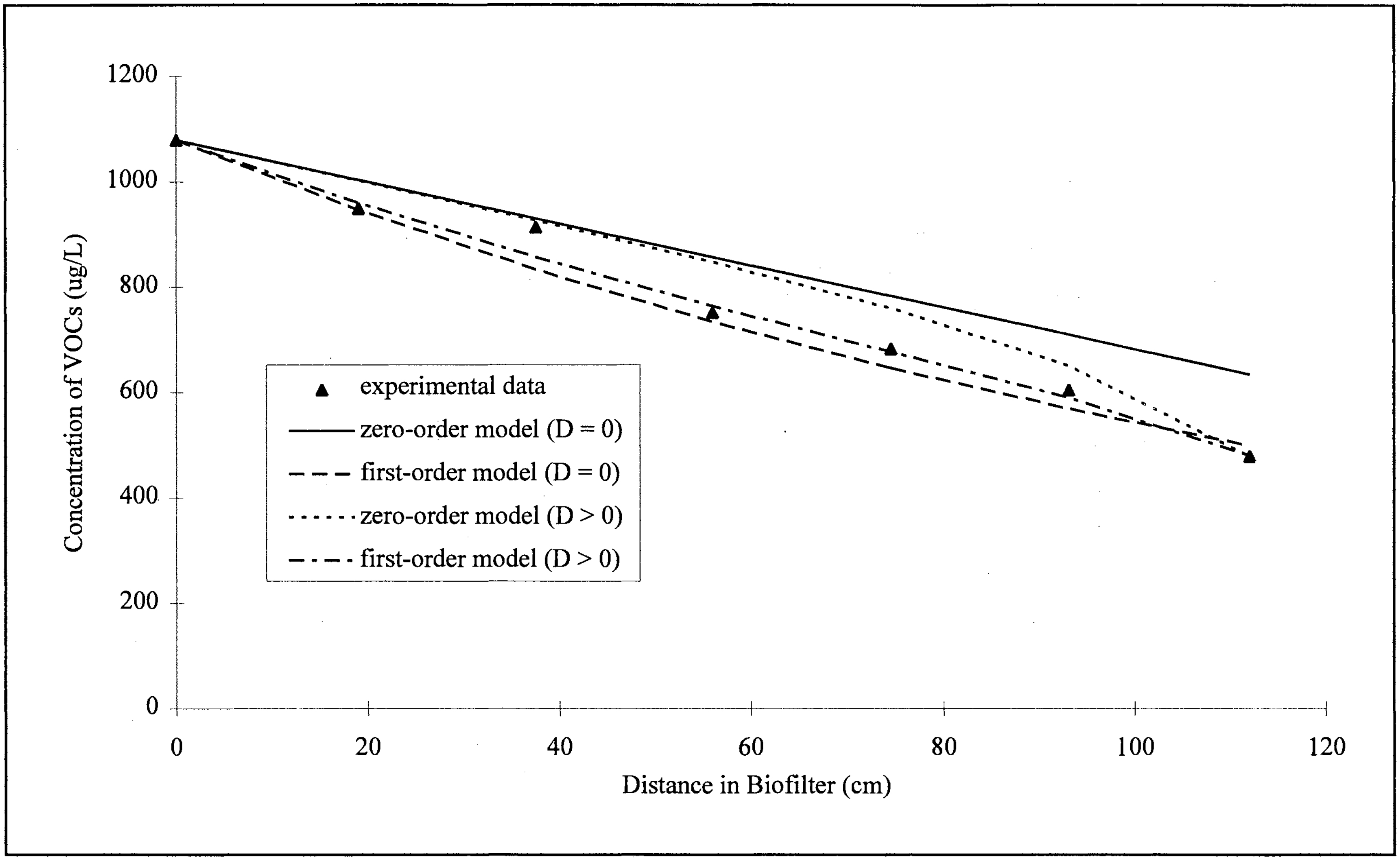

Figure 43. Modeling of Compost Column (Run 3, Air Inlet Conc. = ~1000 ug/L, Residence Time = 5.0 mins)

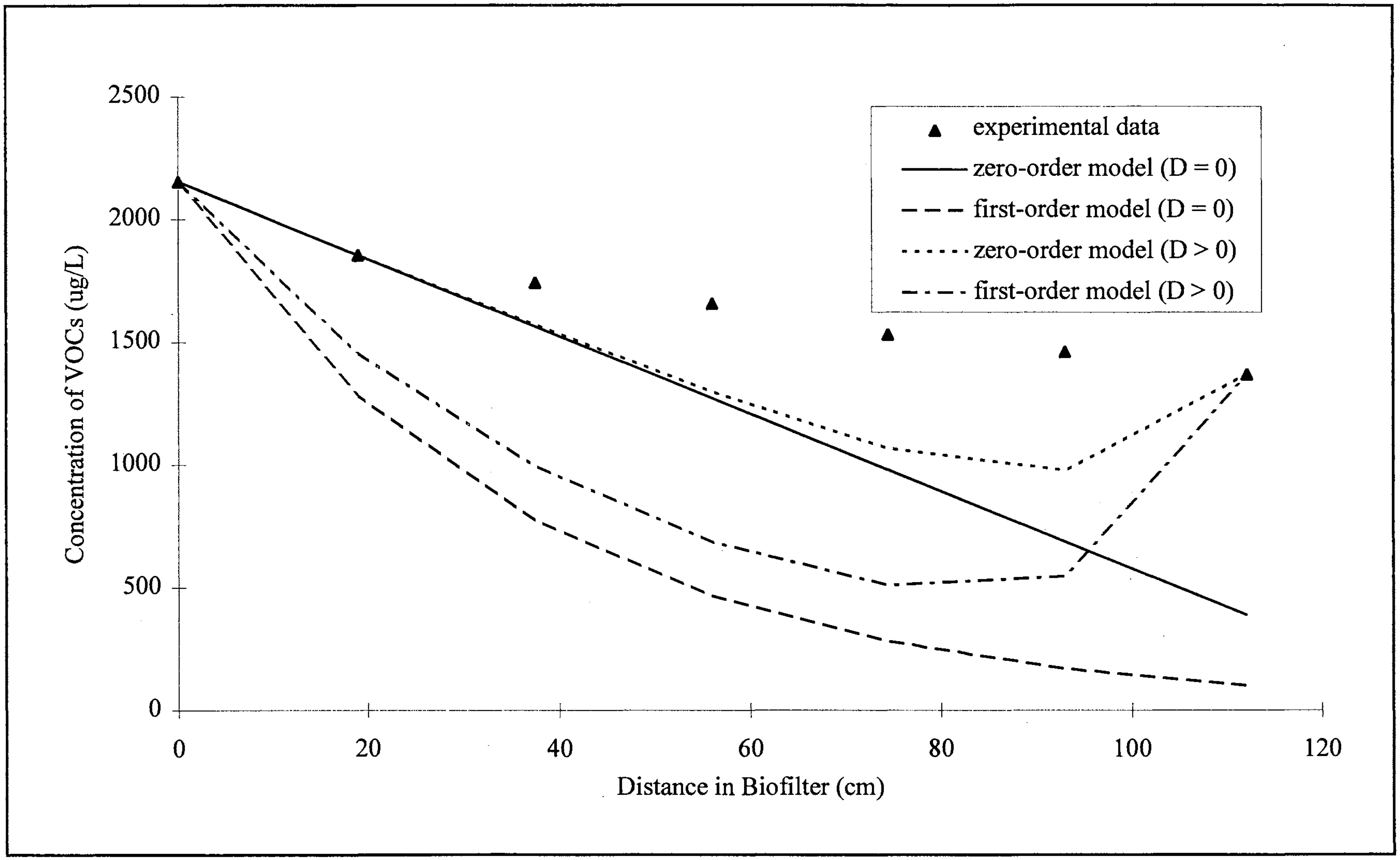

Figure 44. Modeling of Compost Column (Run 5, Air Inlet Conc. = ~2000 ug/L, Residence Time = 20 mins)

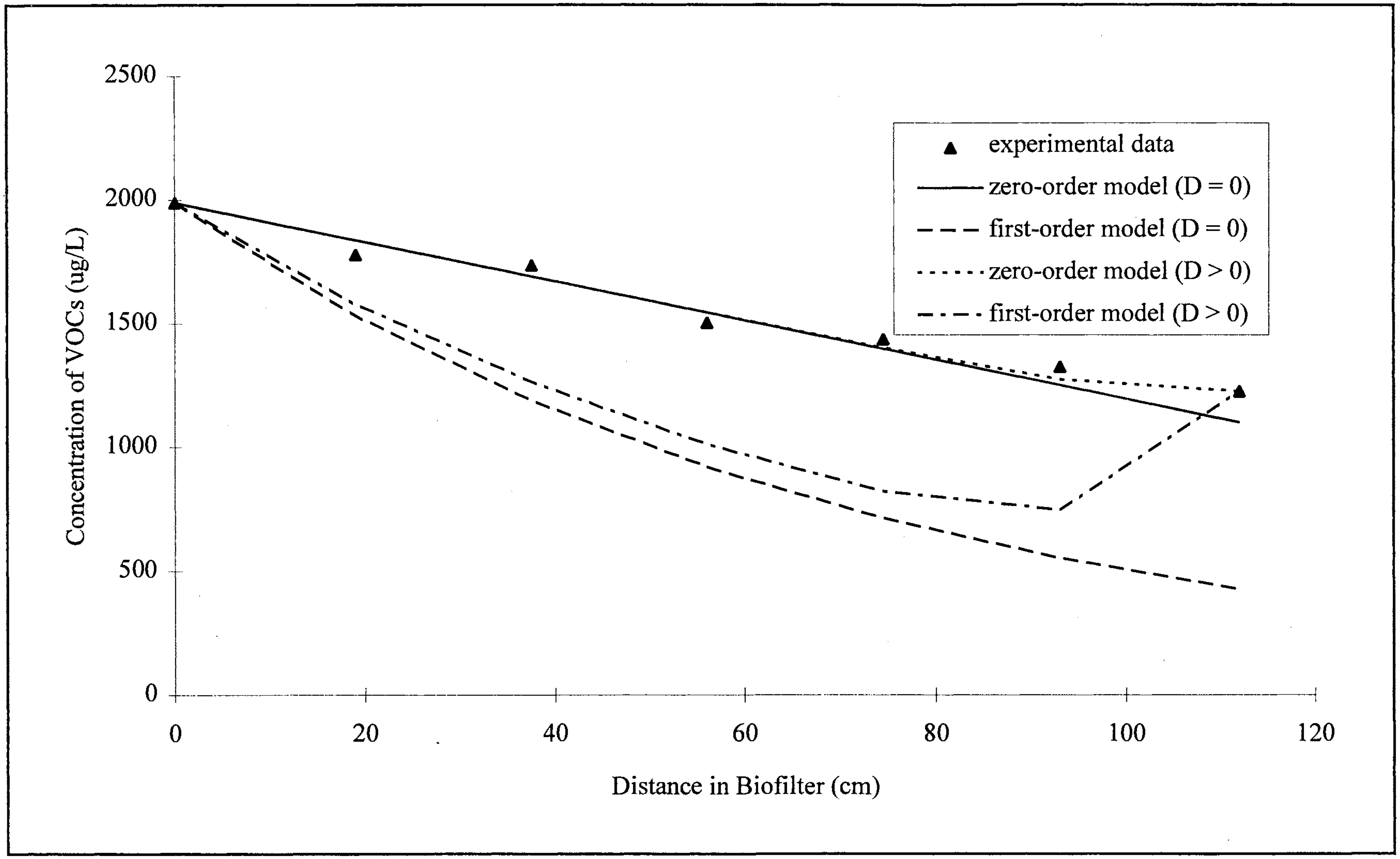

Figure 45. Modeling of Compost Column (Run 6, Air Inlet Conc. = ~2000 ug/L, Residence Time = 10 mins)

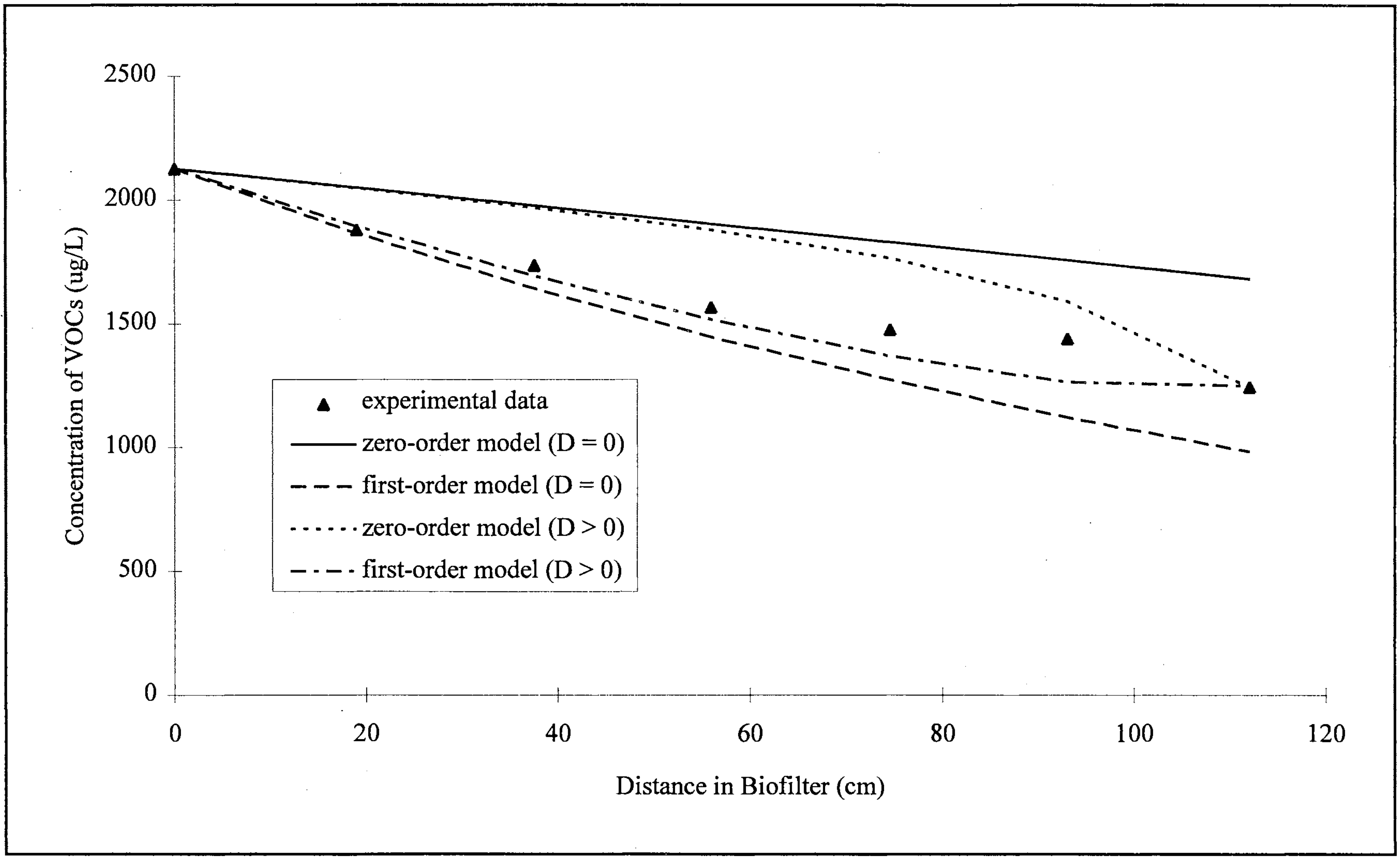

Figure 46. Modeling of Compost Column (Run 7, Air Inlet Conc. = ~2000 ug/L, Residence Time = 5.0 mins)

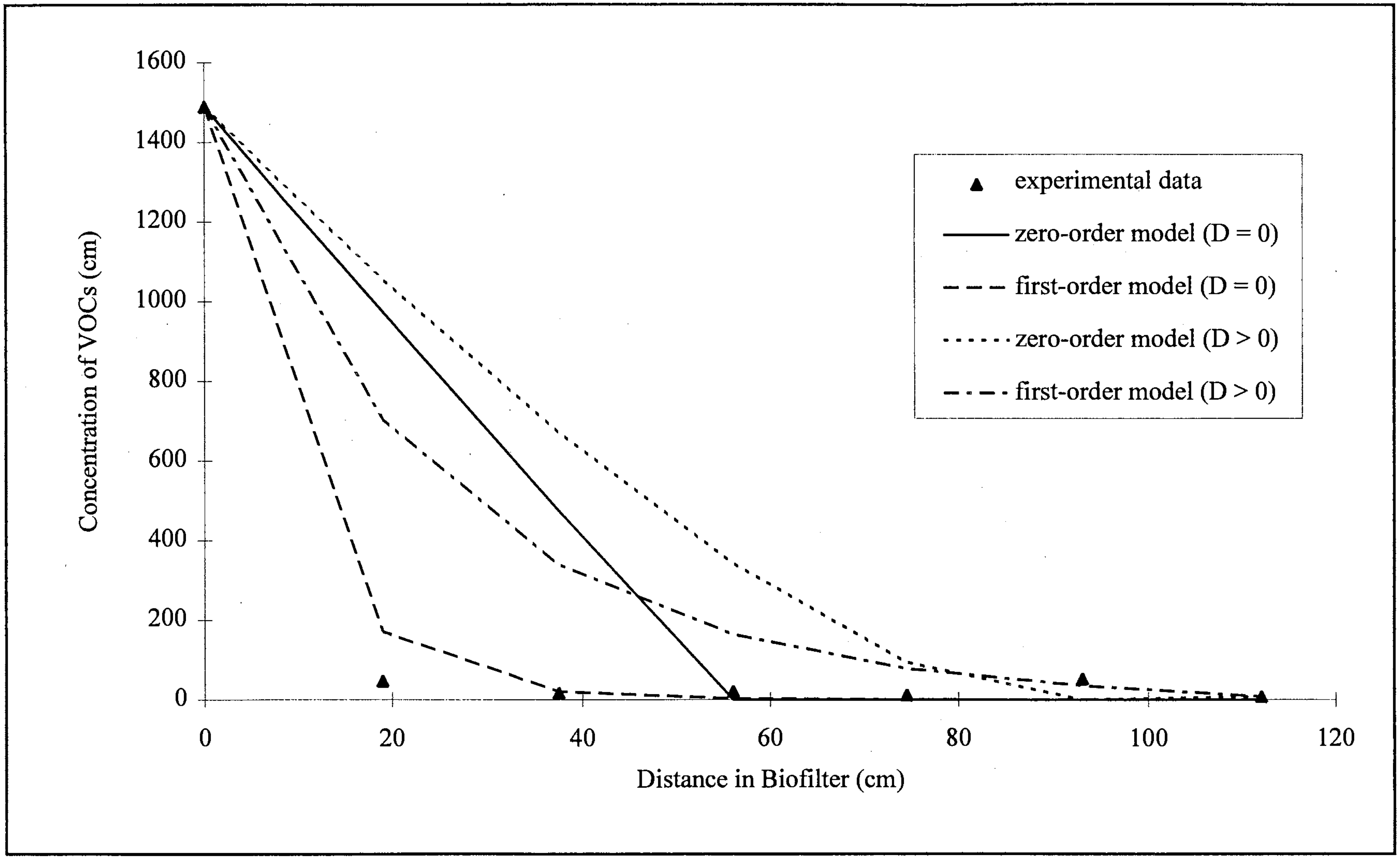

Figure 47. Modeling of Diatomaceous Earth Column (Run 1, Air Inlet Conc. = ~1000 ug/L, Residence Time = 20 mins)

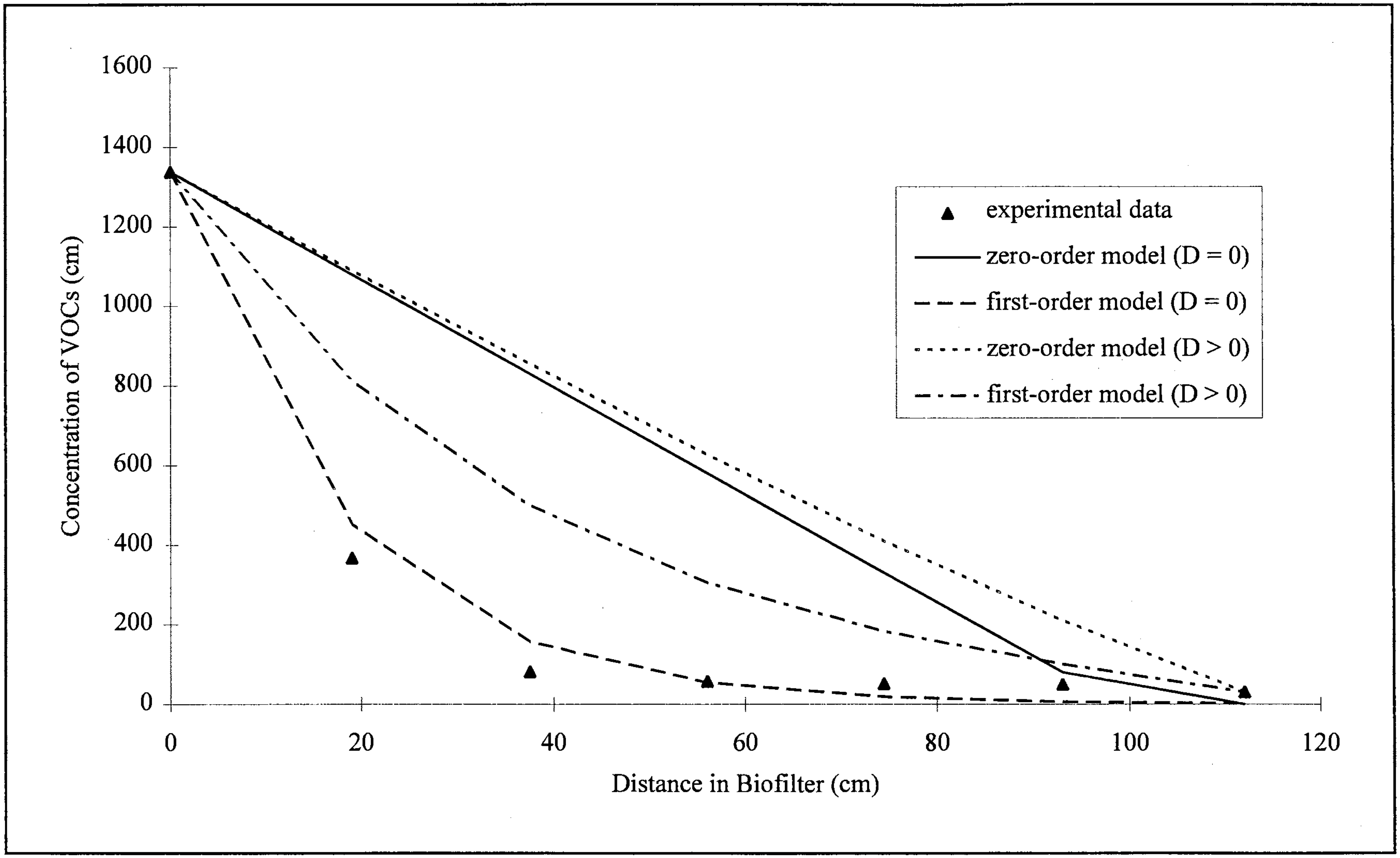

Figure 48. Modeling of Diatomaceous Earth Column (Run 2, Air Inlet Conc. = ~1000 ug/L, Residence Time = 10 mins)

