CONTRACT NO. A032-127
FINAL REPORT
MAY 1992

Biodegradation Technology for Volatile Organic Compound Removal from Airstreams

Phase I: Performance Verification

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY
AIR RESOURCES BOARD
Research Division

BIODEGRADATION TECHNOLOGY FOR VOLATILE ORGANIC COMPOUND REMOVAL FROM AIRSTREAMS

PHASE I: PERFORMANCE VERIFICATION

Final Report
Contract No. A032-127

Prepared for:

Research Division
California Air Resources Board
2020 L Street
Sacramento, CA 95814

Submitted by:

Center for Environmental &
Water Resources Engineering
University of California, Davis

Prepared by:

Sarina J. Ergas
Edward D. Schroeder
Daniel P.Y. Chang

MAY 1992

ABSTRACT

This report presents the results of laboratory and field studies designed to verify the potential application of microbial packed bed systems, generally known as "biofilters", for the removal of volatile organic compounds (VOCs) from off-gases resulting from wastewater treatment. Volatile organic compounds are known to be emitted in significant quantities from many wastewater treatment plants and landfills, as well as various industrial operations. Wastewater treatment plant off-gases are characterized by the diversity and the relatively low concentrations of the compounds present. Six target compounds, benzene, toluene, chloroform, dichloromethane, trichloroethene, and tetrachloroethene were selected for particular emphasis in this study. However, other compounds were monitored during the field segment of the study , including hydrogen sulfide, oxylene, and total VOCs. The target compounds were generally present at levels less than 1 ppmv and many are present at concentrations below 100 ppbv.

Biofilters are packed beds that utilize microbial cultures growing on the packing medium to oxidize VOCs and other degradable compounds in an air stream. The packing medium used in these studies was a mixture of sewage sludge derived compost, wood products, and perlite. Oyster shell was added as a buffering material to control pH. Moisture content of the medium was maintained at greater than 50% by weight throughout the experiments. Gas fluxes used are typically in the range of 1 to 7 ft/min, which was the range used in these studies.

The objectives of the project were (1) to determine the potential of aerobic biofiltration as a method of removing VOC's from gas streams at POTWs and (2) to determine the extent of degradation and potential by-products of six selected compounds (benzene,chloroform, dichloromethane, toluene, tetrachloroethene, and trichloroethene) in a microbial gas cleaning process.

In the laboratory experiments the removal of toluene and benzene was above 80 % and the removals of the chlorinated VOCs were generally less than 50 %. However, there seemed to be an improvement with time in the laboratory work. In the field excellent removals of benzene, toluene, and hydrogen sulfide were observed, with values generally over 90%. Removals of the chlorinated compounds were varied and generally below 40% of the inlet concentrations.

The reasons for the limited removals of chlorinated VOCs are not clear. Possible factors include mass transfer limitations and problems in generating cometabolism.

DISCLAIMER

The statements and conclusions in this report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source or their use in connection with the material reported herein is not to be construed as either an actual or implied endorsement of such procucts

ACKNOWLEDGEMENTS

Many individuals contributed to the completion of this project. Particular appreciation is given to Mr. Robert Morton and Mr. Ross Caballero of the Joint Water Pollution Control Plant of the County Sanitation Districts of Los Angeles County. They, and the technical support staff of the JWPCP contributed throughout the project, but especially during the field studies. The major portion of this project involved operation of the pilot plant biofilter at the JWPCP and much of the analytical work was done there, as well. Fellow faculty, students. and staff of the University of California, Davis took part in the construction of the pilot plant and chemical analyses: Anders Wistrom, Amir Taebi, Rosa Ergas, Bill Sluis, Rosa Ergas, Kate Scow, Dale Uyeminami, and James Bumgardner.

We wish to thank our research project manager, Mr. Ralph Propper, of the California Air Resources Control Board for his steady concern about the progress of the project and for his interest and resourcefulness in dealing with problems as they appeared.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

General

cfm	cubic foot per minute
GAC	granular activated carbon
PID	photoionization detector
POTW	publically owned treatment works
ppbv	parts per billion on a volumetric basis
ppmv	parts per million on a volumetric basis
U_g	gas flux, ft/ min ($ft^3/ft^2 \cdot min$)
VOC	volatile organic compound

Chemicals

BTX	benzen, toluene, xylene
BZ	benzene
DCE	dichloroethene
DCM	dichloromethane (methylene chloride)
PCE	tetrachloroethene (PERC, perchloroethene)
PVC	polyvinyl chloride
TCA	trichloroethane
TCE	trichloroethene
TCM	trichloromethane (chloroform)
TOL	toluene
VC	vinyl chloride
XYL	xylene

Organizations

JWPCP	Joint Water Pollution Control Plant
CSDLAC	County Sanitation Districts of Los Angeles County
CARB	California Air Resources Board
ASTM	American Society of Testing Materials

I. INTRODUCTION

This report presents the results of laboratory and field studies designed to verify the potential application of microbial packed bed systems, generally known as "biofilters", for the removal of volatile organic compounds (VOCs) from off-gases resulting from wastewater treatment. Volatile organic compounds are known to be emitted in significant quantities from many wastewater treatment plants and landfills, as well as various industrial operations. Wastewater treatment plant off-gases are characterized by the diversity of compounds present and the relatively low concentrations of these VOCs [Chang et al., 1987, 1991]. Most of the target compounds are present at levels less than 1 ppmv and many are present at concentrations below 100 ppbv. Many of the emitted VOCs support microbial growth and others have been shown to be microbially degraded through a process known as cometabolism. Because microbial degradation results in destruction of the compounds as well as their removal from the air stream, the use of biofilters is very attractive. An additional advantage of biofiltration is that sulfides are oxidized by chemoautrophic microorganisms that grow in the units. Thus an odor problem connected with treatment plant off-gases is addressed, as well.

The studies reported here are the first phase of a planned two-stage project on application of biofiltration for removal of VOCs from selected off-gases. If the results of the Phase I verification studies were promising, a more detailed evaluation of biolfiltration was anticipated.

Phase I Objectives

The specific objectives of Phase I verification studies were:

1. To determine the potential of aerobic biofiltration as a method of removing VOC's from gas streams at POTWs.

2. To determine the extent of degradation and potential by-products of six selected compounds (benzene,chloroform, dichloromethane, toluene, tetrachloroethene, and trichloroethene) in a microbial gas cleaning process.

BACKGROUND - MICROBIAL GAS CLEANING SYSTEMS

Microbial gas cleaning processes have been in existence for a number of years [Ottengraf, 1983; Ottengraf et al., 1986]. Most efforts have been directed toward odor control from wastewater treatment systems and industrial gas discharges. More recently efforts have been directed toward removal of toxic and hazardous compounds.

History of Microbial Gas Cleaning Using Packed Beds

Packed bed microbial gas cleaning systems have been in sporadic use in the United States for about 30 years, although some references can be found to the practice prior to 1960 [Carlson and Leiser, 1966]. Early systems were used for the removal of sewage related odors, including organic sulfides . Inert media used in biofilters have included both soils and organic materials such as peat and compost, as noted above. Applicaton of the technology has not been widespread, at least in part because of the low design loading rates (< 0.2 cfm/ft^2, 0.06 m^3/m^2•min), poor air distribution, and poor humidity control. Over the last 10 years considerable improvement has been made in both air distribution and humidity control and additionally a better understanding of the need to neutralize acidity generated by the biodegradation process [Ottengraf and Van den Oever, 1983; Hartenstein, 1987; Bishop, 1989]. As a result, packed tower systems, somewhat similar to granular activated carbon (GAC) beds, have been developed that operate at loading rates of 10 to 15 cfm/ft^2 (3.1 to 4.6 m^3/m^2•min). These latter rates are in the range used for GAC adsorption of odor causing and organic compounds from gas streams and would appear to make packed bed microbial treatment suitable for a number of applications.

Kosusko and Nunez [1989], Hartenstein [1987], Strand and Shippert [1986], Wilson and Wilson [1985] have all reported the removal of VOCs from gas streams using soil, peat, or compost systems. Compounds removed included a range of low molecular weight mercaptans and amines, alcohols, aldehydes, aliphatic and aromatic hydrocarbons. Most interesting is that the compounds listed included a number of important chlorinated and unchlorinated toxic VOCs such as dichloromethane (DCM), trichloromethane (TCM), trichloroethane (TCA), trichloroethene (TCE), tetrachoroethene (PCE), and toluene (TOL) and that there is evidence for complete oxidation to carbon dioxide and water [Kosky and Neff ,1988]. This latter observation requires additional confirmation and motivates this study.