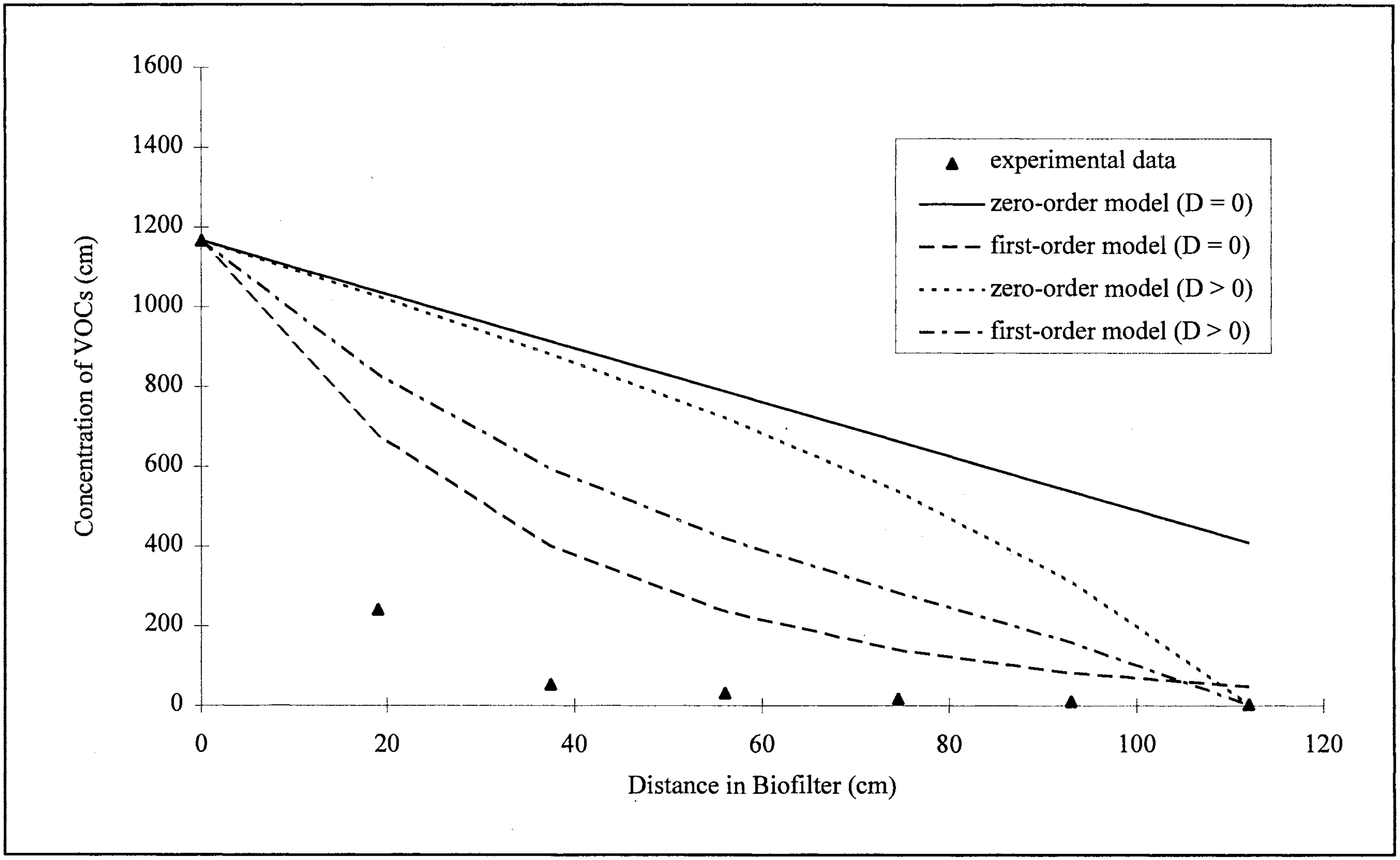

Figure 49. Modeling of Diatomaceous Earth Column (Run 3, Air Inlet Conc. = ~1000 ug/L, Residence Time = 5.0 mins)

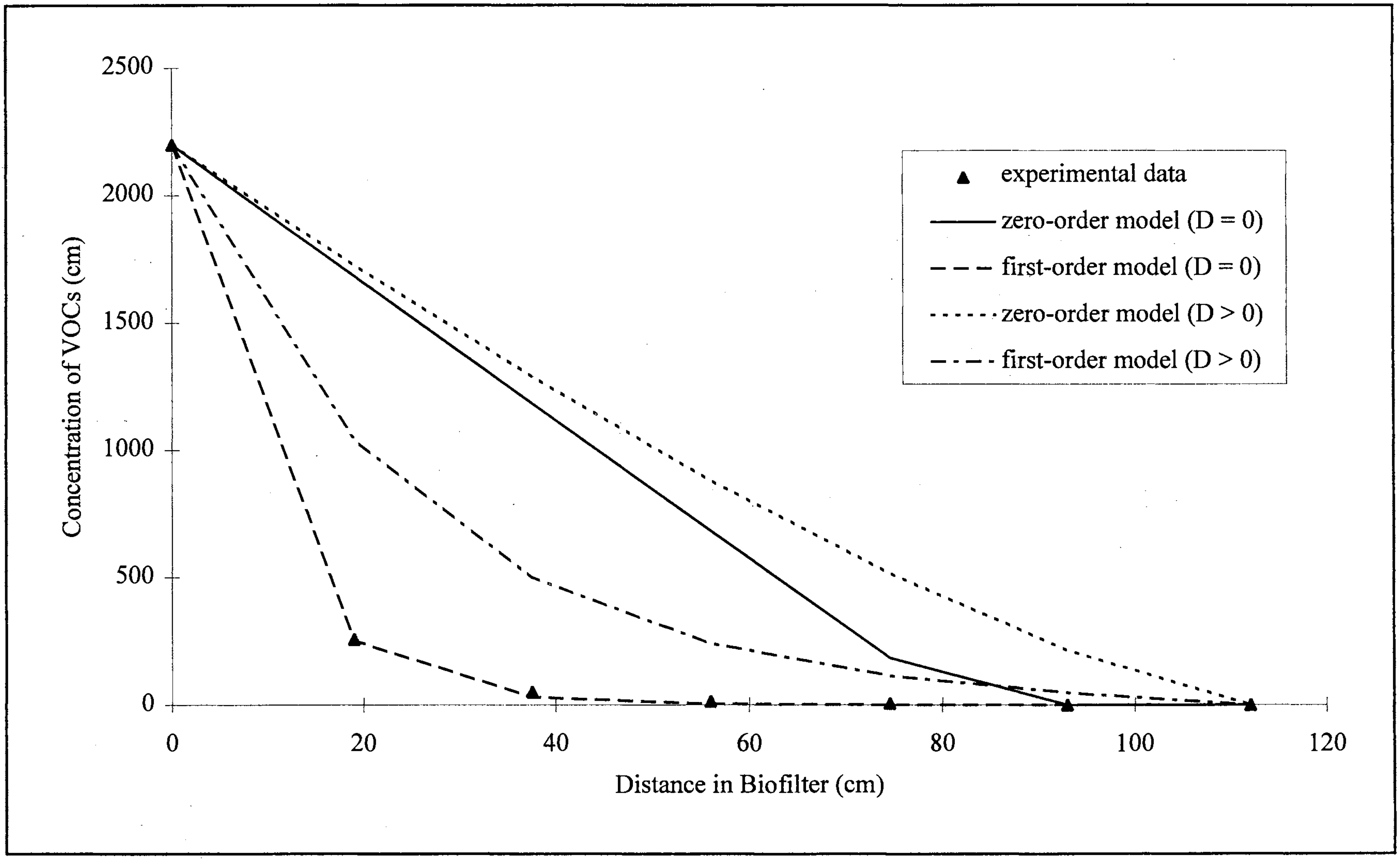

Figure 50. Modeling of Diatomaceous Earth Column (Run 5, Air Inlet Conc. = ~1000 ug/L, Residence Time = 20 mins)

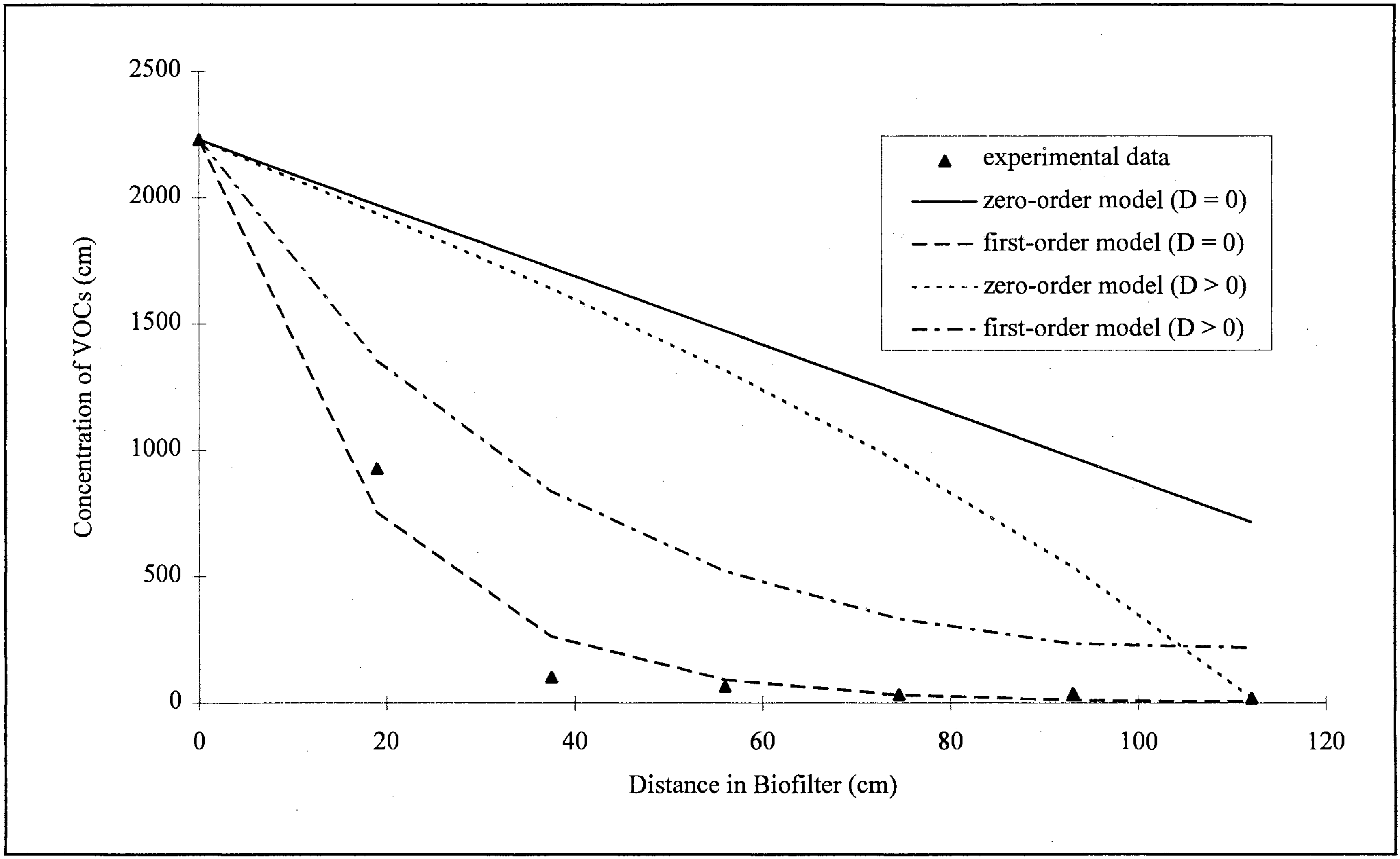

Figure 51. Modeling of Diatomaceous Earth Column (Run 6, Air Inlet Conc. = ~2000 ug/L, Residence Time = 10 mins)

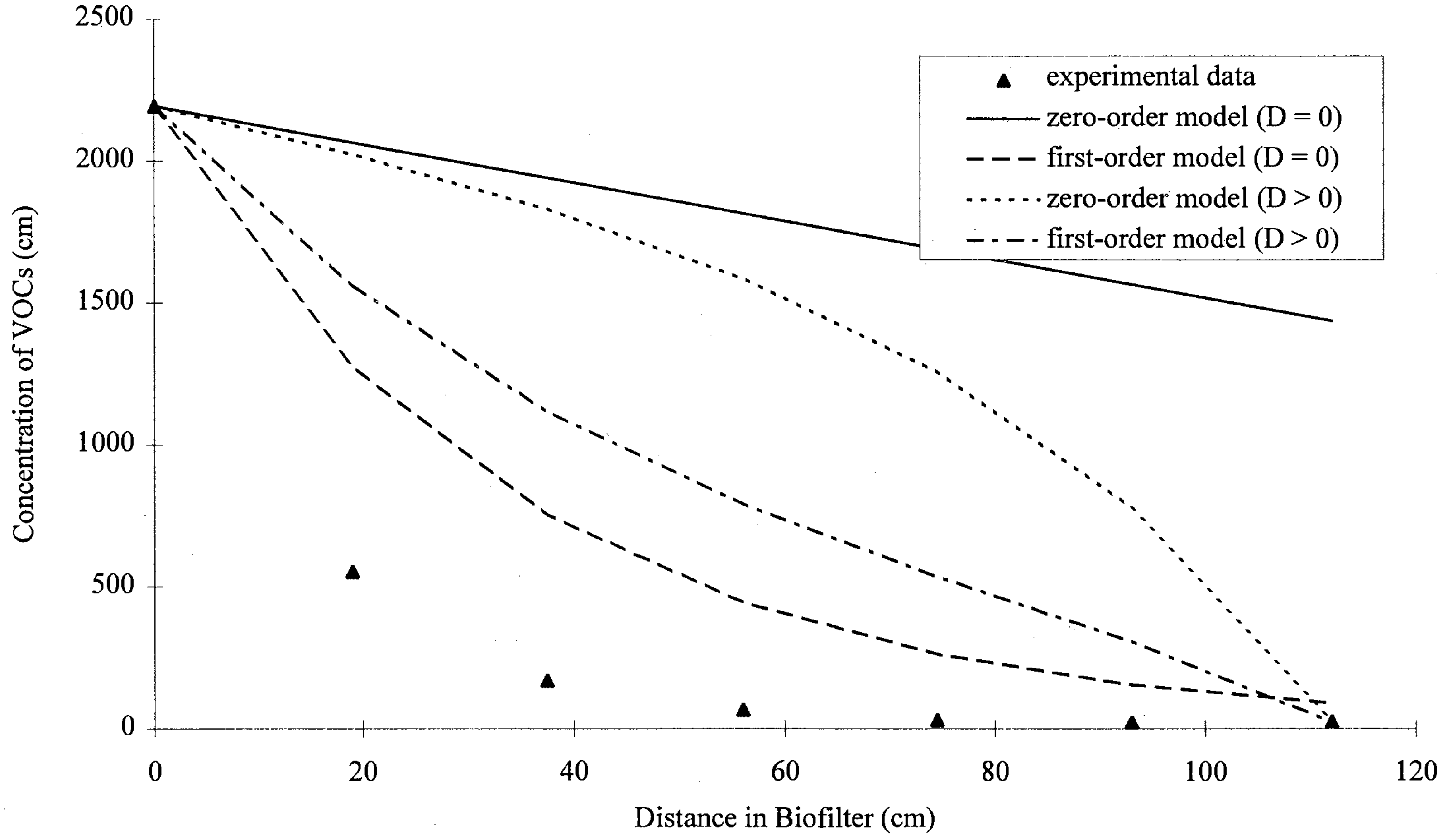

Figure 52. Modeling of Diatomaceous Earth Column (Run 7, Air Inlet Conc. = ~2000 ug/L, Residence Time = 5.0 mins)

Regression Analysis

To determine the best model for each biofiltration system, regression analysis on the models in Table 10 was done. The various types of regression analysis used are as follows:

(1) Simple linear regression analysis:

- For Eq. (11), $C = C_o - \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_o}{U}\right)z$, calculate the coefficient of determination directly using the following formula (Olson, 1987):

$$r^2 = \frac{SS_{regr}}{SS_C} = \frac{SS_{regr}}{SS_{regr} + SS_{error}} \tag{25}$$

$$SS_{regr} = \Sigma\left(\hat{C}_i - \overline{C}\right)^2 \tag{26}$$

$$SS_{error} = \Sigma\left(C_i - \hat{C}_i\right)^2 \tag{27}$$

where,

r^2 = coefficient of determination

SS_C = total variation in C

SS_{regr} = sum of squares due to regression

SS_{error} = error sum of squares

$\hat{C}_i$ = fitted value

$\overline{C}$ = mean of C_i

C_i = observed value

- For Eq. (17), $C = C_0 e^{-\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_1'}{U}\right)z}$, make the transformation first, that is:

$$\ln C = \ln C_o - \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_1'}{U}\right) z \tag{28}$$

Then, calculate a coefficient of determination of Eq. (28) using the Eqs. (25)-(27).

(2) Multiple linear regression:

- For Eq. (13), $C = C_o - \left(\frac{Q}{P}\right)z + \left(\frac{C_e + (Qh/P) - C_O}{e^{Ph} - 1}\right)(e^{pz} - 1)$, make the transformation first, that is:

$$C = a_o + a_1 Z_1 + a_2 Z_2 \tag{29}$$

where,

$$a_o = Co - a_2$$

$$a_1 = -\left(\frac{Q}{P}\right)$$

$$a_2 = \left(\frac{C_e + (Qh/P) - C_O}{e^{Ph} - 1}\right)$$

$$Z_1 = z$$

$$Z_2 = \left(\frac{C_e + (Qh/P) - C_O}{e^{Ph} - 1}\right) e^{pz}$$

Then, calculate a coefficient of multiple determination using the following formula (Olson, 1987):

$$R^2 = \frac{SS_{regr}}{SS_{total}} = \frac{SS_{regr}}{SS_{regr} + SS_{res}} \tag{30}$$

$$SS_{regr} = \Sigma\left(\hat{C}_i - \overline{C}\right)^2 \tag{31}$$

$$SS_{resr} = \Sigma \left(C_i - \hat{C}_i\right)^2 \tag{32}$$

where,

R^2 = coefficient of multiple determination

SS_{total} = total variation in C

SS_{regr} = sum of squares due to regression

SS_{res} = residual sum of squares

$\hat{C}_i$ = fitted value

$\overline{C}$ = mean of C_i

C_i = observed value

- For Eq. (19), $C = A_1 e^{r_1 z} + A_2 e^{r_2 z}$, make the transformation first, that is:

$$C = A_1 Z_1 + A_2 Z_2 \tag{33}$$

where,

A_1, A_2 = constants

$Z_1 = e^{r_1 z}$

$Z_2 = e^{r_2 z}$

All the values of r^2 and R^2 are listed in Table 12. The higher the value of r^2 or R^2, the better the model. It can be seen from Table 12 that the zero-order model with a non-zero value of dispersion coefficient is the best model for the compost column, and for the DE column, the first-order model with a zero value of dispersion coefficient is the best model. But, performing ANOVA on these values of r^2 and R^2, it can be seen that for the compost column, there are no significant differences among these models, and for the DE

Table 12. Coefficient of Determination from Regression Analysis

Biofilter:	Compost				DE			
Model:	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Run No.								
1	0.983	0.958	0.988	0.944	0.691	0.990	0.623	0.774
2	0.857	0.701	0.877	0.829	0.614	0.988	0.589	0.773
3	0.765	0.964	0.931	0.986	0.492	0.762	0.529	0.632
5	0.637	0.556	0.695	0.560	0.620	1.000	0.579	0.825
6	0.954	0.609	0.979	0.615	0.503	0.986	0.556	0.788
7	0.511	0.832	0.722	0.937	0.468	0.792	0.513	0.649
AVG.:	0.785	0.770	0.865	0.812	0.565	0.920	0.565	0.740

Notes:

Model (1) -- $C = C_o - \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_o}{U}\right) z$

Model (2) -- $C = C_o\, e^{-\left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_1'}{U}\right) z} \Rightarrow \ln C = \ln C_o - \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{k_1'}{U}\right) z$

Model (3) -- $C = C_o - \left(\frac{Q}{P}\right) z + \left(\frac{C_e + (Qh/P) - C_o}{e^{Ph} - 1}\right)(e^{Pz} - 1)$

$\Rightarrow \quad C = a_o + a_1 Z_1 + a_2 Z_2$

Model (4) -- $C = A_1 e^{r_1 z} + A_2 e^{r_2 z} \Rightarrow C = A_1 Z_1 + A_2 Z_2$

column, there are significant differences among these models. The results of ANOVA are presented in Appendix N.