Aerobic Microbial VOC Degradation

Microbial degradation of VOC's depends on the presence of particular species capable of oxidizing the compounds in the gas stream. The VOC's of concern in emissions from wastewater treatment plants and landfills include both halogenated and non-halogenated compounds, with a number of the halogenated compounds being very difficult to degrade. Halogenated compounds can be biologically degraded both aerobically and anaerobically [Alexander, 1978; Shelton, 1983; Sleat and Robinson, 1983; Bouwer and McCarty, 1983a,b; Levitt et al., 1985]. A general understanding of the most appropriate approach to microbial degradation of halogenated organics does not exist and current methods are based on

experience with similar compounds. Considerable experience has been developed with the microbial degradation of the most common VOC's emitted from waste management operations.

The four chlorinated VOCs selected as target compounds for this study, TCM, DCM, TCE, and PCE, are all resistant to degradation by soil microorganisms [Smith, 1973; Strand and Shippert, 1983; Nelson et al., 1988, Bohn, 1989]. Bacteria of the genus *Methanobacter* are known to oxidize these compounds through incidental metabolism[1] when grown on methane [Wilson and Wilson, 1985; Strand and Shippert, 1986; Fathepure and Boyd, 1988] and the compounds have been shown to be oxidized to carbon dioxide rather than simply dehalogenated. Similar results have be reported for TCE degradation by a number of species of the genus *Pseudomonas* [Folsom, et al., 1990; Nelson, et al., 1988; Wackett and Householder, 1989; Wackett and Gibson, 1988] and again the principal product was carbon dioxide. The dechlorinated products of these four target halogenated VOCs can be metabolized by other soil microorganisms, also. Toluene and benzene, the two non-chlorinated compounds in the target group are degraded by a number of microbial groups found in soil (particularly those of the genus *Pseudomonas*) and toluene is one of the compounds found to initiate incidental metabolism of trichloroethene [Nelson et al., 1987].

In addition to the target compounds, a number of other compounds are of interest in this study. Examples are chloroethene (vinyl chloride-VC), dichloroethenes (DCE), and xylenes (XYL). The target compounds were selected for work in the initial laboratory phase of the study. Other compounds of interest will be encountered in the field studies conducted in the second and third phases of the research.

Ottengraf and Van den Oever (1983), Kampbell et al. (1987), Hartenstein (1987), Kosky and Neff (1988), and Bohn (1989), have all reported excellent success in the removal of VOC's from various sources using packed bed microbial processes. Kosky and Neff presented characteristic influent/effluent gas chromatograms showing the effectiveness of packed bed microbial processes. Note that two of the target compounds, TCE and TOL are among the 21 compounds listed. Toluene was effectively completely removed and TCE was partially removed. Hartenstein (1987) reported that TCE was removed to the 86 percent level in packed bed microbial processes, but did not indicate whether VC was formed. Presumably

---

[1]Incidental metabolism is often called cometabolism in the literature. The term incidental metabolism is used here to differentiate from breakdown associated with the degradation of non-chlorinated chemical analogs. In incidental metabolism a structurally unrelated compound (e.g. CH_4) is the primary substrate. Breakdown of the target compound is incidental the degradation of the primary substrate.

removal to a higher level is a matter of design and operation since there is no reason to assume that the ability of the microorganisms to degrade the compound changes with concentration.

Biofilter Configuration

Microbial gas cleaning systems have three principal components: the packed bed microbial support system, the gas distribution system, and the humidity control system. A definition sketch of a typical microbial gas cleaning system is shown in Figure 1.

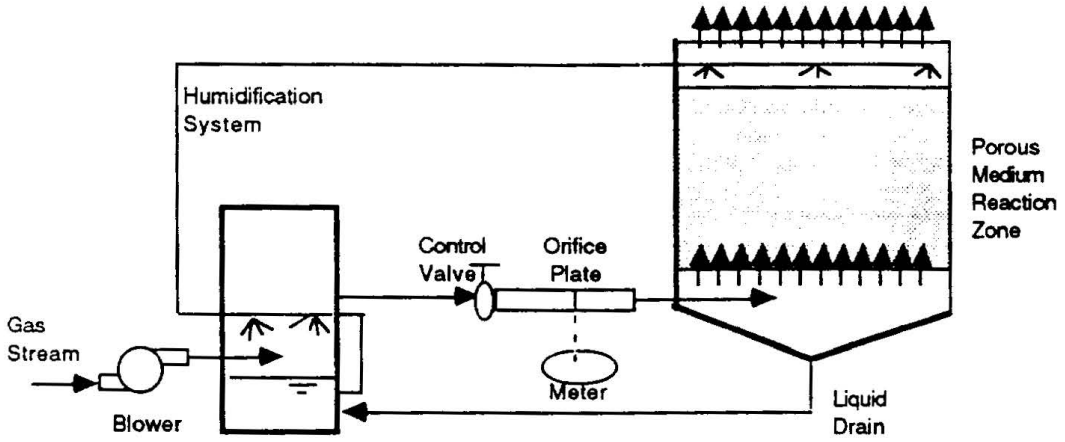


Figure 1. Definition Sketch of Packed Bed Microbial Gas Cleaning System

Packed Bed Microbial Support System: The packed bed microbial support system consists of a porous bed of solid material on which the microbial population grows. Important features of a packed bed are a high porosity, suitable pore size, low density, and an ability to sorb water. High porosity is important in gas flow distribution and in providing maximum contact between the gas stream and the microbial population. Suitable pore size is important because an extremely small pore diameter will result in high head losses and plugging as microbial growth develops, while a large pore size will result in very large volume requirements due to minimal contact between the microorganisms and the gas stream. Low density of the support material is an advantage in construction. The ability to absorb water is a requirement because microorganisms grow best on a wet surface.

Suitable packing materials include soils with a high organic content, peat, refuse-derived compost, and other forms of compost. Because soils tend to have small pore sizes and present difficult humidity control problems their use is not as appropriate as humus or compost. There may be an advantage in using soil in some landfill operations, however.

Among the humus and compost materials, refuse derived compost has proven superior in terms of process operation [Bishop, 1989; Kosky and Neff, 1988]. The reasons for reported differences are probably related to the nutrient availability or factors such as local pH control. Compost derived from waste sludge at the Joint Water Pollution Control Plant (JWPCP) of the County Sanitation Districts of Los Angeles County (CSDLAC) was used in this project.

Treatment plant off-gases usually contain sulfides. A group of aerobic chemoautotrophic bacteria oxidize sufide to sulfite. In solution the sulfite is oxidized to sulfate.

$$H_2S \rightarrow S + 2H^+ + 2e^- \quad (1)$$

$$S + 3H_2O \rightarrow SO_3^{-2} + 6H^+ + 4e^- \quad (2)$$

$$SO_3^{-2} + H_2O \rightarrow SO_4^{-2} + 2H^+ + 2e^- \quad (3)$$

The acid produced can be neutralized by incorporating a buffering agent into the packing material. In these studies crushed oyster shell, which is mostly $CaCO_3$, was used for this purpose.

Compost tends to consolidate when maintained at a high moisture content and a bulking agent can be added to counteract this effect. Perlite, a volcanic material similar to pumice, was used for this purpose in these studies.

Gas Distribution System; Included in the gas distribution system are the blower, ductwork or piping, and orifice network. A blower is required to overcome the pressure loss enountered as the air flows through the system. Most of the pressure loss occurs in the packed bed reaction zone, but frictional losses in the duct work and losses through the orifices are also significant. In most cases, a positive pressure system provides better control than sub-atmospheric operation; e.g. by placing a fan at the downstream end, because leakage will not result in dilution. If there is concern over toxic air contamination (TAC) leackage prior to treatment by the bed, a sub-atmospsheric system would be preferred. The characteristics of the packed bed provide good control of the air flow distribution through the reaction zone. Ductwork serves both to conduct air across the base of the reaction zone and as a drain for excess liquid that may accumulate in the system (the liquid may have a very low pH value and be quite corrosive). In some systems the air ducts and drains are separate units, but this is generally unnecessary. Orifices for air distribution and drainage can be narrow slots or circular holes in the top or sides of the portion of the duct system underlying the reaction zone. Prevention of plugging by the packing medium particles is important and can be accomplished by providing a coarse layer on the bottom of the reaction zone or careful placement and sizing of the orifices. Excess liquid that accumulates in the reaction zone will flow into the duct

system and be conveyed to the humidification chamber (as indicated in Figure 1) or returned to the wastewater treatment system.