Statistical Analysis

In order to determine what main factors influence the degradation of BTEX compounds, one of the SAS (Statistical Analysis System) software, ANOVA (Analysis of Variance), was used for the analysis of the experimental data from both biofilters. The target items, which include air influent concentration, residence time (or air flow rate), and type of filter material, were analyzed against elimination efficiency for each experimental run, where the value of α (significance level) was assumed to be 0.05.

Analysis of Variance (ANOVA)

To perform the ANOVA, the experimental data needs to be tabulated as shown in Appendix O. Three factors, residence time, level of influent concentration, and type of filter material, were then evaluated individually.

Generally, ANOVA is a statistical procedure to determine whether means from two or more samples are drawn from populations with the same mean. The basic steps for performing the ANOVA are as follows:

- Suppose two hypotheses:

H_o: $u_1 = u_2 = \ldots = u_n$ $(i = 1, 2, \ldots, n)$

H_A: H_o is not true.

where,

H_o = null hypothesis

H_A = alternative hypothesis if H_o is false

u_i = mean elimination efficiency under i level of an evaluation item

n = maximum level number of the evaluation item

- If the p-value or Observed Significance Level (OSL) is larger than α, then H_o is accepted and it can be concluded that there is no effect of the evaluation item on the elimination efficiency.
- If the p-value is less than α, then H_o is rejected (or H_A is accepted) which means that there is effect of the evaluation item on the elimination efficiency.

The outputs of ANOVA are listed in Appendix P. These results are summarized in Tables 13-15, and show:

- For the compost and DE columns, residence time has an effect on the elimination efficiency under the conditions of low influent concentration but there is no residence time effect on the elimination efficiency under the conditions of high influent concentration (Table 13). However, checking these results with Figures 11 and 28 in Chapter IV, only one of these results, in which the test condition was the DE medium with a low influent concentration, is not reasonable. In other words, the null hypothesis in this case should be accepted and residence time should have no significant effect on the elimination efficiency. The reason for getting the result from ANOVA might be that at least one of the variance ratios among these data sets is still relatively high (i.e. $\sigma^2_5/\sigma^2_{2.5} = 6.8$). Therefore, the null hypothesis is rejected even though the mean of each data set is close each other.
- Air influent concentration has an effect on the elimination efficiency in the compost column. But for the DE column, there is no effect of air influent

concentration on the elimination efficiency except for a residence time of 2.5 minutes (Table 14).

- When running at residence time of 10-20 minutes at the low influent concentration, there is no effect of type of filter material on the elimination efficiency. But there is an effect of type of filter material on the elimination efficiency under the conditions of the low influent concentration with residence times of 2.5-5.0 minutes. For the condition of the high influent concentration, no matter what the residence time, the type of filter material has an effect on the elimination efficiency (Table 15).

Table 13. Effect of Residence Time on Elimination Efficiency

Test Conditions		P-value	α	H_o	Effect
Filter	Level of Inf. Conc.				
Compost	Low	1.17E-29	0.05	Rejected	Yes
Compost	High	0.0660	0.05	Accepted	No
DE	Low	4.37E-05	0.05	Rejected	Yes
DE	High	0.0818	0.05	Accepted	No

Notes:

1) Low level of influent concentration = ~ 1000 μg/L
2) High level of influent concentration = ~ 2000 μg/L
3) Residence times = 20, 10, 5.0 and 2.5 mins
4) H_o: $u_{20} = u_{10} = u_5 = u_{2.5}$
5) H_A: H_o is not true

Table 14. Effect of Air Influent Concentration on Elimination Efficiency

Test Conditions		P-value	α	H_o	Effect
Filter	Residence Time				
Compost	20 mins	1.79E-25	0.05	Rejected	Yes
Compost	10 mins	3.76E-15	0.05	Rejected	Yes
Compost	5.0 mins	0.0026	0.05	Rejected	Yes
DE	20 mins	0.3475	0.05	Accepted	No
DE	10 mins	0.0693	0.05	Accepted	No
DE	5.0 mins	0.0723	0.05	Accepted	No
DE	2.5 mins	0.0319	0.05	Rejected	Yes

Notes:

1) Low level of influent concentration = ~ 1000 µg/L

2) High level of influent concentration = ~ 2000 µg/L

3) H_o: $u_{Low} = u_{High}$

4) H_A: $= H_o$ is not true

Table 15. Effect of Type of Filter Material on Elimination Efficiency

Test Conditions		P-value	α	H_o	Effect
Level of Inf. Conc.	Residence Time				
Low	20 mins	0.2458	0.05	Accepted	No
Low	10 mins	0.6032	0.05	Accepted	No
Low	5.0 mins	2.93E-12	0.05	Rejected	Yes
Low	2.5 mins	1.26E-11	0.05	Rejected	Yes
High	20 mins	6.45E-20	0.05	Rejected	Yes
High	10 mins	1.22E-13	0.05	Rejected	Yes
High	5.0 mins	1.04E-23	0.05	Rejected	Yes

Notes:

1) Low level of influent concentration = ~ 1000 μg/L

2) High level of influent concentration = ~ 2000 μg/L

3) H_o: $u_{Compost} = u_{DE}$

4) H_A: H_o is not true

Cost Analysis

Biofiltration versus Other Alternatives

Currently there are several technologies which are commonly used for the removal of VOCs from the gas-phase. These include:

- biofiltration
- activated carbon
- oxidation
- incineration

Information on the capital and operating costs of these technologies gathered from the literature is summarized in Tables 16-20 and Figures 53-54. These data show that biofiltration can offer a considerably lower total cost compared to the other alternatives, especially in terms of operating cost (Tables 17-18). Griffin and Paff (1995) stated that from an operational, maintenance, and capital basis, biofiltration is the least expensive technology. As mentioned in Chapter II, the actual costs of these technologies are mainly dependent on the gas flow rate, the contaminant concentration and nature, the type of filter material, the regulatory requirements, and the energy and manpower costs.

Cost Estimation of Biofiltration

The exact cost value of biofiltration is difficult to be predicted; however, the total cost of biofiltration should include both capital and operating costs, which can be expressed in the following equation:

$$Ct = Cc + Co$$

where,

Ct = total cost of biofiltration

Cc = capital cost of biofiltration, including the costs of column's material, equipment, filter material, and pipeline system.

Co = operating cost of biofiltration, including the costs of electricity, manpower, chemicals, and replacement of filter material.

To estimate the cost of biofiltration, the technique known as the Work Breakdown Structure (WBS) was utilized. Based on the definition of WBS from Oberlender (1993), a WBS is a graphical display of the project that shows the division of work in a multi-level system. The number of levels in a WBS will vary, depending upon the size and complexity of the project. The smallest unit in the WBS is a work package. A work package must be defined in sufficient detail so the work can be measured, budgeted, scheduled, and controlled. The WBS is the foundation of a project management system. The WBSs of the two biofiltration systems are illustrated in Figures 55-56.

Table 16. Cost Comparison of VOCs Control - Part I

Technology	Total Cost * ($ /10^6 ft^3 of air treated)
Incineration	130
Chlorine	60
Ozone	60
Activated Carbon (with regeneration)	20
Biofiltration	8

Source: Bohn (1992)

* In 1991 dollars

Table 17. Cost Comparison of VOCs Control - Part II

Technology	Capital & Installation Cost	Yearly Operating Cost
Carbon Adsorption	$20,000	$119,825 - $174,800
Catalytic Oxidation	$55,000	$17,540 - $23,240
Biofiltration	$34,000	$6,600 - $7,800

Source: Togna and Skladany (1994)

Air Flow Rate = 250 cfm

Concentration of Petroleum Hydrocarbon = 4000 ppmv (methane equivalents)

Table 18. Cost Comparison of VOCs Control - Part III

Technology	Capital Cost	Annual Operating Cost
Carbon Adsorption	$20,000	$15,000 - $20,000
Catalytic Oxidation	$45,000	$9,000
Thermal Oxidation	$35,000	$17,000
Biofiltration	$30,000	$3,000

Source: Zurlinden and Carmel (1994)

Air Flow Rate = 50 cfm

Concentration of Total Petroleum Hydrocarbon = 200 ppmv

Table 19. Costs of Biofiltration for VOCs Control - Part I

Author (Year)	Investment Cost ($ /m^3/hr)	Operational Cost ($ /1000 m^3)
Liebe (1989)	4.3 - 4.9	0.27 - 0.97
Kersting (1992)	4.9 - 7.1	0.24 - 0.40
Joziasse (1992)	326 - 4,348*	0.27 - 2.72

Source: Groenestijn and Hesselink (1993)

* $ /m^3 bed

Table 20. Costs of Biofiltration for VOCs Control - Part II

Country	Capital Cost ($ /ft^2 filter area)	Operating Cost ($ /10^5 ft^3 off-gas)
Germany	25 - 95	0.60 - 1.50
Netherlands	25 - 95	0.60 - 1.50
USA	55 - 90	0.30 - 0.60

Source: Leson and Winer (1991)

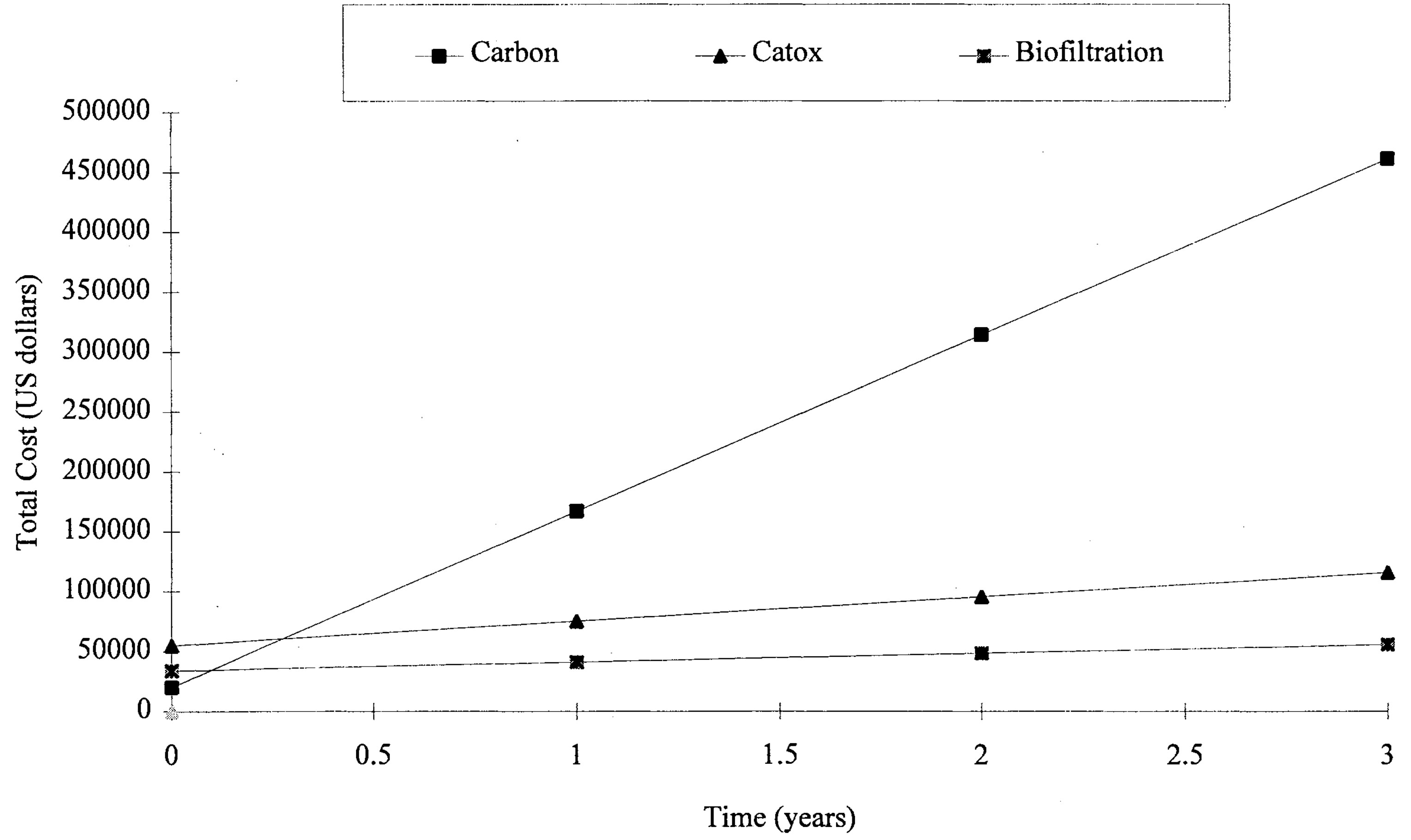

Figure 53. Cost Comparison of Three Technologies (Based on the data in Table 17)

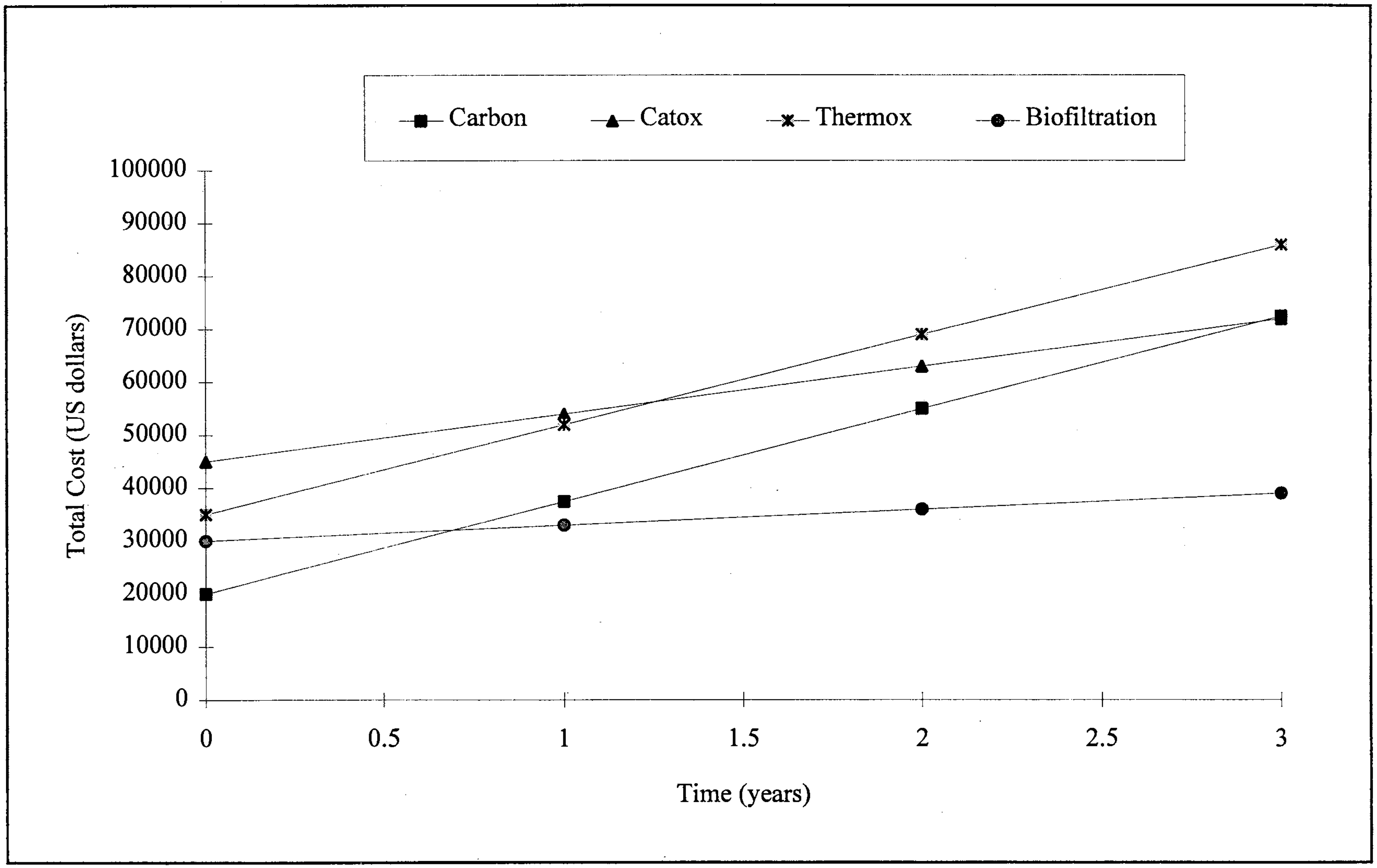

Figure 54. Cost Comparison of Four Technologies (Based on the data in Table 18)

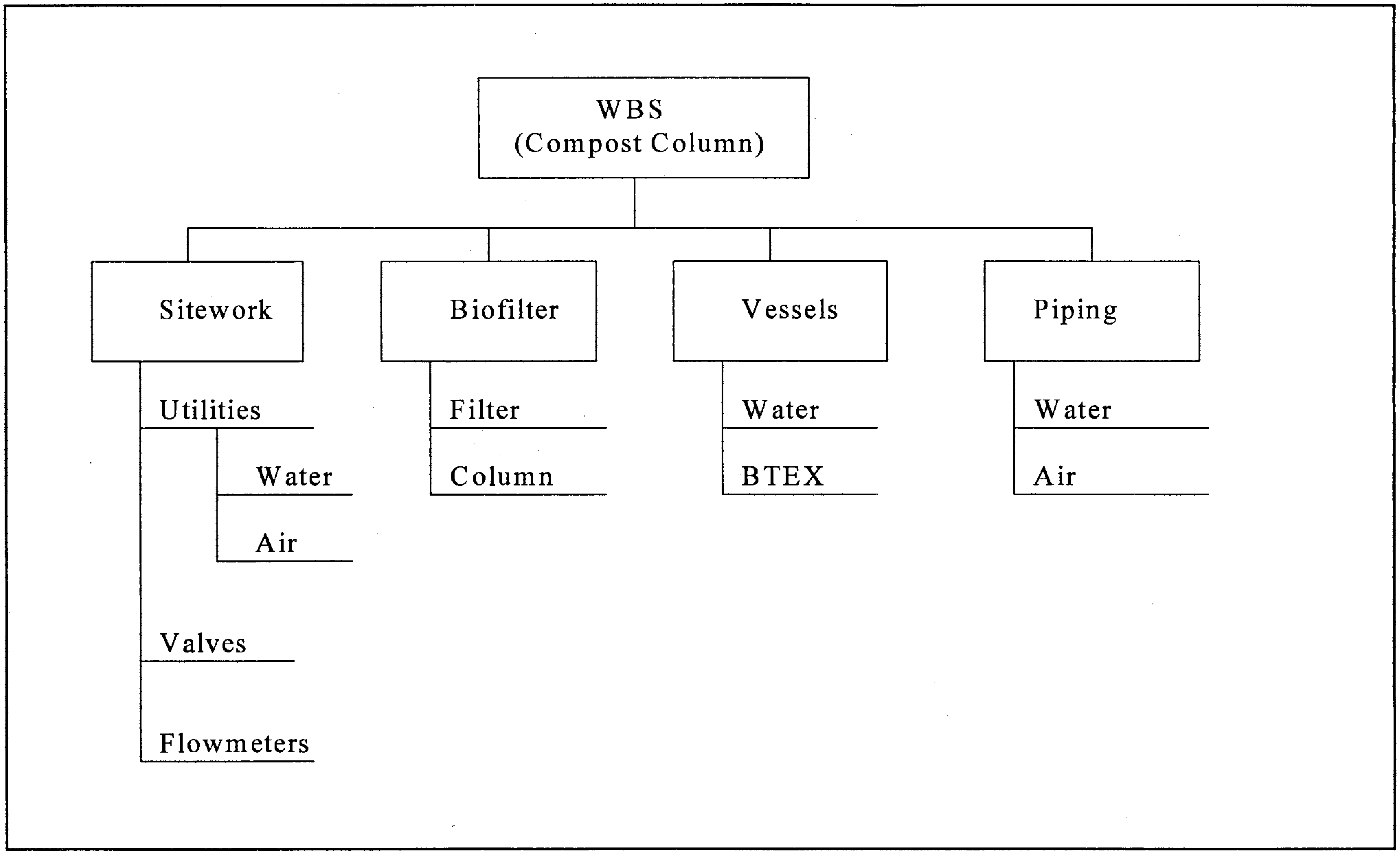

Figure 55. Work Breakdown Structure (WBS) for Compost Column

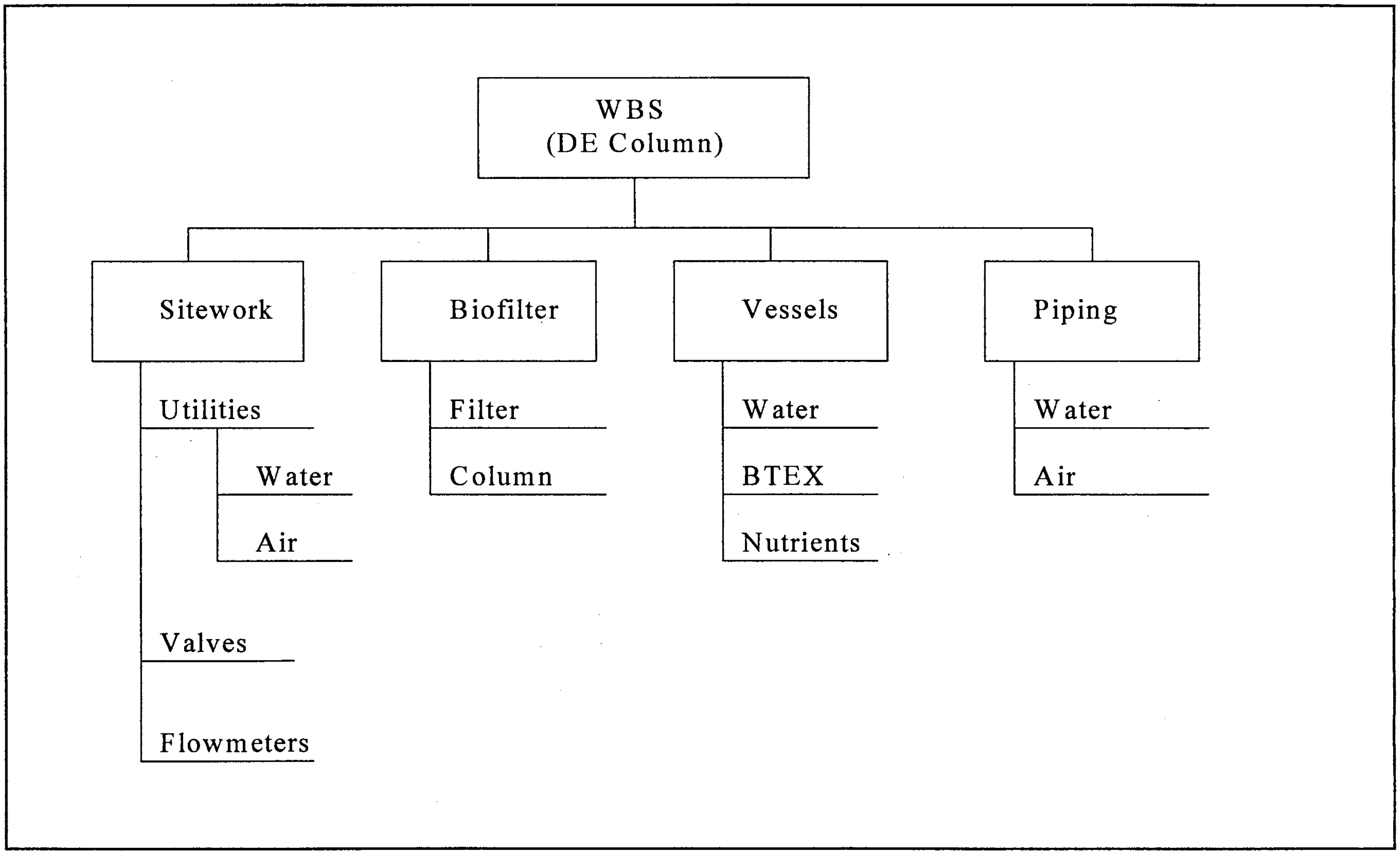

Figure 56. Work Breakdown Structure (WBS) for Diatomaceous Earth Column

In order to establish the work package for each level, the following assumptions were made for both systems:

- Air Flow Rate: $Qg = 50\ \text{ft}^3/\text{min} = 1{,}415\ \text{L/min}$
- Gas Influent Concentration: $Ci = 200$ ppm $= 782\ \mu\text{g/L}$ (Total VOCs)
- Gas Effluent Concentration: $Ce = 20$ ppm $= 78\ \mu\text{g/L}$ (Total VOCs)
- Elimination Rate of Compost: $N_{COM} = 0.20\ \text{mg/cm}^3\cdot\text{day}$ (from the compost column study)
- Elimination Rate of DE: $N_{DE} = 1.00\ \text{mg/cm}^3\cdot\text{day}$ (from the DE compost study)

(1) Compost Column

Total volume of filter required:

$$V_f = Qg(Ci - Ce)/N_{COM} = 1415(782 - 78)*60*24/(0.20*1000) = 7{,}174{,}138\ \text{cm}^3$$

Porosity of compost:

$\varepsilon = 0.59$ (from measurement of compost in a laboratory)

Total bed volume required:

$$V = V_f/(1-\varepsilon) = 7174138/(1 - 0.59) = 17{,}497{,}897\ \text{cm}^3$$

Total pore volume in bed:

$$V_\varepsilon = V - V_f = 17497897 - 7174138 = 10{,}323{,}759\ \text{cm}^3$$

Height of column required:

$H = 250$ cm

Number of columns required:

$n = 4$

Sectional area of column:

$S = (V/n)/H = (17497897/4)/250 = 174{,}997.9\ cm^2$

Diameter of column:

$d = sqrt(4*S/\pi) = sqrt(4*174997.9/3.14) = 149\ cm$

Check:

Residence time of air:

$t = V_\varepsilon/Qg = 10323759/1415000 = 7.30$ mins

Let $t = t_{min} = 10$ mins (from the compost column study), then

$V_\varepsilon = t*Qg = 10*1415000 = 14{,}150{,}000\ cm^3$

$V = V_\varepsilon/\varepsilon = 14150000/0.59 = 23{,}983{,}051\ cm^3$

$V_f = V - V_\varepsilon = 23983051 - 14150000 = 9{,}833{,}051\ cm^3$ (or $12.83\ yd^3$)

$H = 300\ cm$

$S = (V/n)/H = 19{,}985.9\ cm^2$

$d = 160\ cm$

Applied Loading $= Qg*Ci/V_f = 0.16\ mg/cm^3\cdot day$

Vessels:

- For the water vessel (as a humidification reservoir), the assumptions were:

  Diameter of the vessel = 50 cm

  Height of the vessel = 100 cm

- For the BTEX vessel (as a contaminant reservoir), the assumptions included:

  Diameter of the vessel = 50 cm

  Height of the vessel = 100 cm

Piping:

- For water, the assumptions were:

Diameter of pipe = 25 mm

Length of pipe = 10 m

Material of pipe = PVC

- For air, the assumptions included:

Diameter of pipe = 25 mm

Length of pipe = 50 m

Material of pipe = PVC

Sitework:

- Utilities:

Number of air compressor = 1

Number of water pump = 0

- Valves:

Number of valve = 10

Diameter of valve = 25-100 mm

- Flowmeters:

Number of flowmeter = 8

Diameter of flowmeter = 25-100 mm

(2) DE Column

Total volume of filter required:

$V_f = Qg(Ci - Ce)/N_{DE} = 1415(782 - 78)*60*24/(1.0*1000) = 1,434,828\ cm^3$

Porosity of DE:

$\varepsilon = 0.69$ (from measurement of DE in a laboratory)

Total bed volume required:

$V = V_f/(1-\varepsilon) = 1434828/(1 - 0.69) = 4{,}628{,}476\ cm^3$

Total pore volume in bed:

$V_\varepsilon = V - V_f = 1434828 - 4628476 = 3{,}193{,}649\ cm^3$

Height of columns required:

H = 200 cm

Number of column required:

n = 2

Sectional area of column:

$S = (V/n)/H = (4628476/2)/200 = 11571.19\ m^2$

Diameter of column:

$d = sqrt(4*S/\pi) = sqrt(4*11571.19/3.14) = 121$ cm

Check:

Residence time of air:

$t = V_\varepsilon/Qg = 3193649/1415000 = 2.26$ mins

Let $t = t_{min} = 2.5$ mins (from the DE column study), then

$V_\varepsilon = tQg = 2.5*1415000 = 3{,}537{,}500\ cm^3$

$V = V_\varepsilon/\varepsilon = 3537500/0.69 = 5{,}126{,}812\ cm^3$

$V_f = V - V_\varepsilon = 1589312\ cm^3$ (or $56.54\ ft^3$)

Since the bed density is $32\ lbs/ft^3$ (from the manufacturer's manual of diatomaceous earth), the total mass of DE required is:

Mass = 56.54*32 = 1,809 lbs

H = 225 cm

$S = (V/n)/H = 11{,}392.91\ cm^2$

d = 120 cm

Applied Loading = $Qg*Ci/V_f$ = 1.00 mg/cm^3·day

Vessels:

- For the water vessel (as a humidification reservoir), the assumptions were:

  Diameter of the vessel = 50 cm

  Height of the vessel = 100 cm

- For the BTEX vessel (as a contaminant reservoir), the assumptions included:

  Diameter of the vessel = 50 cm

  Height of the vessel = 100 cm

- For the nutrient vessel, the assumptions were:

  Diameter of the vessel = 50 cm

  Height of the vessel = 100 cm

Piping:

- For water, the assumptions were:

  Diameter of pipe = 25 mm

  Length of pipe = 20 m

  Material of pipe = PVC

- For air, the assumptions included:

  Diameter of pipe = 25 mm

  Length of pipe = 50 m

  Material of pipe = PVC

Sitework:

- Utilities:

Number of air compressor = 1

Number of water pump = 1

- Valves:

Number of valve = 14

Diameter of valve = 25-100 mm

- Flowmeters:

Number of flowmeter = 8

Diameter of flowmeter = 25-100 mm

The above design results are listed in Tables 21-22. The capital cost of the compost column (~$22,400) is significantly lower than that of the DE column (~$32,200). The main reason is that the cost of the DE medium (~$12,200) is very expensive compared to that of the compost medium (~$170).

Since operating costs of the two systems are difficult to predict, referring to the values in Tables 17-18, a ratio of 15% of capital cost to operating cost was used to predict the operating costs:

For the compost system, Co = 15%Cc = 0.15*22399 = 3,360 US $

For the DE system, Co = 15%Cc = 0.15*32,175 = 4,826 US $

Obviously, compared to the compost system, the nutrient recirculation in the DE system will cause an increase in the operating cost.

Thus, the total costs of these two systems are:

For the compost system, Ct = Cc + Co = 22,399 + 3,360 = 25,759 US $

For the DE system, Ct = Cc + Co = 32,175 + 4,826 = 37,001 US $

It is noted that, based on the above calculation, the total cost of the compost system (~$26,000) is lower than the value of $40,600-41,800 (Togna and Skladany,1994), and $33,000 (Zurlinden and Carmel, 1994). But, the total cost of the DE system (~$37,000) is within these literature values.

Table 21 Capital Cost of the Compost Column

Item in WBS	Quantity/Capacity	Cost (US $) Unit Price	Cost (US $) Total Price
Biofilter			
Filter	12.83 yd^3	13.04/yd^3	167
Column (Steel)	1,500 gallon, n = 4	2,350/ea.	9,400
Vessels (Steel)			
Water	275 gallon, n = 1	375/ea.	375
BTEX	275 gallon, n = 1	375/ea.	375
Piping (PVC)			
Water	1″, 30 ft	9.65/ft	290
Air	1″, 150 ft	9.65/ft	1,448
Sitework			
Utilities			
Compressor	50 ft^3/m, n = 1	3,760/ea.	3,760
Valves	1-4″, n = 10	480/ea.	4,800
Flowmeters	1-4″, n = 8	223/ea.	1,784
		$\Sigma =$	22,399

Notes: (1) The unit cost of the compost was from James et al. (1990).

(2) The unit cost of the air compressor was from Grainger General Catalog: Industrial and Commercial Equipment and Supplies, W. W. Grainger, Inc., (1991).

(3) All the other unit costs were from Mossman (1995).

(4) An inflation rate of 3% per year was used to bring prices up to 1995 level.

Table 22 Capital Cost of the DE Column

Item in WBS	Quantity/Capacity	Cost (US $) Unit Price	Cost (US $) Total Price
Biofilter			
Filter	1,809 lbs	6.75/lb	12,211
Column (Steel)	1,500 gallon, n = 2	2,350/ea.	4,700
Vessels (Steel)			
Water	275 gallon, n = 1	375/ea.	375
BTEX	275 gallon, n = 1	375/ea.	375
Piping (PVC)			
Water	1″, 60 ft	9.65/ft	579
Air	1″, 150 ft	9.65/ft	1,448
Sitework			
Utilities			
Compressor	50 ft^3/m, n = 1	3,760/ea.	3,760
Water Pump	10 gpm, n = 1	223/ea.	223
Valves	1-4″, n = 14	480/ea.	6,720
Flowmeters	1-4″, n = 8	223/ea.	1,784
		Σ =	32,175

Notes: (1) The unit cost of the diatomaceous earth was from Swartz. (1995).

(2) The unit costs of the air compressor and water pump were from Grainger General Catalog: Industrial and Commercial Equipment and Supplies, W. W. Grainger, Inc., (1991).

(3) All the other unit costs were from Mossman (1995).

(4) An inflation rate of 3% per year was used to bring prices up to 1995 level.

CHAPTER V

CONCLUSIONS

This project was designed to investigate the degradation of contaminated air streams containing a selected mixture of BTEX compounds (toluene, ethylbenzene, and o-xylene) by biofiltration. The objectives of this study included:

1) to demonstrate the feasibility of eliminating a selected mixture of BTEX compounds by biofiltration;
2) to provide the data of elimination efficiencies from biofilters for the selected mixture of BTEX compounds;
3) to compare elimination rates of the selected mixture of BTEX compounds obtained from biofilters containing two different support media;
4) to present some design criteria which can be used in a full-scale biofilter;
5) to develop a model for predicting the elimination of the selected mixture of BTEX compounds by biofiltration; and
6) to estimate the cost of eliminating the selected mixture of BTEX compounds by biofiltration.

To achieve the above objectives, two biofilters (compost and diatomaceous earth) were built and run at two levels of inlet concentration (~1000 and 2000 μg VOCs/L), and four levels of residence time (20, 10, 5.0, and 2.5 minutes) in the Environmental

Engineering Laboratory at Oklahoma State University for over two years. Through investigation of the biofilters on a lab-scale, the major findings of this research are as follows:

1) The elimination of selected BTEX compounds by biofiltration from a contaminated air stream is a feasible and effective method. For the selected BTEX compounds, this technology can provide between 31.4-100% elimination efficiency in terms of total VOCs at an applied loading of 0.11-0.88 mg VOCs/cm^3 compost·day, and 96.7-100% at an applied loading of 0.20-2.39 mg VOCs/cm^3 DE·day, respectively.
2) For the selected BTEX compounds, the ranges of the elimination rates were 0.11-0.37 mg VOCs/m^3·day for the compost biofilter and 0.20-2.35 mg VOCs/m^3·day for the DE biofilter. Under the same experimental conditions, such as applied loading, residence time (or air flow rate) and influent gas concentration, the DE column offered a higher elimination rate.
3) The main design criteria for the degradation of selected BTEX compounds using biofiltration are gas influent concentration, residence time (or air flow rate), and type of filter material. For the compost column, there are effects of residence time (2.5-20 minutes) and gas influent concentration (~1000-2000 μg VOCs/L) on the elimination efficiency, which for this study ranged from 31.4-100%. For the DE column, these two parameters have no effects on the elimination efficiency when the ranges of residence time and gas influent concentration are controlled between 2.5-20 minutes (even though the 2.5-min residence time should not be included statistically) and ~1000-2000 μg

VOCs/L, respectively, resulting in elimination efficiencies of 96.7-100%. For residence times of 10-20 minutes, and gas influent concentration of ~1000 μg VOCs/L, there was no effect of filter material type (compost or DE) on the elimination efficiency. To obtain an ~90% elimination efficiency, a residence time of 10 minutes is required for a compost biofilter at a low inlet concentration, and 2.5 minutes for a DE biofilter under low or high inlet concentration.

4) Under the operating conditions, there are no significant differences among four mathematical models developed in this study in terms of the best fit for the removal of VOCs in the compost column. But, the first-order model with a zero value for the dispersion coefficient is the best model for the prediction of VOC removal in the DE column.
5) Compared to other VOC control technologies, biofiltration can offer a considerably lower total cost. For the selected BTEX compounds, the total cost of a compost biofilter will be approximately $26,000, and about $37,000 for a DE biofilter under the conditions of a 50 ft^3/min air flow rate, a 200 ppm VOC inlet concentration, and a 90% elimination efficiency.
6) Statistical analysis (ANOVA) revealed that the influent concentration and residence time had significant effects on the elimination efficiency for the compost column, but no significant effects for the diatomaceous earth column. The type of filter material had significant effects on elimination efficiency at a high inlet concentration, but no significant effects for a residence time of 10-20 minutes.

7) Biodegradation was the dominant removal mechanism in the biofilters. Physical adsorption capacities of the filter media (compost and diatomaceous earth) in the biofilters were very small, especially for the diatomaceous earth medium. For the compost and DE columns, the elimination capacities of 99.5% and 99.9%, respectively, were attributed to biological degradation for the selected mixture of BTEX compounds.

CHAPTER VI

RECOMMENDATIONS

Although biofiltration technology has been demonstrated as an effective alternative in the application of air pollution control, the following aspects are recommended for further investigation:

1) Evaluate the effect of a lower residence time (< 2.5 minutes) on the elimination efficiency for a DE biofilter. Compared to other VOC control technologies, this might give a more competitive advantage with an acceptable elimination efficiency.
2) Utilize a lower recirculation rate of nutrient solution (< 5 mL/min) on the DE biofilter. This could help prevent sampling ports from blocking, and offer a better channel for air flow.
3) Investigate the effect of other factors, such as moisture, temperature, nutrients, pH of filter bed, microorganisms, and interactions of BTEX compounds, on a biofilter. This would provide a better understanding of both fundamental and applied aspects of biofiltration.
4) Study the feasibility of two cycle columns for a biofiltration system. One column would be regenerating (by endogenous decay) while the other is on line. It may prevent the column from the unnecessary accumulation of biofilm.

5) Conduct a batch test to measure degradation rate constants for biofiltration. This might improve the model's goodness of fit.
6) Run a tracer test with a completely inert tracer, such as argon, to provide a more accurate value of dispersion coefficient.
7) During further investigation of biofiltration, control experimental conditions as a Balance Case which requires the same number of the observed data for each experimental run. It will make the data analysis with SAS possible or easier.
8) Develop solutions (either analytical or numerical) for the Monod equation, either with or without considering a dispersion coefficient. This would broaden the applicability of biofiltration.
9) Obtain more detailed cost information of biofiltration, especially for operating cost. This would also assist in presenting a relatively accurate cost value during an evaluation phase so that a final decision on several alternatives can be easily made.

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APPENDIXES

Appendix A. Raw Data of Adsorption Study - Compost Medium

Time	Concentration (µg/L)			
(mins)	Toluene	Ethylbenzene	o-Xylene	Total
Influent:				
0.00	1036	498	398	1932
0.90	798	377	302	1477
2.45	626	296	235	1157
3.32	566	268	103	937
4.47	527	248	202	977
5.63	535	270	216	1021
6.60	553	262	208	1023
7.42	498	239	191	928
8.30	494	235	186	915
8.70	463	217	179	859
9.62	461	219	174	854
11.55	439	205	153	797
12.37	455	210	160	825
Effluent:				
0.00	0	0	0	0
0.65	0	0	0	0
2.33	198	0	0	198
3.25	431	0	0	431
4.23	635	40	6	681
5.17	695	84	9	788
6.48	697	165	0	862
7.33	634	212	11	857
8.17	572	239	50	861
9.38	537	259	93	889
10.25	512	255	120	887
12.23	481	241	155	877
13.02	462	225	162	849

Appendix B. Raw Data of Adsorption Study - Diatomaceous Earth Medium

Time	Concentration (μg/L)			
(mins)	Toluene	Ethylbenzene	o-Xylene	Total
Influent:				
0.00	451	465	667	1583
1.12	616	487	688	1790
1.73	704	523	741	1968
2.38	515	437	629	1581
3.03	904	586	826	2316
3.70	572	509	372	1454
Effluent:				
0.00	0	0	0	0
0.20	192	146	69	407
0.52	541	556	854	1950
0.82	560	508	733	1801
1.42	711	501	688	1901
2.03	756	544	777	2077
2.72	717	548	777	2042
3.35	820	577	834	2231
4.00	755	551	819	2125

Appendix C. Calculation of Physical Adsorption Capacity - Compost and Diatomaceous Earth Media

(1) Compost Medium:

T	Ci	Ce	Ce/Ci	Δt	$\overline{Ci}$	$\overline{Ce}$	$\overline{Ci}-\overline{Ce}$	Δt($\overline{Ci}-\overline{Ce}$)
(hrs)	(μg/L)	(μg/L)		(hrs)	(μg/L)	(μg/L)	(μg/L)	(hrs·μg/L)
0.00	1932	0	0.00	0.9	1705	0	1705	1534.05
0.90	1477	0	0.00	1.55	1317	100	1217	1886.35
2.45	1157	200	0.17	0.87	1047	320	727	632.49
3.32	937	440	0.47	1.15	957	570	387	445.05
4.47	977	700	0.72	1.16	999	750	249	288.84
5.63	1021	800	0.78	0.97	1022	830	192	186.24
6.60	1023	860	0.84	0.82	976	860	116	94.71
7.42	928	860	0.93	0.88	922	863	59	51.92
8.30	915	865	0.95	0.4	887	868	20	7.8
8.70	859	870	1.01	0.92	857	885	0	0
9.62	854	900	1.05	1.93	826	895	0	0
11.55	797	890	1.12	0.82	811	870	0	0
12.37	825	850	1.03					
			Σ	12.37			4671	5127.45

Physical Adsorption Capacity:

$$[\Sigma\ Qg*\Delta t*(\overline{Ci}-\overline{Ce})]/M = 0.042*5127.45*60/398.5 = 32.42\ \mu g/gm$$

Where,

Qg = 42 mL/min (air flow rate)

M = 398.5 gm (mass of compost)

t = time, hour

Ci, $\overline{Ci}$ = influent and average concentrations

Ce, $\overline{Ce}$ = effluent and average concentrations

Appendix C. Calculation of Physical Adsorption Capacity - Compost and Diatomaceous Earth Media (Cont'd)

(2) Diatomaceous Earth Medium:

T (hrs)	Ci (μg/L)	Ce (μg/L)	Ce/Ci	Δt (hrs)	$\overline{Ci}$ (μg/L)	$\overline{Ce}$ (μg/L)	$\overline{Ci}-\overline{Ce}$ (μg/L)	$\Delta t(\overline{Ci}-\overline{Ce})$ (hrs·μg/L)
0.00	1583	0	0.00	0.20	1602	204	1398	279.55
0.20	1620	407	0.25	0.32	1648	1179	469	149.97
0.52	1675	1950	1.16	0.30	1703	1876	0	0.00
0.82	1730	1801	1.04	0.60	1803	1851	0	0.00
1.42	1875	1901	1.01	0.61	1838	1989	0	0.00
2.03	1800	2077	1.15	0.69	1888	2060	0	0.00
2.72	1975	2042	1.03	0.63	1938	2137	0	0.00
3.35	1900	2231	1.17	0.35	1677	2203	0	0.00
3.70	1454	2175	1.50					
			Σ	3.70			1866	429.52