Humidity Control Humidity control can be achieved by spraying water over the surface of the packed bed or humidifying the influent air. Both options are shown in Figure 1, but in most cases both methods do not need to be used simultaneously. Off-gases from wastewater treatment units are usually close to water vapor saturation vapor pressures and, if some cooling occurs in the biofiltration unit, the stream may not need to be humidified. Maintaining the correct level of humidity and moisture in the medium is done by trial and error. Too little moisture results in dry zones and loss of microbial activity. Too much moisture results in reduced VOC transport rates because of increased transfer resistance through the liquid film and subsequent development of anaerobic zones within the packed bed. Anaerobic zones result in poor product gas quality and production of odors.

II. EXPERIMENTAL PROGRAM

To assay the effectiveness of biofiltration in VOC removal from wastewater treatment plant emissions, a pilot scale biofilter, designed to treat aproximately 200 cfm (5.7 m^3/min) of air, was constructed in the environmental engineering laboratories of the Department of Civil and Environmental Engineering of the University of California, Davis. The experimental program was conducted in two phases: (1) a laboratory phase at Davis, and (2) a field phase at the JWPCP. During the laboratory testing phase of the project, the system was run for eight weeks using a synthetic gas stream consisting of benzene, toluene, dichloromethane, trichloromethane, trichloroethene, and tetrachloroethene. Loading rates were varied and removal efficiencies of the six VOCs were determined for each flux. The biofilter was then taken to the Joint Water Pollution Control Plant (JWPCP) of the County Sanitation Districts of Los Angeles (CSDLA) where it was used to treat air emissions from a covered primary effluent screening station.

Reactor Description

Primary components of the pilot plant included the reactor chamber, gas intake system, humidification chamber, gas flow measurement systems, and filter bed, as shown in Figure 2. All of the rigid piping was schedule 40 PVC. Flexible ducting was either of PVC or neoprene impregnated, wire reinforced, cotton.

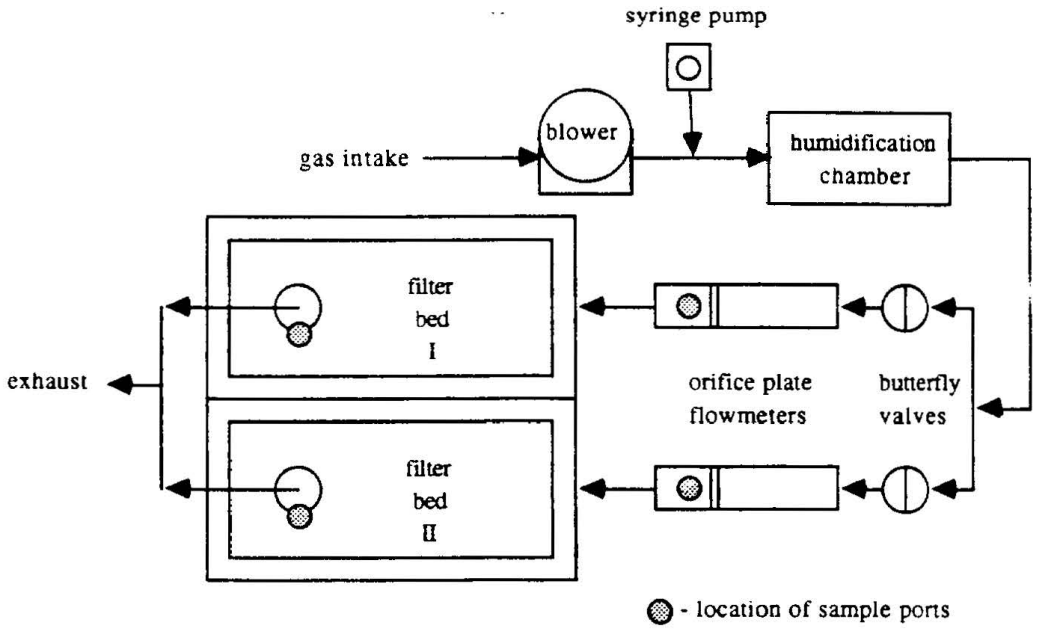


Figure 2. Schematic diagram of pilot plant biofilter system

Reactor Chamber: The steel reactor chamber measured 8 ft x 8 ft x 4 ft. and was divided into separate biofilter units, each 4 ft x 8 ft x 4 ft. Steel, diamond mesh grating supported by 1 inch channels was placed 8 inches above the floor of each unit for the purposes of forming an inlet air distribution plenum and for supporting the filter medium. Plywood sheets (4 ft x 8 ft x 0.5 inch) with 6 inch diameter galvanized vents were used as covers. A neoprene gasket was placed between the plywood and the lip of the reactor chamber and the cover was held in place by clamps. All surfaces were coated with epoxy paint to retard corrosion.