Physical Adsorption Capacity:

$$[\Sigma\, Qg*\Delta t*(\overline{Ci}-\overline{Ce})]/M = 0.048*429.52*60/389.1 = 3.18\ \mu g/gm$$

Where,

Qg = 48 mL/min (air flow rate)

M = 389.1 gm (mass of diatomaceous earth)

t = time, hour

Ci, $\overline{Ci}$ = influent and average concentrations

Ce, $\overline{Ce}$ = effluent and average concentrations

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent

Run No. 0 (Acclimation Period):

- Influent:

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
10/14/93	0	759	298	262	1319
10/15/93	1	1051	282	168	1501
10/16/93	2	1247	304	166	1717
10/17/93	3	1437	398	209	2044
10/18/93	4	2284	690	365	3339
10/19/93	5	2166	686	371	3223
10/20/93	6	827	256	140	1222
10/21/93	7	1081	327	178	1587
10/22/93	8	1257	395	220	1871
10/23/93	9	1157	353	189	1699
10/24/93	10	1172	367	197	1736
10/25/93	11	1138	365	203	1705
10/26/93	12	1373	428	225	2026
10/27/93	13	1143	359	167	1669
10/28/93	14	896	301	47	1245
11/02/93	19	1092	365	199	1656
11/03/93	20	1210	400	220	1830
11/04/93	21	1211	431	235	1878
11/05/93	22	1181	424	233	1838
11/06/93	23	1170	409	224	1803
11/07/93	24	1148	415	222	1784
11/08/93	25	1169	420	230	1819
11/09/93	26	1130	414	227	1770
11/10/93	27	1220	455	252	1927
11/11/93	28	1210	458	250	1918
11/12/93	29	1069	403	224	1695
AVG.		1223	400	216	1839
S.D.		328	100	62	473

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time	Concentration (μg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 0 (Acclimation Period):					
• Effluent:					
10/14/93	0	0	0	0	0
10/15/93	1	883	224	154	1260
10/16/93	2	348	0	114	461
10/17/93	3	0	0	41	41
10/18/93	4	0	0	0	0
10/19/93	5	0	0	0	0
10/20/93	6	0	0	0	0
10/21/93	7	0	0	0	0
10/22/93	8	0	0	0	0
10/23/93	9	0	0	0	0
10/24/93	10	0	0	0	0
10/25/93	11	0	0	0	0
10/26/93	12	0	0	0	0
10/27/93	13	0	0	0	0
10/28/93	14	0	0	0	0
11/02/93	19	0	0	0	0
11/03/93	20	0	0	0	0
11/04/93	21	0	0	0	0
11/05/93	22	0	0	0	0
11/06/93	23	0	0	0	0
11/07/93	24	0	0	0	0
11/08/93	25	0	0	0	0
11/09/93	26	0	0	0	0
11/10/93	27	0	0	0	0
11/11/93	28	0	0	0	0
11/12/93	29	0	0	0	0

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time (days)	Concentration (µg/L) Toluene	Ethylbenzene	o-Xylene	Total
Run No. 1 (Air Flow Rate = 25 mL/min):					
• Influent:					
11/12/93	29	554	218	146	918
11/13/93	30	404	157	107	668
11/14/93	31	378	142	91	610
11/15/93	32	341	130	89	560
11/16/93	33	675	243	162	1079
11/17/93	34	652	278	165	1095
11/18/93	35	582	224	143	949
11/19/93	36	717	303	204	1224
11/20/93	37	721	315	212	1247
11/21/93	38	688	293	197	1178
11/22/93	39	783	349	238	1371
11/23/93	40	664	296	205	1164
11/24/93	41	628	283	186	1097
11/25/93	42	550	249	165	964
11/26/93	43	439	204	143	787
11/27/93	44	504	234	160	899
11/28/93	45	684	330	233	1247
11/29/93	46	682	342	240	1263
AVG.		591	255	171	1018
S.D.		131	67	47	240
Run No. 1 (Air Flow Rate = 25 mL/min):					
• Effluent:					
11/12/93	29	0	0	0	0
11/13/93	30	0	0	0	0
11/14/93	31	0	0	0	0

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 1 (Air Flow Rate = 25 mL/min):					
• Effluent (Cont'd)					
11/15/93	32	0	0	0	0
11/16/93	33	0	0	0	0
11/17/93	34	0	0	0	0
11/18/93	35	0	0	0	0
11/19/93	36	0	0	0	0
11/20/93	37	0	0	0	0
11/21/93	38	0	0	0	0
11/22/93	39	0	0	0	0
11/23/93	40	0	0	0	0
11/24/93	41	0	0	0	0
11/25/93	42	0	0	0	0
11/26/93	43	0	0	0	0
11/27/93	44	0	0	0	0
11/28/93	45	0	0	0	0
11/29/93	46	0	0	0	0
AVG.		0	0	0	0
S.D.		0	0	0	0
Run No. 2 (Air Flow Rate = 50 mL/min):					
• Influent:					
11/29/93	46	596	326	200	1123
11/30/93	47	576	292	174	1042
12/1/93	48	618	300	183	1100
12/2/93	49	636	298	177	1111
12/3/93	50	585	268	153	1007
12/4/93	51	626	290	171	1086

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 2 (Air Flow Rate = 50 mL/min):					
• Influent (Cont'd):					
12/5/93	52	565	263	155	983
12/6/93	53	705	328	194	1228
12/7/93	54	742	345	198	1284
12/8/93	55	540	256	148	944
12/9/93	56	583	269	155	1007
12/10/93	57	590	282	163	1035
12/11/93	58	576	270	158	1004
12/12/93	59	499	239	135	873
12/13/93	60	494	235	129	858
12/14/93	61	469	220	122	812
12/15/93	62	482	245	147	874
12/16/93	63	475	243	144	862
AVG.		575	276	161	1013
S.D.		76	35	23	130
Run No. 2 (Air Flow Rate = 50 mL/min):					
• Effluent:					
11/29/93	46	0	0	9	9
11/30/93	47	0	0	0	0
12/1/93	48	0	0	0	0
12/2/93	49	69	0	5	75
12/3/93	50	0	0	0	0
12/4/93	51	0	0	0	0
12/5/93	52	0	0	0	0
12/6/93	53	128	0	72	201
12/7/93	54	63	0	30	93

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time (days)	Concentration (µg/L) Toluene	Ethylbenzene	o-Xylene	Total
Run No. 2 (Air Flow Rate = 50 mL/min):					
• Effluent (Cont'd):					
12/8/93	55	0	0	0	0
12/9/93	56	0	0	0	0
12/10/93	57	0	0	0	0
12/11/93	58	0	0	0	0
12/12/93	59	0	0	0	0
12/13/93	60	0	0	0	0
12/14/93	61	0	0	0	0
12/15/93	62	28	0	25	53
12/16/93	63	88	0	50	139
AVG.		21	0	11	32
S.D.		39	0	21	59
Run No. 3 (Air Flow Rate = 100 mL/min):					
• Influent:					
*12/16/93	63	568	240	158	966
*12/17/93	64	275	118	35	428
*12/18/93	65	466	187	127	781
*12/19/93	66	468	199	132	799
*12/20/93	67	449	189	111	749
*12/21/93	68	526	208	125	859
*12/22/93	69	871	368	227	1466
*12/23/93	70	572	262	167	1001
*12/24/93	71	563	273	181	1017
*12/25/93	72	548	242	160	950
*12/26/93	73	724	312	200	1236
*12/27/93	74	440	200	130	770

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Run No. 3 (Air Flow Rate = 100 mL/min):

- Influent (Cont'd):

Date	Time		Concentration (µg/L)		
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
*12/28/93	75	431	182	120	733
**12/29/93	76	400	176	114	690
**12/30/93	77	626	265	36	927
12/31/93	78	608	279	191	1078
1/01/94	79	744	360	245	1349
1/02/94	80	677	325	215	1218
1/03/94	81	503	237	149	889
1/04/94	82	343	165	46	553
1/05/94	83	547	266	175	988
1/06/94	84	712	354	245	1311
1/07/94	85	537	288	191	1017
**1/08/94	86	497	218	132	847
1/09/94	87	627	295	99	1020
1/10/94	88	664	327	109	1101
1/11/94	89	512	250	171	934
1/12/94	90	523	280	122	925
**1/13/94	91	523	182	72	777
1/14/94	92	482	183	88	753
1/15/94	93	600	231	43	874
1/16/94	94	489	204	68	761
1/17/94	95	384	159	86	630
1/18/94	96	556	234	56	846
1/19/94	97	496	227	135	858
1/20/94	98	637	294	176	1107
1/21/94	99	678	336	192	1206
**1/22/94	100	686	345	4	1034
**1/23/94	101	704	346	224	1274
**1/24/94	102	637	329	67	1034
1/25/94	103	578	295	70	943
1/26/94	104	748	397	244	1388

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time	Concentration (μg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 3 (Air Flow Rate = 100 mL/min):					
• Influent (Cont'd):					
1/27/94	105	750	408	258	1416
**1/28/94	106	412	202	131	745
**1/29/94	107	343	173	118	633
**1/30/94	108	417	195	62	675
**1/31/94	109	366	203	61	631
2/01/94	110	645	361	225	1231
2/02/94	111	645	371	230	1246
2/03/94	112	737	459	304	1500
2/04/94	113	667	405	266	1339
2/05/94	114	596	389	244	1229
2/06/94	115	626	407	258	1291
2/07/94	116	634	443	289	1366
AVG.		598	308	173	1079
S.D.		103	83	79	247
Run No. 3 (Air Flow Rate = 100 mL/min):					
• Effluent:					
*12/16/93	63	0	0	0	0
*12/17/93	64	0	0	15	15
*12/18/93	65	0	0	0	0
*12/19/93	66	8	0	19	27
*12/20/93	67	104	0	80	184
*12/21/93	68	63	0	52	116
*12/22/93	69	145	19	101	266
*12/23/93	70	264	52	141	456
*12/24/93	71	2	0	0	2

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Run No. 3 (Air Flow Rate = 100 mL/min):

- Effluent (Cont'd):

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
*12/25/93	72	0	0	0	0
*12/26/93	73	0	0	0	0
*12/27/93	74	17	0	0	17
*12/28/93	75	17	0	0	17
*12/29/93	76	204	68	120	391
*12/30/93	77	0	0	0	0
12/31/93	78	233	77	15	325
1/01/94	79	159	39	147	345
1/02/94	80	329	16	0	345
1/03/94	81	290	89	103	481
1/04/94	82	32	0	68	100
1/05/94	83	214	48	83	345
1/06/94	84	379	95	39	514
1/07/94	85	291	19	4	314
**1/08/94	86	8	0	19	27
1/09/94	87	95	36	50	181
1/10/94	88	332	119	85	537
1/11/94	89	239	77	65	382
1/12/94	90	247	120	35	402
**1/13/94	91	0	0	0	0
1/14/94	92	248	63	0	311
1/15/94	93	170	38	10	218
1/16/94	94	265	87	34	386
1/17/94	95	279	100	85	464
1/18/94	96	197	67	45	309
1/19/94	97	291	91	73	454
1/20/94	98	514	185	67	767
1/21/94	99	394	196	179	769
**1/22/94	100	41	0	55	96
**1/23/94	101	0	0	0	0

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 3 (Air Flow Rate = 100 mL/min):					
• Effluent (Cont'd):					
**1/24/94	102	284	54	146	484
1/25/94	103	218	100	63	382
1/26/94	104	165	72	127	364
1/27/94	105	420	175	180	776
**1/28/94	106	136	0	175	311
**1/29/94	107	0	0	0	0
**1/30/94	108	0	0	0	0
**1/31/94	109	0	0	0	0
2/01/94	110	149	32	48	229
2/02/94	111	290	142	170	602
2/03/94	112	504	271	255	1029
2/04/94	113	481	280	279	1039
2/05/94	114	297	174	95	566
2/06/94	115	284	180	211	674
2/07/94	116	322	208	226	756
AVG.		278	107	95	479
S.D.		113	73	78	234
Run No. 4 (Air Flow Rate = 200 mL/min):					
• Influent:					
5/23/94	221	548	481	366	1395
5/24/94	222	515	436	323	1273
5/25/94	223	433	334	230	998
5/26/94	224	431	320	212	963
5/27/94	225	404	298	215	917
5/28/94	226	430	335	217	983

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time (days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 4 (Air Flow Rate = 200 mL/min):					
• Influent (Cont'd):					
5/29/94	227	365	276	188	829
5/30/94	228	399	316	210	925
5/31/94	229	416	336	110	862
6/01/94	230	502	421	284	1207
6/02/94	231	439	371	242	1052
6/03/94	232	353	294	201	848
AVG.		436	352	233	1021
S.D.		59	63	66	180
Run No. 4 (Air Flow Rate = 200 mL/min):					
• Effluent:					
5/23/94	221	294	113	213	620
5/24/94	222	318	190	256	765
5/25/94	223	339	197	223	760
5/26/94	224	304	192	238	734
5/27/94	225	264	149	157	570
5/28/94	226	299	177	191	667
5/29/94	227	257	189	215	661
5/30/94	228	292	177	197	667
5/31/94	229	291	187	214	692
6/01/94	230	313	186	202	701
6/02/94	231	310	207	229	745
6/03/94	232	254	185	204	643
AVG.		295	179	212	685
S.D.		26	25	25	59

Concentration (μg/L) applies to the Toluene, Ethylbenzene, o-Xylene and Total columns.

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time	Concentration (μg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 5 (Air Flow Rate = 25 mL/min):					
• Influent:					
*2/07/94	116	799	449	401	1650
*2/08/94	117	958	455	421	1835
*2/09/94	118	844	388	352	1584
*2/10/94	119	855	392	356	1603
*2/11/94	120	819	382	347	1548
*2/12/94	121	905	454	411	1770
*2/13/94	122	685	357	323	1365
*2/14/94	123	1049	629	588	2266
*2/15/94	124	380	168	161	709
*2/16/94	125	513	193	149	855
*2/17/94	126	1185	542	445	2172
*2/18/94	127	789	345	268	1403
*2/19/94	128	865	442	347	1654
2/20/94	129	1145	573	465	2182
2/21/94	130	878	461	393	1733
2/22/94	131	876	443	362	1681
2/23/94	132	877	492	428	1797
2/25/94	134	1197	753	705	2656
2/26/94	135	1112	692	632	2436
2/27/94	136	1181	717	632	2530
2/28/94	137	1054	655	612	2321
3/01/94	138	770	490	450	1710
3/02/94	139	757	503	455	1714
3/03/94	140	1313	927	828	3067
3/04/94	141	863	669	619	2151
3/05/94	142	812	624	614	2050
3/06/94	143	844	680	641	2165
3/07/94	144	786	646	600	2032
3/08/94	145	913	810	776	2499
3/09/94	146	765	726	718	2208

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 5 (Air Flow Rate = 25 mL/min):					
• Influent (Cont'd):					
3/10/94	147	644	610	607	1862
AVG.		933	637	585	2155
S.D.		187	129	133	382
Run No. 5 (Air Flow Rate = 25 mL/min):					
• Effluent:					
*2/07/94	116	11	9	133	153
*2/08/94	117	245	96	261	602
*2/09/94	118	134	39	233	405
*2/10/94	119	449	54	173	676
*2/11/94	120	448	160	144	753
*2/12/94	121	617	269	380	1267
*2/13/94	122	347	150	299	796
*2/14/94	123	596	234	402	1232
*2/15/94	124	12	8	17	38
*2/16/94	125	0	0	0	0
*2/17/94	126	23	4	4	32
*2/18/94	127	6	0	0	6
*2/19/94	128	0	0	0	0
2/20/94	129	517	175	309	1001
2/21/94	130	424	180	354	958
2/22/94	131	428	168	303	899
2/23/94	132	481	217	271	969
2/25/94	134	777	399	531	1707
2/26/94	135	757	384	481	1622
2/27/94	136	847	486	589	1923

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 5 (Air Flow Rate = 25 mL/min):					
• Effluent (Cont'd):					
2/28/94	137	685	398	544	1627
3/01/94	138	408	246	400	1055
3/02/94	139	407	236	405	1048
3/03/94	140	917	528	670	2115
3/04/94	141	706	421	649	1776
3/05/94	142	380	227	438	1045
3/06/94	143	568	358	603	1528
3/07/94	144	464	300	558	1321
3/08/94	145	564	374	690	1628
3/09/94	146	402	282	535	1219
3/10/94	147	349	290	553	1192
AVG.		560	315	494	1369
S.D.		177	108	130	377
Run No. 6 (Air Flow Rate = 50 mL/min):					
• Influent:					
*3/10/94	147	483	669	581	1733
*3/11/94	148	1133	726	630	2490
*3/13/94	149	1086	455	406	1947
*3/14/94	150	848	357	262	1468
*3/15/94	151	997	424	293	1713
*3/16/94	153	2696	1221	862	4778
*3/17/94	154	1803	841	572	3215
3/18/94	155	1047	482	352	1882
3/19/94	156	1183	582	452	2217
3/20/94	157	1040	495	387	1922

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 6 (Air Flow Rate = 50 mL/min):					
• Influent (Cont'd):					
3/21/94	158	1006	487	356	1849
3/22/94	159	945	450	329	1723
3/23/94	160	984	495	398	1877
3/24/94	161	753	371	272	1395
3/25/94	162	871	407	305	1583
3/26/94	163	1180	578	433	2191
3/27/94	164	942	470	343	1755
3/28/94	165	733	332	369	1435
3/29/94	166	1037	559	440	2036
3/30/94	167	959	627	548	2134
3/31/94	168	995	604	537	2135
4/01/94	169	1302	889	819	3011
4/02/94	170	1069	721	640	2431
4/03/94	171	893	636	659	2188
4/04/94	172	906	628	508	2041
AVG.		991	545	453	1989
S.D.		142	133	143	377
Run No. 6 (Air Flow Rate = 50 mL/min):					
• Effluent:					
*3/10/94	147	262	318	529	1108
*3/11/94	148	9	16	14	39
*3/13/94	149	22	24	21	67
*3/14/94	150	451	113	256	819
*3/15/94	151	568	132	286	986
*3/16/94	153	2514	995	905	4414

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time (days)	Concentration (μg/L) Toluene	Ethylbenzene	o-Xylene	Total
Run No. 6 (Air Flow Rate = 50 mL/min):					
• Effluent (Cont'd):					
*3/17/94	154	1430	496	578	2504
3/18/94	155	780	298	221	1299
3/19/94	156	771	219	390	1379
3/20/94	157	500	131	340	970
3/21/94	158	481	116	307	903
3/22/94	159	339	74	189	602
3/23/94	160	302	84	239	625
3/24/94	161	257	67	201	525
3/25/94	162	628	186	277	1091
3/26/94	163	981	320	340	1640
3/27/94	164	811	304	369	1485
3/28/94	165	653	214	292	1159
3/29/94	166	656	280	343	1279
3/30/94	167	593	269	499	1361
3/31/94	168	633	252	406	1291
4/01/94	169	1287	717	876	2879
4/02/94	170	639	291	606	1535
4/03/94	171	423	143	375	942
4/04/94	172	472	200	425	1097
AVG.		622	231	372	1226
S.D.		251	147	163	523
Run No. 7 (Air Flow Rate = 100 mL/min):					
• Influent:					
*4/04/94	172	1057	630	489	2177
*4/05/94	173	1015	545	392	1953

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Run No. 7 (Air Flow Rate = 100 mL/min):

- Influent (Cont'd):

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
*4/06/94	174	1003	555	431	1989
*4/07/94	175	988	526	382	1895
4/08/94	176	1205	665	493	2363
4/09/94	177	1083	585	411	2078
4/10/94	178	1017	531	388	1937
4/11/94	179	1063	556	393	2012
4/12/94	180	966	524	381	1871
4/13/94	181	940	484	351	1774
4/14/94	182	950	526	371	1846
4/15/94	183	963	551	418	1932
4/16/94	184	1138	649	488	2275
4/17/94	185	1116	644	483	2243
4/18/94	186	1162	685	508	2355
4/19/94	187	1127	689	513	2329
4/20/94	188	1192	732	538	2462
4/21/94	189	1122	688	498	2308
AVG.		1074	608	445	2127
S.D.		92	79	63	230

Run No. 7 (Air Flow Rate = 100 mL/min):

- Effluent:

Date	Time (days)	Toluene	Ethylbenzene	o-Xylene	Total
*4/04/94	172	741	333	416	1490
*4/05/94	173	666	287	407	1359
*4/06/94	174	850	330	432	1612
*4/07/94	175	709	276	400	1385
4/08/94	176	822	306	409	1537

Appendix D. Raw Data of Compost Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time (days)	Concentration (µg/L) Toluene	 Ethylbenzene	 o-Xylene	 Total
Run No. 7 (Air Flow Rate = 100 mL/min):					
• Effluent (Cont'd):					
4/09/94	177	720	274	395	1388
4/10/94	178	623	217	320	1161
4/11/94	179	666	248	355	1268
4/12/94	180	627	249	374	1250
4/13/94	181	608	224	339	1171
4/14/94	182	538	202	343	1084
4/15/94	183	492	183	338	1013
4/16/94	184	451	157	305	913
4/17/94	185	675	253	377	1304
4/18/94	186	777	299	424	1500
4/19/94	187	678	280	415	1374
4/20/94	188	584	241	387	1211
4/21/94	189	603	256	401	1261
AVG.		633	242	370	1245
S.D.		102	42	37	174

* The data on these dates were not included in the calculation of average (AVG.) and standard deviation (S.D.) because the biofilter system had not reached steady-state.

** The data on these dates were not included in the calculation of average (AVG.) and standard deviation (S.D.) because there were some operational problems in the biofilter system.

Appendix E. Raw Data of Compost Column Study - Average Contaminant Concentrations from Other Sampling Ports

Sampling Port	Concentration (µg/L)			
	Toluene	Ethylbenzene	o-Xylene	Total
• Run No. 1:				
2	459	80	182	720
3	281	20	139	441
4	133	8	108	250
5	27	0	29	56
6	5	0	7	12
• Run No. 2:				
2	543	211	161	915
3	501	189	152	843
4	446	148	137	731
5	356	101	120	577
6	273	57	124	454

Appendix E. Raw Data of Compost Column Study - Average Contaminant Concentrations from Other Sampling Ports (Cont'd)

Sampling Port	Concentration (μg/L)			
	Toluene	Ethylbenzene	o-Xylene	Total
• Run No. 3:				
2	536	253	161	950
3	517	240	156	914
4	449	188	114	752
5	406	159	119	683
6	363	142	100	605
• Run No. 5:				
2	829	498	530	1857
3	779	450	514	1743
4	739	419	500	1658
5	677	379	475	1530
6	627	356	477	1460

Appendix E. Raw Data of Compost Column Study - Average Contaminant Concentrations from Other Sampling Ports (Cont'd)

Sampling Port	Concentration (μg/L)			
	Toluene	Ethylbenzene	o-Xylene	Total
• Run No. 6:				
2	909	455	417	1780
3	889	429	419	1737
4	778	341	384	1504
5	740	309	387	1437
6	676	272	376	1324
• Run No. 7:				
2	972	510	399	1881
3	902	429	405	1737
4	826	361	380	1568
5	775	320	381	1476
6	731	314	395	1440

Appendix F. Raw Data of Diatomaceous Earth Column Study - Daily Contaminant Concentrations from Influent and Effluent

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 1 (Air Flow Rate = 25 mL/min):					
• Influent:					
*8/05/94	0	757	345	252	1353
*8/06/94	1	737	359	285	1381
*8/07/94	2	667	320	236	1223
*8/08/94	3	925	493	163	1581
*8/09/94	4	1218	685	503	2406
*8/10/94	5	24	0	0	24
8/11/94	6	742	483	364	1588
8/12/94	7	777	507	512	1797
8/13/94	8	634	437	355	1426
8/14/94	9	627	411	329	1367
8/15/94	10	806	556	423	1784
8/16/94	11	860	598	478	1936
8/17/94	12	733	511	418	1662
8/18/94	13	666	487	401	1554
8/19/94	14	599	436	366	1401
8/20/94	15	566	415	168	1148
8/21/94	16	555	406	344	1304
8/22/94	17	517	374	318	1208
8/23/94	18	518	365	299	1183
AVG.		662	460	367	1489
S.D.		113	70	86	254
Run No. 1 (Air Flow Rate = 25 mL/min):					
• Effluent:					
*8/05/94	0	660	334	115	1109
*8/06/94	1	14	9	16	39

Appendix F. Raw Data of Diatomaceous Earth Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time (days)	Concentration (μg/L) Toluene	Ethylbenzene	o-Xylene	Total
Run No. 1 (Air Flow Rate = 25 mL/min):					
• Effluent (Cont'd):					
*8/07/94	2	166	186	34	386
*8/08/94	3	196	307	73	576
*8/09/94	4	217	364	209	790
*8/10/94	5	0	0	0	0
8/11/94	6	0	0	0	0
8/12/94	7	0	0	0	0
8/13/94	8	0	0	0	0
8/14/94	9	0	0	0	0
8/15/94	10	0	99	0	99
8/16/94	11	0	0	0	0
8/17/94	12	0	0	0	0
8/18/94	13	0	0	0	0
8/19/94	14	0	0	0	0
8/20/94	15	0	0	0	0
8/21/94	16	0	0	0	0
8/22/94	17	0	0	0	0
8/23/94	18	0	0	0	0
AVG.		0	8	0	8
S.D.		0	27	0	27
Run No. 2 (Air Flow Rate = 50 mL/min):					
• Influent:					
*8/23/94	18	771	482	340	1593
8/24/94	19	597	465	271	1333
8/25/94	20	538	354	245	1138
8/26/94	21	544	359	253	1157

Appendix F. Raw Data of Diatomaceous Earth Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time		Concentration (µg/L)		
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 2 (Air Flow Rate = 50 mL/min):					
• Influent (Cont'd):					
8/27/94	22	526	347	201	1074
8/28/94	23	726	506	368	1600
8/29/94	24	627	445	318	1390
8/30/94	25	649	468	346	1462
8/31/94	26	573	414	293	1280
9/01/94	27	749	538	386	1673
9/02/94	28	525	365	238	1127
9/03/94	29	602	451	327	1380
9/04/94	30	589	441	326	1357
9/05/94	31	578	438	315	1330
9/06/94	32	600	459	334	1393
9/07/94	33	593	459	340	1392
9/08/94	34	561	439	329	1330
AVG.		599	434	306	1338
S.D.		64	54	51	163
Run No. 2 (Air Flow Rate = 50 mL/min):					
• Effluent:					
*8/23/94	18	60	248	125	432
8/24/94	19	0	16	0	16
8/25/94	20	0	29	0	29
8/26/94	21	0	25	0	25
8/27/94	22	0	1	0	1
8/28/94	23	0	83	0	83
8/29/94	24	0	32	23	55
8/30/94	25	0	46	0	46

Appendix F. Raw Data of Diatomaceous Earth Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 2 (Air Flow Rate = 50 mL/min):					
• Effluent (Cont'd):					
8/31/94	26	0	11	0	11
9/01/94	27	0	38	0	38
9/02/94	28	0	2	0	2
9/03/94	29	0	17	6	24
9/04/94	30	0	11	0	11
9/05/94	31	0	17	0	17
9/06/94	32	0	2	0	2
9/07/94	33	0	58	0	58
9/08/94	34	0	77	0	77
AVG.		0	29	2	31
S.D.		0	26	6	26
Run No. 3 (Air Flow Rate = 100 mL/min):					
• Influent:					
*9/08/94	34	481	328	291	1100
9/09/94	35	562	388	354	1303
9/10/94	36	513	366	327	1206
9/11/94	37	498	349	307	1154
9/12/94	38	517	372	333	1222
9/13/94	39	524	381	347	1252
9/14/94	40	485	356	316	1156
9/15/94	41	477	360	332	1170
9/16/94	42	463	334	310	1107
9/17/94	43	455	328	308	1091
9/18/94	44	364	263	241	867
9/19/94	45	353	260	231	843

Appendix F. Raw Data of Diatomaceous Earth Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time	Concentration (μg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 3 (Air Flow Rate = 100 mL/min):					
• Influent (Cont'd):					
9/20/94	46	547	390	352	1289
9/21/94	47	586	430	395	1411
9/22/94	48	526	390	345	1261
AVG.		491	355	321	1167
S.D.		67	47	43	156
Run No. 3 (Air Flow Rate = 100 mL/min):					
• Effluent:					
*9/08/94	34	0	28	0	28
9/09/94	35	0	4	0	4
9/10/94	36	0	2	0	2
9/11/94	37	0	0	0	0
9/12/94	38	0	0	0	0
9/13/94	39	0	0	0	0
9/14/94	40	0	0	0	0
9/15/94	41	0	0	0	0
9/16/94	42	0	0	0	0
9/17/94	43	0	0	0	0
9/18/94	44	0	0	0	0
9/19/94	45	0	17	0	17
9/20/94	46	0	6	0	6
9/21/94	47	0	6	21	27
9/22/94	48	0	0	0	0
AVG.		0	2	2	4
S.D.		0	5	6	8

Appendix F. Raw Data of Diatomaceous Earth Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 4 (Air Flow Rate = 200 mL/min):					
• Influent:					
*12/05/94	122	504	217	220	941
12/06/94	123	511	238	212	961
12/07/94	124	492	283	258	1033
12/08/94	125	434	344	291	1069
12/09/94	126	327	430	363	1119
12/10/94	127	417	274	229	920
12/11/94	128	1038	413	186	1637
12/12/94	129	972	293	237	1502
AVG.		599	325	254	1177
S.D.		284	73	58	279
Run No. 4 (Air Flow Rate = 200 mL/min):					
• Effluent:					
*12/05/94	122	0	75	220	295
12/06/94	123	0	43	0	43
12/07/94	124	0	31	0	31
12/08/94	125	0	14	0	14
12/09/94	126	0	73	0	73
12/10/94	127	0	27	0	27
12/11/94	128	0	61	0	61
12/12/94	129	0	22	0	22
AVG.		0	39	0	39
S.D.		0	22	0	22

Appendix F. Raw Data of Diatomaceous Earth Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Run No. 5 (Air Flow Rate = 25 mL/min):

- Influent:

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
*9/22/94	48	780	524	429	1734
*9/23/94	49	1073	627	513	2212
*9/24/94	50	964	544	456	1963
9/25/94	51	921	487	366	1774
9/26/94	52	1150	645	499	2294
9/27/94	53	1059	625	498	2182
9/28/94	54	1119	685	554	2358
9/29/94	55	991	586	473	2051
9/30/94	56	1000	609	480	2089
10/01/94	57	945	600	481	2027
10/02/94	58	1056	687	573	2316
10/03/94	59	1122	732	626	2480
10/04/94	60	1025	672	561	2259
10/05/94	61	1014	674	573	2261
10/06/94	62	1028	689	581	2298
AVG.		1036	641	522	2199
S.D.		70	65	70	188

Run No. 5 (Air Flow Rate = 25 mL/min):

- Effluent:

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
*9/22/94	48	19	147	0	166
*9/23/94	49	0	85	0	85
*9/24/94	50	0	49	0	49
9/25/94	51	0	0	0	0
9/26/94	52	0	0	0	0
9/27/94	53	0	0	0	0

Appendix F. Raw Data of Diatomaceous Earth Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 5 (Air Flow Rate = 25 mL/min):					
• Effluent (Cont'd):					
9/28/94	54	0	0	0	0
9/29/94	55	0	0	0	0
9/30/94	56	0	0	0	0
10/01/94	57	0	0	0	0
10/02/94	58	0	0	0	0
10/03/94	59	0	0	0	0
10/04/94	60	0	0	0	0
10/05/94	61	0	0	0	0
10/06/94	62	0	0	0	0
AVG.		0	0	0	0
S.D.		0	0	0	0
Run No. 6 (Air Flow Rate = 50 mL/min):					
• Influent:					
10/07/94	63	920	614	584	2119
10/08/94	64	901	593	561	2055
10/09/94	65	873	580	529	1982
10/10/94	66	987	658	625	2270
10/11/94	67	990	679	651	2321
10/12/94	68	969	650	621	2240
10/13/94	69	857	574	531	1961
10/14/94	70	902	622	599	2123
10/15/94	71	846	575	557	1978
10/16/94	72	897	618	598	2113
10/17/94	73	1021	710	676	2406
10/18/94	74	1059	781	739	2579

Appendix F. Raw Data of Diatomaceous Earth Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time		Concentration (µg/L)		
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 6 (Air Flow Rate = 50 mL/min):					
• Influent (Cont'd):					
10/19/94	75	1032	777	725	2535
10/20/94	76	1044	773	728	2545
AVG.		950	657	623	2230
S.D.		73	76	72	218
Run No. 6 (Air Flow Rate = 50 mL/min):					
• Effluent:					
10/07/94	63	0	0	0	0
10/08/94	64	0	35	0	35
10/09/94	65	0	0	0	0
10/10/94	66	0	0	0	0
10/11/94	67	0	0	0	0
10/12/94	68	0	0	0	0
10/13/94	69	0	123	0	123
10/14/94	70	0	68	0	68
10/15/94	71	0	30	0	30
10/16/94	72	0	15	0	15
10/17/94	73	0	0	6	6
10/18/94	74	0	0	0	0
10/19/94	75	0	0	0	0
10/20/94	76	0	0	0	0
AVG.		0	19	0	20
S.D.		0	36	1	36

Appendix F. Raw Data of Diatomaceous Earth Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time	Concentration (µg/L)			
	(days)	Toluene	Ethylbenzene	o-Xylene	Total
Run No. 7 (Air Flow Rate = 100 mL/min):					
• Influent:					
*10/20/94	76	1073	632	557	2262
*10/21/94	77	844	495	435	1775
10/22/94	78	1053	631	553	2237
10/23/94	79	1046	641	557	2244
10/24/94	80	1043	645	563	2251
10/25/94	81	703	458	383	1544
10/26/94	82	1344	915	842	3101
10/27/94	83	1367	1015	949	3331
10/28/94	84	1500	1086	1016	3602
10/29/94	85	1360	1032	970	3361
10/30/94	86	840	648	627	2115
10/31/94	87	728	585	563	1876
11/01/94	88	543	473	452	1467
11/02/94	89	569	491	714	1775
11/03/94	90	917	751	685	2353
11/04/94	91	778	708	669	2155
11/05/94	92	437	369	330	1136
11/06/94	93	364	326	673	1363
11/07/94	94	549	439	405	1393
AVG.		891	660	644	2194
S.D.		353	234	205	757
Run No. 7 (Air Flow Rate = 100 mL/min):					
• Effluent:					
*10/20/94	76	53	164	14	231
*10/21/94	77	14	46	2	61

Appendix F. Raw Data of Diatomaceous Earth Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time (days)	Concentration (µg/L) Toluene	Ethylbenzene	o-Xylene	Total
Run No. 7 (Air Flow Rate = 100 mL/min):					
• Effluent (Cont'd):					
10/22/94	78	0	48	0	48
10/23/94	79	0	15	0	15
10/24/94	80	0	6	0	6
10/25/94	81	0	0	0	0
10/26/94	82	0	98	0	98
10/27/94	83	0	57	0	57
10/28/94	84	0	75	0	75
10/29/94	85	0	9	0	9
10/30/94	86	0	34	0	34
10/31/94	87	0	0	0	0
11/01/94	88	0	0	0	0
11/02/94	89	0	0	0	0
11/03/94	90	0	0	0	0
11/04/94	91	0	72	0	72
11/05/94	92	0	0	0	0
11/06/94	93	0	0	0	0
11/07/94	94	0	27	0	27
AVG.		0	26	0	26
S.D.		0	32	0	32
Run No. 8 (Air Flow Rate = 200 mL/min):					
• Influent:					
*12/12/94	129	1693	546	409	2649
12/13/94	130	1217	393	324	1933
12/14/94	131	1792	647	541	2980
12/15/94	132	1116	535	472	2122

Appendix F. Raw Data of Diatomaceous Earth Column Study - Daily Contaminant Concentrations from Influent and Effluent (Cont'd)

Date	Time (days)	Concentration (µg/L) Toluene	Ethylbenzene	o-Xylene	Total
Run No. 8 (Air Flow Rate = 200 mL/min):					
• Influent (Cont'd):					
12/16/94	133	1080	625	530	2235
12/17/94	134	994	972	781	2747
12/18/94	135	528	681	607	1816
12/19/94	136	250	571	545	1366
AVG.		997	632	543	2171
S.D.		496	177	138	551
Run No. 8 (Air Flow Rate = 200 mL/min):					
• Effluent (Cont'd):					
*12/12/94	129	0	264	25	289
12/13/94	130	0	49	0	49
12/14/94	131	0	91	0	91
12/15/94	132	0	30	0	30
12/16/94	133	0	0	0	0
12/17/94	134	0	40	0	40
12/18/94	135	0	23	0	23
12/19/94	136	0	0	0	0
AVG.		0	33	0	33
S.D.		0	31	0	31

* The data on these dates were not oncluded in the calculation of average (AVG.) and standard deviation (S.D.) because the biofilter system had not reached steady-state.

Appendix G. Raw Data of Diatomaceous Earth Column Study - Average Contaminant Concentrations from Other Sampling Ports

Sampling Port	Concentration (µg/L)			
	Toluene	Ethylbenzene	o-Xylene	Total
• Run No. 1:				
2	19	23	5	47
3	0	17	0	17
4	0	14	7	21
5	0	12	0	12
6	35	14	3	52
• Run No. 2:				
2	77	189	102	368
3	0	78	4	82
4	0	58	0	58
5	0	52	0	52
6	0	50	0	50

Appendix G. Raw Data of Diatomaceous Earth Column Study - Average Contaminant Concentrations from Other Sampling Ports (Cont'd)

Sampling Port	Concentration (µg/L)			
	Toluene	Ethylbenzene	o-Xylene	Total
• Run No. 3:				
2	27	170	45	242
3	0	54	0	54
4	0	33	0	33
5	0	18	0	18
6	0	11	0	11
• Run No. 5:				
2	43	176	38	257
3	0	51	0	51
4	0	14	0	14
5	0	6	0	6
6	0	0	0	0

Appendix G. Raw Data of Diatomaceous Earth Column Study - Average Contaminant Concentrations from Other Sampling Ports (Cont'd)

Sampling Port	Concentration (µg/L)			
	Toluene	Ethylbenzene	o-Xylene	Total
• Run No. 6:				
2	306	379	245	930
3	0	102	3	104
4	0	63	3	65
5	0	32	3	34
6	0	37	3	39
• Run No. 7:				
2	198	233	123	554
3	10	135	24	169
4	0	67	0	67
5	0	31	0	31
6	0	24	0	24

Appendix H. Raw Data of Tracer Study - Compost Column

Air Flow Rate (mL/min)					
25		50		100	
Time (mins)	C (mg/L)*	Time (mins)	C (mg/L)*	Time (mins)	C (mg/L)*
0	0.07	0	0.05	0	0.03
3	0.06	2	0.04	2	0.03
6	0.05	5	0.08	5	17.06
8	11.56	7	19.32	7	22.89
11	23.80	10	33.59	9	9.67
14	25.39	12	30.46	11	3.31
16	20.05	14	19.45	14	1.17
19	14.00	17	11.36	16	0.36
21	9.28	19	6.13	18	0.13
26	4.21	22	3.04	21	0.06
28	2.60	24	1.59	23	0.04
31	1.63	27	0.76	26	0.04
34	0.97	29	0.41	28	0.00
37	0.60	31	0.23	31	0.03
40	0.34	34	0.14	37	0.04
44	0.21	36	0.11	47	0.00
47	0.13	39	0.07	52	0.02
51	0.08	42	0.05	61	0.00
57	0.06	45	0.06	69	0.03
60	0.07	48	0.04	77	0.00
64	0.07	51	0.05	83	0.04
68	0.06	54	0.00	90	0.03
74	0.05	56	0.05		
80	0.05	58	0.05		
84	0.07	60	0.06		
89	0.08	71	0.04		
92	0.05	80	0.05		
		92	0.06		

* Concentration of Methane in Gas-Phase.

Appendix I. Raw Data of Tracer Study - Diatomaceous Earth Column

Air Flow Rate (mL/min)					
25		50		100	
Time (mins)	C (mg/L)*	Time (mins)	C (mg/L)*	Time (mins)	C (mg/L)*
0	0.00	0	0.00	0	0.10
4	0.00	2	0.36	1	0.12
7	15.63	4	22.70	3	2.31
9	30.73	7	22.18	5	8.73
16	8.40	10	12.94	8	8.02
19	3.77	13	5.47	11	3.71
22	1.90	16	1.00	14	1.32
25	0.37	21	0.32	17	0.42
28	0.46	25	0.00	21	0.17
31	0.19	28	0.07	24	0.00
35	0.11	32	0.02	28	0.12
42	0.07	39	0.03	32	0.12
48	0.06	48	0.03	39	0.13
54	0.05	56	0.03	43	0.12
62	0.27	61	0.02	49	0.18
71	0.00	81	0.04	55	0.16
80	0.03	90	0.02	60	0.22
92	0.02			90	0.15
				93	0.11

* Concentration of Methane in Gas-Phase.

Appendix J. Calculation of Dispersion Coefficient - Compost and Diatomaceous Earth Media

To determine dispersion coefficients for both the compost and diatomaceous earth media, six calculation tables are prepared at the end of this Appendix.

Using the Equations below provided by Levenspiel (1972), the dispersion coefficients can be calculated and shown as follows:

These Equations are:

- $\bar{t} = \dfrac{\int_0^\infty tC\,dt}{\int_0^\infty C\,dt} = \dfrac{\sum t_i C_i \Delta t_i}{\sum C_i \Delta t_i}$
- $\sigma^2 = \dfrac{\int_0^\infty t^2 C\,dt}{\int_0^\infty C\,dt} - \bar{t}^2 = \dfrac{\sum t_i^2 C_i \Delta t_i}{\sum C_i \Delta t_i} - \bar{t}^2$
- $\theta = \dfrac{t}{\bar{t}}$
- $\sigma_\theta^2 = \dfrac{\sigma^2}{\bar{t}^2}$
- $\dfrac{D}{uL} = \dfrac{\sigma_\theta^2}{2}$
- $u = \dfrac{L}{\bar{t}}$

The dispersion coefficients for the compost are:

- Qg = 25 mL/min, D = 1.47 cm^2/sec
- Qg = 50 mL/min, D = 2.08 cm^2/sec
- Qg = 100 mL/min, D = 7.37 cm^2/sec

The dispersion coefficients for the diatomaceous earth are:

- Qg = 25 mL/min, D = 3.85 cm^2/sec
- Qg = 50 mL/min, D = 7.22 cm^2/sec
- Qg = 100 mL/min, D = 10.92 cm^2/sec

Appendix J. Calculation of Dispersion Coefficient - Compost and Diatomaceous Earth Media (Cont'd)

(1) Compost Column:

t (mins)	C (µg/L)	Δt (mins)	CΔt (µg/L·min)	tCΔt (min^2·µg/L)	t^2CΔt (min^3·µg/L)
• Qg = 25 mL/min:					
0	0.07	3	0.20	0.00	0.00
3	0.06	3	0.17	0.52	1.57
6	0.05	2	0.11	0.63	3.80
8	11.56	3	34.67	277.37	2218.98
11	23.80	3	71.40	785.40	8639.44
14	25.39	2	50.78	710.96	9953.46
16	20.05	3	60.16	962.50	15399.94
19	14.00	2	27.99	531.89	10105.92
21	9.28	5	46.41	974.67	20468.15
26	4.21	2	8.43	219.15	5697.95
28	2.60	3	7.80	218.53	6118.78
31	1.63	3	4.90	151.91	4709.16
34	0.97	3	2.91	98.83	3360.38
37	0.60	3	1.79	66.23	2450.36
40	0.34	4	1.37	54.72	2188.87
44	0.21	3	0.64	28.01	1232.62
47	0.13	4	0.51	24.08	1131.87
51	0.08	6	0.51	25.99	1325.66
57	0.06	3	0.17	9.55	544.56
60	0.07	4	0.30	17.82	1069.04
64	0.07	4	0.27	17.13	1096.13
68	0.06	6	0.34	23.19	1577.19
74	0.05	6	0.32	24.01	1776.72
80	0.05	4	0.20	15.63	1250.78
84	0.07	5	0.33	27.57	2316.21
89	0.08	3	0.23	20.88	1858.42
92	0.05				
SUM:	116	92	322.91	5287.21	106495.97

Appendix J. Calculation of Dispersion Coefficient - Compost and Diatomaceous Earth Media (Cont'd)

(1) Compost Column (Cont'd):

t (mins)	C (µg/L)	Δt (mins)	CΔt (µg/L·min)	tCΔt (min^2·µg/L)	t^2CΔt (min^3·µg/L)
• Qg = 50 mL/min:					
0	0.05	2	0.09	0.00	0.00
2	0.04	3	0.13	0.26	0.52
5	0.08	2	0.15	0.76	3.78
7	19.32	3	57.97	405.78	2840.48
10	33.59	2	67.19	671.90	6718.98
12	30.46	2	60.93	731.11	8773.30
14	19.45	3	58.36	817.07	11438.93
17	11.36	2	22.72	386.28	6566.79
19	6.13	3	18.39	349.35	6637.58
22	3.04	2	6.09	133.97	2947.42
24	1.59	3	4.76	114.22	2741.34
27	0.76	2	1.52	41.03	1107.75
29	0.41	2	0.82	23.87	692.16
31	0.23	3	0.70	21.62	670.34
34	0.14	2	0.28	9.69	329.36
36	0.11	3	0.33	12.03	433.11
39	0.07	3	0.20	7.74	301.82
42	0.05	3	0.16	6.78	284.70
45	0.06	3	0.19	8.36	376.38
48	0.04	3	0.13	6.03	289.61
51	0.05	3	0.16	8.10	413.25
54	0.00	2	0.00	0.00	0.00
56	0.05	2	0.11	5.95	333.22
58	0.05	2	0.09	5.26	304.83
60	0.06	11	0.69	41.48	2488.83
71	0.04	9	0.39	27.56	1956.70
80	0.05	12	0.59	47.46	3797.09
92	0.06				
SUM:	127.36	92	303.14	3883.66	62448.28

Appendix J. Calculation of Dispersion Coefficient - Compost and Diatomaceous Earth Media (Cont'd)

(1) Compost Column (Cont'd):

t (mins)	C (μg/L)	Δt (mins)	CΔt (μg/L·min)	tCΔt (min^2·μg/L)	t^2CΔt (min^3·μg/L)
• Qg = 100 mL/min:					
0	0.03	2	0.06	0.00	0.00
2	0.03	3	0.08	0.16	0.32
5	17.06	2	34.13	170.63	853.13
7	22.89	2	45.79	320.53	2243.69
9	9.67	2	19.33	173.99	1565.92
11	3.31	3	9.94	109.31	1202.46
14	1.17	2	2.35	32.84	459.79
16	0.36	2	0.73	11.67	186.76
18	0.13	3	0.39	7.09	127.60
21	0.06	2	0.12	2.53	53.13
23	0.04	3	0.12	2.70	62.16
26	0.04	2	0.07	1.91	49.54
28	0.00	3	0.00	0.00	0.00
31	0.03	6	0.18	5.59	173.18
37	0.04	10	0.40	14.76	546.18
47	0.00	5	0.00	0.00	0.00
52	0.02	9	0.20	10.36	538.93
61	0.00	8	0.00	0.00	0.00
69	0.03	8	0.28	19.31	1332.42
77	0.00	6	0.00	0.00	0.00
83	0.04	7	0.25	20.87	1732.02
90	0.03				
SUM:	55.00	90	114.42	904.25	11127.25

Appendix J. Calculation of Dispersion Coefficient - Compost and Diatomaceous Earth Media (Cont'd)

(2) Diatomaceous Earth Column:

t (mins)	C (µg/L)	Δt (mins)	CΔt (µg/L·min)	tCΔt (min^2·µg/L)	t^2CΔt (min^3·µg/L)
• Qg = 25 mL/min:					
0	0.00	4	0.00	0.00	0.00
4	0.00	3	0.00	0.00	0.00
7	15.63	2	31.26	218.85	1531.96
9	30.73	7	215.11	1935.99	17423.88
16	8.40	3	25.20	403.24	6451.92
19	3.77	3	11.31	214.84	4082.05
22	1.90	3	5.71	125.64	2764.15
25	0.37	3	1.12	27.88	697.00
28	0.46	3	1.39	39.05	1093.47
31	0.19	4	0.76	23.61	731.96
35	0.11	7	0.75	26.30	920.60
42	0.07	6	0.44	18.39	772.48
48	0.06	6	0.36	17.37	833.67
54	0.05	8	0.44	23.67	1277.99
62	0.27	9	2.40	148.68	9218.16
71	0.00	9	0.00	0.00	0.00
80	0.03	12	0.35	27.78	2222.45
92	0.02				
SUM:	62.08	92	296.60	3251.31	50021.75

Appendix J. Calculation of Dispersion Coefficient - Compost and Diatomaceous Earth Media (Cont'd)

(2) Diatomaceous Earth Column (Cont'd):

t (mins)	C (μg/L)	Δt (mins)	CΔt (μg/L·min)	tCΔt (min^2·μg/L)	t^2CΔt (min^3·μg/L)
• Qg = 50 mL/min:					
0	0.00	2.00	0.00	0.00	0.00
2	0.36	2.00	0.73	1.46	2.92
4	22.70	3.00	68.09	272.35	1089.39
7	22.18	3.00	66.54	465.77	3260.40
10	12.94	3.00	38.81	388.10	3881.01
13	5.47	3.00	16.42	213.41	2774.33
16	1.00	5.00	5.00	79.96	1279.42
21	0.32	4.00	1.29	27.03	567.61
25	0.00	3.00	0.00	0.00	0.00
28	0.07	4.00	0.28	7.82	219.02
32	0.02	7.00	0.13	4.03	128.99
39	0.03	9.00	0.24	9.18	357.89
48	0.03	8.00	0.20	9.83	471.70
56	0.03	5.00	0.15	8.59	481.07
61	0.02	20.00	0.46	27.89	1701.44
81	0.04	9.00	0.33	26.91	2179.63
90	0.02				
SUM:	65.22	90.00	198.65	1542.33	18394.82

Appendix J. Calculation of Dispersion Coefficient - Compost and Diatomaceous Earth Media (Cont'd)

(2) Diatomaceous Earth Column (Cont'd):

t	C	Δt	CΔt	tCΔt	$t^2C\Delta t$
(mins)	(µg/L)	(mins)	(µg/L·min)	(min^2·µg/L)	(min^3·µg/L)
• Qg = 100 mL/min:					
0	0.10	1	0.10	0.00	0.00
1	0.12	2	0.24	0.24	0.24
3	2.31	2	4.61	13.84	41.52
5	8.73	3	26.19	130.97	654.84
8	8.02	3	24.05	192.43	1539.43
11	3.71	3	11.13	122.39	1346.24
14	1.32	3	3.95	55.34	774.72
17	0.42	4	1.67	28.41	483.00
21	0.17	3	0.51	10.72	225.19
24	0.00	4	0.00	0.00	0.00
28	0.12	4	0.49	13.76	385.40
32	0.12	7	0.83	26.61	851.66
39	0.13	4	0.51	19.90	776.21
43	0.12	6	0.73	31.32	1346.64
49	0.18	6	1.10	53.91	2641.51
55	0.16	5	0.79	43.23	2377.81
60	0.22	30	6.55	392.90	23574.29
90	0.15	3	0.44	39.75	3577.77
93	0.11				
SUM:	26.20	93	83.90	1175.74	40596.48

Appendix K. Determination of Mathematical Model's Coefficient - Ignoring the Effect of Dispersion Coefficient

(1) Zero-Order:

Run No.	z (cm)	C (μg/L)	Curve-Fit	R^2	k_o
• Compost Column:					
1	0.0	1018	C = 878 - 9.32z	0.911	1.2552
	19.0	720			
	37.5	441			
	56.0	250			
	74.5	56			
	93.0	12			
	112.0	0			
2	0.0	1013	C = 1096 - 7.93z	0.909	2.1376
	19.0	915			
	37.5	843			
	56.0	731			
	74.5	577			
	93.0	454			
	112.0	32			
3	0.0	1079	C = 1073 - 5.22z	0.988	2.8147
	19.0	950			
	37.5	914			
	56.0	752			
	74.5	683			
	93.0	605			
	112.0	479			
5	0.0	2155	C = 2044 - 6.46z	0.944	0.8705
	19.0	1857			
	37.5	1743			
	56.0	1658			
	74.5	1530			
	93.0	1460			
	112.0	1369			
6	0.0	1989	C = 1947 - 6.72z	0.976	1.8106
	19.0	1780			

Appendix K. Determination of Mathematical Model's Coefficient - Ignoring the Effect of Dispersion Coefficient (Cont'd)

(1) Zero-Order (Cont'd):

Run No.	z (cm)	C (μg/L)	Curve-Fit	R^2	k_o
• Compost Column (Cont'd):					
	37.5	1737			
	56.0	1504			
	74.5	1437			
	93.0	1324			
	112.0	1226			
7	0.0	2127	C = 2047 - 7.28z	0.963	3.9207
	19.0	1881			
	37.5	1737			
	56.0	1568			
	74.5	1476			
	93.0	1440			
	112.0	1245			
				AVG.:	2.1349
• Diatomaceous Earth Column:					
1	0.0	1438	C = 690 - 8.25z	0.386	1.4700
	19.0	47			
	37.5	17			
	56.0	21			
	74.5	12			
	93.0	52			
	112.0	8			
2	0.0	1338	C = 777 - 8.82z	0.546	3.1432
	19.0	368			
	37.5	82			
	56.0	58			
	74.5	52			
	93.0	50			
	112.0	31			

Appendix K. Determination of Mathematical Model's Coefficient - Ignoring the Effect of Dispersion Coefficient (Cont'd)

(1) Zero-Order (Cont'd):

Run No.	z (cm)	C (μg/L)	Curve-Fit	R^2	k_o
• Diatomaceous Earth Column (Cont'd):					
3	0.0	1167	C = 648 - 7.67z	0.523	5.4651
	19.0	242			
	37.5	54			
	56.0	33			
	74.5	18			
	93.0	11			
	112.0	4			
5	0.0	2199	C = 1132 - 13.77z	0.460	2.4533
	19.0	257			
	37.5	51			
	56.0	14			
	74.5	6			
	93.0	0			
	112.0	0			
6	0.0	2230	C = 1402 - 16.30z	0.616	5.8084
	19.0	930			
	37.5	104			
	56.0	65			
	74.5	34			
	93.0	39			
	112.0	20			
7	0.0	2194	C = 1267 - 14.81z	0.558	10.5544
	19.0	554			
	37.5	169			
	56.0	67			
	74.5	31			
	93.0	24			
	112.0	26			
				AVG.:	4.8157

Appendix K. Determination of Mathematical Model's Coefficient - Ignoring the Effect of Dispersion Coefficient (Cont'd)

(2) First-Order:

Run No.	z (cm)	C (µg/L)	ln C	Curve-Fit	R^2	k_1'
• Compost Column:						
1	0.0	1018	6.93	ln C = 7.85 - 0.0596z	0.898	0.0080
	19.0	720	6.58			
	37.5	441	6.09			
	56.0	250	5.52			
	74.5	56	4.03			
	93.0	12	2.48			
	112.0	0	------			
2	0.0	1013	6.92	ln C = 7.45 - 0.0234z	0.599	0.0063
	19.0	915	6.82			
	37.5	843	6.74			
	56.0	731	6.59			
	74.5	577	6.36			
	93.0	454	6.12			
	112.0	32	3.47			
3	0.0	1079	6.98	ln C = 7.02 - 0.0070z	0.975	0.0038
	19.0	950	6.86			
	37.5	914	6.82			
	56.0	752	6.62			
	74.5	683	6.53			
	93.0	605	6.41			
	112.0	479	6.17			
5	0.0	2155	7.68	ln C = 7.63 - 0.0038z	0.971	0.0005
	19.0	1857	7.53			
	37.5	1743	7.46			
	56.0	1658	7.41			
	74.5	1530	7.33			
	93.0	1460	7.29			
	112.0	1369	7.22			
6	0.0	1989	7.60	ln C = 7.59 - 0.0043z	0.985	0.0012
	19.0	1780	7.48			

Appendix K. Determination of Mathematical Model's Coefficient - Ignoring the Effect of Dispersion Coefficient (Cont'd)

(2) First-Order (Cont'd):

Run No.	z (cm)	C (μg/L)	ln C	Curve-Fit	R^2	k_1'
• Compost Column (Cont'd):						
	37.5	1737	7.46			
	56.0	1504	7.32			
	74.5	1437	7.27			
	93.0	1324	7.19			
	112.0	1226	7.11			
7	0.0	2127	7.66	ln C = 7.64 - 0.0044z	0.977	0.0024
	19.0	1881	7.54			
	37.5	1737	7.46			
	56.0	1568	7.36			
	74.5	1476	7.30			
	93.0	1440	7.27			
	112.0	1245	7.13			
					AVG.:	0.0037
• Diatomaceous Earth Column:						
1	0.0	1438	7.27	ln C = 5.34 - 0.0303z	0.491	0.0054
	19.0	47	3.85			
	37.5	17	2.83			
	56.0	21	3.04			
	74.5	12	2.48			
	93.0	52	3.95			
	112.0	8	2.08			
2	0.0	1338	7.20	ln C = 6.39 - 0.0302z	0.807	0.0108
	19.0	368	5.91			
	37.5	82	4.41			
	56.0	58	4.06			
	74.5	52	3.95			
	93.0	50	3.91			
	112.0	31	3.43			

Appendix K. Determination of Mathematical Model's Coefficient - Ignoring the Effect of Dispersion Coefficient (Cont'd)

(2) First-Order (Cont'd):

Run No.	z (cm)	C (μg/L)	ln C	Curve-Fit	R^2	k_1'
• Diatomaceous Earth Column (Cont'd):						
3	0.0	1167	7.06	ln C = 6.43 - 0.0467z	0.950	0.0333
	19.0	242	5.49			
	37.5	54	3.99			
	56.0	33	3.50			
	74.5	18	2.89			
	93.0	11	2.40			
	112.0	4	1.39			
5	0.0	2199	7.70	ln C = 9.31 - 0.1581z	0.853	0.0282
	19.0	257	5.55			
	37.5	51	3.93			
	56.0	14	2.64			
	74.5	6	1.79			
	93.0	0	------			
	112.0	0	------			
6	0.0	2230	7.71	ln C = 7.12 - 0.0415z	0.869	0.0148
	19.0	930	6.84			
	37.5	104	4.64			
	56.0	65	4.17			
	74.5	34	3.53			
	93.0	39	3.66			
	112.0	20	3.00			
7	0.0	2194	7.69	ln C = 7.03 - 0.0408z	0.899	0.0291
	19.0	554	6.32			
	37.5	169	5.13			
	56.0	67	4.20			
	74.5	31	3.43			
	93.0	24	3.18			
	112.0	26	3.26			
					AVG.:	0.0203

Appendix L. Determination of Mathematical Model's Coefficient - Considering the Effect of Dispersion Coefficient

(1) Zero-Order:

Run No.	z (cm)	C (μg/L)	k_o (μg/L·sec)	U (cm/sec)	D (cm^2/sec)	P	Q
• Compost Column:							
1	0.0	1018	2.1349	0.094	1.47	0.0639	1.0092
	19.0	720					
	37.5	441					
	56.0	250					
	74.5	56					
	93.0	12					
	112.0	0					
2	0.0	1013	2.1349	0.187	2.08	0.0899	0.7133
	19.0	915					
	37.5	843					
	56.0	731					
	74.5	577					
	93.0	454					
	112.0	32					
3	0.0	1079	2.1349	0.374	7.37	0.0507	0.2013
	19.0	950					
	37.5	914					
	56.0	752					
	74.5	683					
	93.0	605					
	112.0	479					
5	0.0	2155	2.1349	0.094	1.47	0.0639	1.0092
	19.0	1857					
	37.5	1743					
	56.0	1658					
	74.5	1530					
	93.0	1460					
	112.0	1369					
6	0.0	1989	2.1349	0.187	2.08	0.0899	0.7133
	19.0	1780					

Appendix L. Determination of Mathematical Model's Coefficient - Considering the Effect of Dispersion Coefficient (Cont'd)

(1) Zero-Order (Cont'd):

Run No.	z (cm)	C (μg/L)	k_o (μg/L·sec^{-1})	U (cm/sec)	D (cm^2/sec)	P	Q
• Compost Column (Cont'd):							
	37.5	1737					
	56.0	1504					
	74.5	1437					
	93.0	1324					
	112.0	1226					
7	0.0	2127	2.1349	0.374	7.37	0.0507	0.2013
	19.0	1881					
	37.5	1737					
	56.0	1568					
	74.5	1476					
	93.0	1440					
	112.0	1245					
• Diatomaceous Earth Column:							
1	0.0	1489	4.8157	0.080	3.85	0.0208	0.5620
	19.0	47					
	37.5	17					
	56.0	21					
	74.5	12					
	93.0	52					
	112.0	8					
2	0.0	1338	4.8157	0.160	7.22	0.0222	0.2997
	19.0	368					
	37.5	82					
	56.0	58					
	74.5	52					
	93.0	50					
	112.0	31					

Appendix L. Determination of Mathematical Model's Coefficient - Considering the Effect of Dispersion Coefficient (Cont'd)

(1) Zero-Order (Cont'd):

Run No.	z (cm)	C (µg/L)	k_o (µg/L·sec^{-1})	U (cm/sec)	D (cm^2/sec)	P	Q
• Diatomaceous Earth Column (Cont'd):							
3	0.0	1167	4.8157	0.320	10.92	0.0293	0.1981
	19.0	242					
	37.5	54					
	56.0	33					
	74.5	18					
	93.0	11					
	112.0	4					
5	0.0	2199	4.8157	0.080	3.85	0.0208	0.5620
	19.0	257					
	37.5	51					
	56.0	14					
	74.5	6					
	93.0	0					
	112.0	0					
6	0.0	2230	4.8157	0.160	7.22	0.0222	0.2997
	19.0	930					
	37.5	104					
	56.0	65					
	74.5	34					
	93.0	39					
	112.0	20					
7	0.0	2194	4.8157	0.320	10.92	0.0293	0.1981
	19.0	554					
	37.5	169					
	56.0	67					
	74.5	31					
	93.0	24					
	112.0	26					

Appendix L. Determination of Mathematical Model's Coefficient - Considering the Effect of Dispersion Coefficient (Cont'd)

(2) First-Order:

- Compost Column:

Run No.	z (cm)	C (μg/L)	k_1' (sec^{-1})	U (cm/sec)	D (cm^2/sec)	r1	r2	A1	A2
1	0.0	1018	0.0037	0.094	1.47	0.0846	-0.0207	-0.0077	1018
	19.0	720							
	37.5	441							
	56.0	250							
	74.5	56							
	93.0	12							
	112.0	0							
2	0.0	1013	0.0037	0.187	2.08	0.1020	-0.0121	-0.0025	1013
	19.0	915							
	37.5	843							
	56.0	731							
	74.5	577							
	93.0	454							
	112.0	32							
3	0.0	1079	0.0037	0.374	7.37	0.0569	-0.0061	-0.1094	1079
	19.0	950							
	37.5	914							
	56.0	752							
	74.5	683							
	93.0	605							
	112.0	479							
5	0.0	2155	0.0037	0.094	1.47	0.0846	-0.0207	0.0886	2155
	19.0	1857							
	37.5	1743							
	56.0	1658							
	74.5	1530							
	93.0	1460							
	112.0	1369							

Appendix L. Determination of Mathematical Model's Coefficient - Considering the Effect of Dispersion Coefficient (Cont'd)

(2) First-Order (Cont'd):

Run No.	z (cm)	C (µg/L)	k_1' (sec^{-1})	U (cm/sec)	D (cm^2/sec)	r1	r2	A1	A2
• Compost Column (Cont'd):									
6	0.0	1989	0.0037	0.187	2.08	0.1020	-0.0121	0.0078	1989
	19.0	1780							
	37.5	1737							
	56.0	1504							
	74.5	1437							
	93.0	1324							
	112.0	1226							
7	0.0	2127	0.0037	0.374	7.37	0.0569	-0.0061	0.2995	2127
	19.0	1881							
	37.5	1737							
	56.0	1568							
	74.5	1476							
	93.0	1440							
	112.0	1245							
• Diatomaceous Earth Column:									
1	0.0	1489	0.0203	0.080	3.85	0.0602	-0.0394	-0.0120	1489
	19.0	47							
	37.5	17							
	56.0	21							
	74.5	12							
	93.0	52							
	112.0	8							
2	0.0	1338	0.0203	0.160	7.22	0.0483	-0.0262	-0.1812	1338
	19.0	368							
	37.5	82							
	56.0	58							
	74.5	52							
	93.0	50							

Appendix L. Determination of Mathematical Model's Coefficient - Considering the Effect of Dispersion Coefficient (Cont'd)

(2) First-Order (Cont'd):

- Diatomaceous Earth Column (Cont'd):

Run No.	z (cm)	C (μg/L)	k_1' (sec^{-1})	U (cm/sec)	D (cm^2/sec)	r1	r2	A1	A2
	112.0	31							
3	0.0	1167	0.0203	0.320	10.92	0.0471	-0.0178	-0.8022	1168
	19.0	242							
	37.5	54							
	56.0	33							
	74.5	18							
	93.0	11							
	112.0	4							
5	0.0	2199	0.0203	0.080	3.85	0.0612	-0.0394	-0.0317	2199
	19.0	257							
	37.5	51							
	56.0	14							
	74.5	6							
	93.0	0							
	112.0	0							
6	0.0	2230	0.0203	0.160	7.22	0.0483	-0.0262	-0.4436	2230
	19.0	930							
	37.5	104							
	56.0	65							
	74.5	34							
	93.0	39							
	112.0	20							
7	0.0	2194	0.0203	0.320	10.92	0.0471	-0.0178	-1.4130	2195
	19.0	554							
	37.5	169							
	56.0	67							
	74.5	31							
	93.0	24							
	112.0	26							

Appendix M. Prediction of Contaminant Concentrations - Zero-Order and First-Order Models

Run No.	z (cm)	Observed Value (µg/L)	Predicted Value (µg/L)			
			Zero-Order (D = 0)	First-Order (D = 0)	Zero-Order (D ≠ 0)	First-Order (D ≠ 0)
• Compost Column:						
1	0	1018	1018	1018	1018	1018
	19	720	718	605	719	687
	37.5	441	426	365	432	468
	56	250	134	220	154	319
	74.5	56	0	133	0	214
	93	12	0	80	0	128
	112	0	0	48	0	0
2	0	1013	1013	1013	1013	1013
	19	915	862	780	862	805
	37.5	843	715	605	715	643
	56	731	569	469	568	514
	74.5	577	422	364	419	406
	93	454	275	282	258	296
	112	32	124	217	32	33
3	0	1079	1079	1079	1079	1079
	19	950	1004	947	1003	961
	37.5	914	930	834	927	857
	56	752	857	734	848	764
	74.5	683	783	647	760	677
	93	605	710	569	651	590
	112	479	635	500	479	481
5	0	2155	2155	2155	2155	2155
	19	1857	1855	1282	1857	1455
	37.5	1743	1563	773	1570	994
	56	1658	1271	466	1297	686
	74.5	1530	979	281	1067	509
	93	1460	687	169	978	546
	112	1369	387	101	1369	1367

Appendix M. Prediction of Contaminant Concentrations - Zero-Order and First-Order Models (Cont'd)

Run No.	z (cm)	Observed Value (µg/L)	Predicted Value (µg/L)			
			Zero-Order (D = 0)	First-Order (D = 0)	Zero-Order (D ≠ 0)	First-Order (D ≠ 0)
• Compost Column (Cont'd):						
6	0	1989	1989	1989	1989	1989
	19	1780	1838	1532	1838	1581
	37.5	1737	1691	1188	1692	1264
	56	1504	1545	921	1545	1012
	74.5	1437	1398	714	1402	823
	93	1324	1251	554	1274	748
	112	1226	1100	426	1226	1227
7	0	2127	2127	2127	2127	2127
	19	1881	2052	1867	2049	1895
	37.5	1737	1978	1644	1970	1695
	56	1568	1905	1447	1880	1519
	74.5	1476	1831	1274	1767	1371
	93	1440	1758	1122	1592	1266
	112	1245	1683	985	1245	1250
• Diatomaceous Earth Column:						
1	0	1489	1489	1489	1489	1489
	19	47	975	171	1056	704
	37.5	17	475	21	673	340
	56	21	0	3	343	164
	74.5	12	0	0	94	78
	93	52	0	0	0	35
	112	8	0	0	8	8
2	0	1338	1338	1338	1338	1338
	19	368	1081	453	1091	813
	37.5	82	831	158	856	500
	56	58	581	55	628	306
	74.5	52	331	19	411	183
	93	50	80	7	211	101
	112	31	0	2	31	31

Appendix M. Prediction of Contaminant Concentrations - Zero-Order and First-Order Models (Cont'd)

Run No.	z (cm)	Observed Value (µg/L)	Predicted Value (µg/L)			
			Zero-Order (D = 0)	First-Order (D = 0)	Zero-Order (D ≠ 0)	First-Order (D ≠ 0)
• Diatomaceous Earth Column (Cont'd):						
3	0	1167	1167	1167	1167	1167
	19	242	1039	679	1027	831
	37.5	54	913	401	882	594
	56	33	788	237	723	420
	74.5	18	663	140	539	283
	93	11	538	82	312	159
	112	4	410	48	4	2
5	0	2199	2199	2199	2199	2199
	19	257	1685	252	1729	1040
	37.5	51	1185	31	1291	502
	56	14	684	4	883	241
	74.5	6	184	0	517	114
	93	0	0	0	214	48
	112	0	0	0	0	0
6	0	2230	2230	2230	2230	2230
	19	930	1973	755	1940	1357
	37.5	104	1723	263	1641	838
	56	65	1473	92	1318	521
	74.5	34	1223	32	956	333
	93	39	972	11	539	235
	112	20	715	4	20	218
7	0	2194	2194	2194	2194	2194
	19	554	2066	1277	2025	1562
	37.5	169	1940	753	1830	1118
	56	67	1815	445	1586	790
	74.5	31	1690	262	1257	536
	93	24	1565	155	780	306
	112	26	1437	90	26	23

Appendix N. Outputs of Statistical Analysis - Regression Analysis

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- Compost Column:

SUMMARY:

Groups	Count	Sum	Average	Variance
Model (1)	6	4.707	0.7845	0.034065
Model (2)	6	4.62	0.77	0.03066
Model (3)	6	5.192	0.865333	0.016395
Model (4)	6	4.871	0.811833	0.033185

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.031788	3	0.010596	0.37	0.774915	3.10
Within Groups	0.57153	20	0.028576			
Total	0.603318	23				

- Diatomaceous Earth Column:

SUMMARY:

Groups	Count	Sum	Average	Variance
Model (1)	6	3.388	0.564667	0.007977
Model (2)	6	5.5179	0.91965	0.012322
Model (3)	6	3.389	0.564833	0.001643
Model (4)	6	4.441	0.740167	0.006344

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.518497	3	0.172832	24.44	6.79E-07	3.10
Within Groups	0.14143	20	0.007072			
Total	0.659927	23				

Appendix O. Raw Data of Statistical Analysis - Analysis of Variance

(1) Effect of Residence Time on Elimination Efficiency:

Test Conditions	Elimination Efficiency (%)						
Inf. Conc.:	Low				High		
T (mins):	20	10	5	2.5	20	10	5
• Compost Column:							
	100.0	99.2	69.9	55.6	54.1	31.0	34.9
	100.0	100.0	74.4	39.9	44.7	37.8	33.2
	100.0	100.0	71.7	23.9	46.5	49.5	40.1
	100.0	93.3	45.9	23.8	46.1	51.1	37.0
	100.0	100.0	82.0	37.8	35.7	65.1	33.2
	100.0	100.0	65.1	32.1	33.4	66.7	34.0
	100.0	100.0	60.8	20.2	24.0	62.4	41.3
	100.0	83.7	69.1	28.0	29.9	31.1	47.6
	100.0	92.7	82.3	19.7	38.3	25.1	59.9
	100.0	100.0	51.2	41.9	38.9	15.4	41.9
	100.0	100.0	59.1	29.2	31.0	19.3	36.3
	100.0	100.0	56.5	24.3	17.4	37.2	41.0
	100.0	100.0	58.7		49.0	36.2	50.8
	100.0	100.0	75.0		29.4	39.6	45.4
	100.0	100.0	49.2		35.0	4.4	
	100.0	100.0	26.3		34.9	36.8	
	100.0	93.9	63.5		44.8	57.0	
	100.0	83.9	47.1		36.0	46.3	
			30.7				
			36.2				
			59.6				
			73.8				
			45.2				
			81.4				
			51.7				
			31.4				
			22.4				
			53.9				
			47.8				
			44.6				

Appendix O. Raw Data of Statistical Analysis - Analysis of Variance (Cont'd)

(1) Effect of Residence Time on Elimination Efficiency (Cont'd):

Test Conditions	Elimination Efficiency (%)							
Inf. Conc.:	Low				High			
T (mins):	20	10	5	2.5	20	10	5	2.5
• Diatomaceous Earth Column:								
	100.0	98.8	99.7	95.5	100.0	100.0	97.8	97.5
	100.0	97.5	99.9	97.0	100.0	98.3	99.3	97.0
	100.0	97.8	100.0	98.7	100.0	100.0	99.7	98.6
	100.0	99.9	100.0	93.5	100.0	100.0	100.0	100.0
	94.5	94.8	100.0	97.1	100.0	100.0	96.8	98.5
	100.0	96.0	100.0	96.3	100.0	100.0	98.3	98.7
	100.0	96.9	100.0	98.5	100.0	93.7	97.9	100.0
	100.0	99.1	100.0		100.0	96.8	99.7	
	100.0	97.7	100.0		100.0	98.5	98.4	
	100.0	99.8	100.0		100.0	99.3	100.0	
	100.0	98.3	98.0		100.0	99.8	100.0	
	100.0	99.2	99.6		100.0	100.0	100.0	
	100.0	98.7	98.1			100.0	100.0	
		99.8	100.0			100.0	96.6	
		95.8					100.0	
		94.2					100.0	
							98.1	

Appendix O. Raw Data of Statistical Analysis - Analysis of Variance (Cont'd)

(2) Effect of Influent Concentration on Elimination Efficiency:

Test Conditions	Elimination Efficiency (%)					
T (mins):	20		10		5	
Inf. Conc.:	Low	High	Low	High	Low	High
• Compost Column:						
	100.0	54.1	99.2	31.0	69.9	34.9
	100.0	44.7	100.0	37.8	74.4	33.2
	100.0	46.5	100.0	49.5	71.7	40.1
	100.0	46.1	93.3	51.1	45.9	37.0
	100.0	35.7	100.0	65.1	82.0	33.2
	100.0	33.4	100.0	66.7	65.1	34.0
	100.0	24.0	100.0	62.4	60.8	41.3
	100.0	29.9	83.7	31.1	69.1	47.6
	100.0	38.3	92.7	25.1	82.3	59.9
	100.0	38.9	100.0	15.4	51.2	41.9
	100.0	31.0	100.0	19.3	59.1	36.3
	100.0	17.4	100.0	37.2	56.5	41.0
	100.0	49.0	100.0	36.2	58.7	50.8
	100.0	29.4	100.0	39.6	75.0	45.4
	100.0	35.0	100.0	4.4	49.2	
	100.0	34.9	100.0	36.8	26.3	
	100.0	44.8	93.9	57.0	63.5	
	100.0	36.0	83.9	46.3	47.1	
					30.7	
					36.2	
					59.6	
					73.8	
					45.2	
					81.4	
					51.7	
					31.4	
					22.4	
					53.9	
					47.8	
					44.6	

Appendix O. Raw Data of Statistical Analysis - Analysis of Variance (Cont'd)

(2) Effect of Influent Concentration on Elimination Efficiency (Cont'd):

Test Conditions	Elimination Efficiency (%)							
T (mins):	20		10		5		2.5	
Inf. Conc.	Low	High	Low	High	Low	High	Low	High
• Diatomaceous Earth Column:								
	100.0	100.0	98.8	100.0	99.7	97.8	95.5	97.5
	100.0	100.0	97.5	98.3	99.9	99.3	97.0	97.0
	100.0	100.0	97.8	100.0	100.0	99.7	98.7	98.6
	100.0	100.0	99.9	100.0	100.0	100.0	93.5	100.0
	94.5	100.0	94.8	100.0	100.0	96.8	97.1	98.5
	100.0	100.0	96.0	100.0	100.0	98.3	96.3	98.7
	100.0	100.0	96.9	93.7	100.0	97.9	98.5	100.0
	100.0	100.0	99.1	96.8	100.0	99.7		
	100.0	100.0	97.7	98.5	100.0	98.4		
	100.0	100.0	99.8	99.3	100.0	100.0		
	100.0	100.0	98.3	99.8	98.0	100.0		
	100.0	100.0	99.2	100.0	99.6	100.0		
	100.0		98.7	100.0	98.1	100.0		
			99.8	100.0	100.0	96.6		
			95.8			100.0		
			94.2			100.0		
						98.1		

Appendix O. Raw Data of Statistical Analysis - Analysis of Variance (Cont'd)

(3) Effect of Type of Filter on Elimination Efficiency:

Test Conditions	Elimination Efficiency (%)							
T (mins):	20		10		5		2.5	
Filter:	COM	DE	COM	DE	COM	DE	COM	DE
• Low Influent Concentration:								
	100.0	100.0	99.2	98.8	69.9	99.7	55.6	95.5
	100.0	100.0	100.0	97.5	74.4	99.9	39.9	97.0
	100.0	100.0	100.0	97.8	71.7	100.0	23.9	98.7
	100.0	100.0	93.3	99.9	45.9	100.0	23.8	93.5
	100.0	94.5	100.0	94.8	82.0	100.0	37.8	97.1
	100.0	100.0	100.0	96.0	65.1	100.0	32.1	96.3
	100.0	100.0	100.0	96.9	60.8	100.0	20.2	98.5
	100.0	100.0	83.7	99.1	69.1	100.0	28.0	
	100.0	100.0	92.7	97.7	82.3	100.0	19.7	
	100.0	100.0	100.0	99.8	51.2	100.0	41.9	
	100.0	100.0	100.0	98.3	59.1	98.0	29.2	
	100.0	100.0	100.0	99.2	56.5	99.6	24.3	
	100.0	100.0	100.0	98.7	58.7	98.1		
	100.0		100.0	99.8	75.0	100.0		
	100.0		100.0	95.8	49.2			
	100.0		100.0	94.2	26.3			
	100.0		93.9		63.5			
	100.0		83.9		47.1			
					30.7			
					36.2			
					59.6			
					73.8			
					45.2			
					81.4			
					51.7			
					31.4			
					22.4			
					53.9			
					47.8			
					44.6			

Appendix O. Raw Data of Statistical Analysis - Analysis of Variance (Cont'd)

(3) Effect of Type of Filter on Elimination Efficiency (Cont'd):

Test Conditions	Elimination Efficiency (%)					
T (mins):	20		10		5	
Filter:	COM	DE	COM	DE	COM	DE
• High Influent Concentration:						
	54.1	100.0	31.0	100.0	34.9	97.8
	44.7	100.0	37.8	98.3	33.2	99.3
	46.5	100.0	49.5	100.0	40.1	99.7
	46.1	100.0	51.1	100.0	37.0	100.0
	35.7	100.0	65.1	100.0	33.2	96.8
	33.4	100.0	66.7	100.0	34.0	98.3
	24.0	100.0	62.4	93.7	41.3	97.9
	29.9	100.0	31.1	96.8	47.6	99.7
	38.3	100.0	25.1	98.5	59.9	98.4
	38.9	100.0	15.4	99.3	41.9	100.0
	31.0	100.0	19.3	99.8	36.3	100.0
	17.4	100.0	37.2	100.0	41.0	100.0
	49.0		36.2	100.0	50.8	100.0
	29.4		39.6	100.0	45.4	96.6
	35.0		4.4			100.0
	34.9		36.8			100.0
	44.8		57.0			98.1
	36.0		46.3			

Appendix P. Outputs of Statistical Analysis - Analysis of Variance

(1) Effect of Residence Time on Elimination (Compost Column):

- Low Influent Concentration:

SUMMARY:

Groups	Count	Sum	Average	Variance
T = 20 mins	18	1800	100	0
T = 10 mins	18	1746.662	97.0368	29.65758
T = 5.0 mins	30	1686.259	56.20862	278.2649
T = 2.5 mins	12	376.2733	31.35611	113.8897

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	52698.7	3	17566.23	132.28	1.17E-29	2.73
Within Groups	9826.649	74	132.7926			
Total	62525.35	77				

- High Influent Concentration:

SUMMARY:

Groups	Count	Sum	Average	Variance
T = 20 mins	18	669.1486	37.17492	85.56802
T = 10 mins	18	711.7439	39.54133	300.3311
T = 5.0 mins	14	576.5176	41.17983	58.5478

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	130.6559	2	65.32797	0.42	0.659893	3.20
Within Groups	7321.407	47	155.7746			
Total	7452.063	49				

Appendix P. Outputs of Statistical Analysis - Analysis of Variance (Cont'd)

(1) Effect of Residence Time on Elimination (Diatomaceous Earth Column):

- Low Influent Concentration:

SUMMARY:

Groups	Count	Sum	Average	Variance
T = 20 mins	13	1294.457	99.57364	2.36316
T = 10 mins	16	1564.583	97.78644	3.234156
T = 5.0 mins	14	1395.21	99.65788	0.477002
T = 2.5 mins	7	676.573	96.65329	3.25189

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	65.09558	3	21.69853	9.73	4.37E-05	2.81
Within Groups	102.5826	46	2.230057			
Total	167.6782	49				

- High Influent Concentration:

SUMMARY:

Groups	Count	Sum	Average	Variance
T = 20 mins	12	1200	100	0
T = 10 mins	14	1386.407	99.02908	3.229858
T = 5.0 mins	17	1682.785	98.98733	1.411151
T = 2.5 mins	7	690.3045	98.61493	1.317765

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	11.24895	3	3.74965	2.38	0.081817	2.81
Within Groups	72.47317	46	1.575504			
Total	83.72212	49				

Appendix P. Outputs of Statistical Analysis - Analysis of Variance (Cont'd)

(2) Effect of Influent Concentration on Elimination (Compost Column):

- T = 20 mins:

SUMMARY:

Groups	Count	Sum	Average	Variance
Low	18	1800	100	0
High	18	669.1486	37.17492	85.56802

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	35522.91	1	35522.91	830.28	1.79E-25	4.13
Within Groups	1454.656	34	42.78401			
Total	36977.57	35				

- T = 10 mins:

SUMMARY:

Groups	Count	Sum	Average	Variance
Low	18	1746.662	97.0368	29.65758
High	18	711.7439	39.54133	300.3311

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	29751.57	1	29751.57	180.32	3.76E-15	4.13
Within Groups	5609.808	34	164.9944			
Total	35361.38	35				

- T = 5.0 mins:

SUMMARY:

Groups	Count	Sum	Average	Variance
Low	30	1686.259	56.20862	278.2649
High	14	576.5176	41.17983	58.5478

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2155.98	1	2155.98	10.25	0.002601	4.07
Within Groups	8830.805	42	210.2573			
Total	10986.78	43				

Appendix P. Outputs of Statistical Analysis - Analysis of Variance (Cont'd)

(2) Effect of Influent Concentration on Elimination (Diatomaceous Earth Column):

- T = 20 mins:

SUMMARY:	Groups	Count	Sum	Average	Variance
	Low	13	1294.457	99.57364	2.36316
	High	12	1200	100	0

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.134317	1	1.134317	0.92	0.34745	4.28
Within Groups	28.35792	23	1.232953			
Total	29.49223	24				

- T = 10 mins:

SUMMARY:	Groups	Count	Sum	Average	Variance
	Low	16	1564.583	97.78644	3.234156
	High	14	1386.407	99.02908	3.229858

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	11.52973	1	11.52973	3.57	0.069332	4.2
Within Groups	90.5005	28	3.232161			
Total	102.0302	29				

- T = 5.0 mins:

SUMMARY:	Groups	Count	Sum	Average	Variance
	Low	14	1395.21	99.65788	0.477002
	High	17	1682.785	98.98733	1.411151

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.452061	1	3.452061	3.48	0.072319	4.18
Within Groups	28.77945	29	0.992395			
Total	32.23151	30				

- T = 2.5 mins:

SUMMARY:	Groups	Count	Sum	Average	Variance
	Low	7	676.573	96.65329	3.25189
	High	7	690.3045	98.61493	1.317765

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	13.46811	1	13.46811	5.89	0.031856	4.75
Within Groups	27.41793	12	2.284828			
Total	40.88604	13				

Appendix P. Outputs of Statistical Analysis - Analysis of Variance (Cont'd)

(3) Effect of Type of Filter on Elimination (Low Influent Concentration):

- T = 20 mins:

SUMMARY:	Groups	Count	Sum	Average	Variance	
	COM	18	1800	100	0	
	DE	13	1294.457	99.57364	2.36316	
ANOVA:						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.372157	1	1.372157	1.4	0.245802	4.18
Within Groups	28.35792	29	0.977859			
Total	29.73007	30				

- T = 10 mins:

SUMMARY:	Groups	Count	Sum	Average	Variance	
	COM	18	1746.662	97.0368	29.65758	
	DE	16	1564.583	97.78644	3.234156	
ANOVA:						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.760076	1	4.760076	0.28	0.603217	4.15
Within Groups	552.6912	32	17.2716			
Total	557.4513	33				

- T = 5.0 mins:

SUMMARY:	Groups	Count	Sum	Average	Variance	
	COM	30	1686.259	56.20862	278.2649	
	DE	14	1395.21	99.65788	0.477002	
ANOVA:						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	18020.27	1	18020.27	93.72	2.93E-12	4.07
Within Groups	8075.884	42	192.283			
Total	26096.16	43				

- T = 2.5 mins:

SUMMARY:	Groups	Count	Sum	Average	Variance	
	COM	12	376.2733	31.35611	113.8897	
	DE	7	676.573	96.65329	3.25189	
ANOVA:						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	18850.14	1	18850.14	251.87	1.26E-11	4.45
Within Groups	1272.298	17	74.84108			
Total	20122.44	18				

Appendix P. Outputs of Statistical Analysis - Analysis of Variance (Cont'd)

(3) Effect of Type of Filter on Elimination (High Influent Concentration):

- T = 20 mins:

SUMMARY:

Groups	Count	Sum	Average	Variance
COM	18	669.1486	37.17492	85.56802
DE	12	1200	100	0

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	28418.33	1	28418.33	547.01	6.45E-20	4.2
Within Groups	1454.656	28	51.95201			
Total	29872.99	29				

- T = 10 mins:

SUMMARY:

Groups	Count	Sum	Average	Variance
COM	18	711.7439	39.54133	300.3311
DE	14	1386.407	99.02908	3.229858

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	27867.99	1	27867.99	162.41	1.22E-13	4.17
Within Groups	5147.617	30	171.5872			
Total	33015.61	31				

- T = 5.0 mins:

SUMMARY:

Groups	Count	Sum	Average	Variance
COM	14	576.5176	41.17983	58.5478
DE	17	1682.785	98.98733	1.411151

ANOVA:

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	25655.69	1	25655.69	949.362	1.04E-23	4.182965
Within Groups	783.6999	29	27.02413			
Total	26439.39	30				

VITA

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