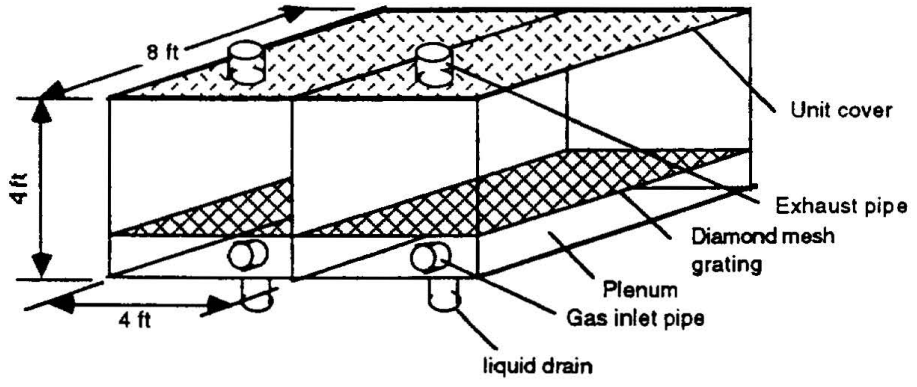


Figure 3. Definition sketch of pilot plant reactor

Gas Intake System: The gas intake system consisted of a 9 inch radial blower, motor and 5 inch diameter ducting. During the laboratory tests, a constant mass flow rate of organic solvents was injected into the inlet gas stream using 2 syringe pumps (Sage, model 341B) fitted with 50 ml glass gas tight syringes (Hamilton, 2500 series). The compounds used were reagent grade TCE, TCM, TOL, BZ (Fisher Scientific, Fairlawn, NJ), DCM (Mallinckrodt Inc, Paris, KY), and PCE (Eastman Kodak, Rochester, NY). During the field experiments at the JWPCP, the syringe pump assembly was removed and the inlet was connected to the head space above covered primary clarifiers. In a final set of experiments at the JWPCP the syringe pumps were reinstalled to all increasing the feed concentration of PCE and DCM.

Humidification System: In the laboratory system, moisture was provided by humidifying the influent gases. Gas flow was routed through a (24x30x48 inch) polyethylene lined fiberglass tank with a stainless steel pigtail style spray nozzle (Lechler, model 474) in the bottom of the cover. A float valve maintained a constant reservoir of water in the bottom of the tank. Water was circulated from the reservoir to the spray nozzle with a positive displacement pump. In the field experiments, the humidification system was found to be unnecessary because the humidity of the gas stream from the primary clarifiers was sufficient to maintain filter bed moisture content.

Gas Flow Measurement: Gas flow exiting the humidification chamber was split between a two-chambered filter bed. Orifice plates were used to measure the flow rate to each chamber. Pressure drop across the orifice plates was measured with magnehelic pressure gauges. Gas flow was controlled with cast iron butterfly valves upstream of the orifice plates and sample ports were located downstream of the orifice plates.

Filter Medium: The filter medium consisted of air dried compost, perlite, and crushed oyster shell. Water and microbial cultures (activated sludge from the U.C. Davis wastewater treatment plant and microbial cultures grown on toluene in the laboratory) were added to bring the mixture to a moisture content of 55%. The compost (Nitrohumus™, Kellogg Company, Carson, CA) contained 50% digested sewage sludge from the JWPCP and 50% forest products and made up approximately half of the mixture. Perlite (Nor-Cal Perlite Co., Richmond, CA), an expanded volcanic material which is ordinarily used for increasing the porosity of potting soil, was added to decrease the pressure drop across the bed. Enough perlite was added to make the dry mixture approximately 50% perlite by volume. Crushed oyster shell (Jerico Dredging Inc.,Petaluma, CA), a source of calcium carbonate, was added as

a pH buffer at 1 meq/ gram of filter media. The dry componnets and liquids were mixed in 3 ft^3 batches in a portable concrete mixer.

The microbial amendment used consisted of mixed liquor suspended solids from the University of California, Davis wastewater treatment plant at 650 ml per cubic ft of filter media and a toluene degrading organism, TOL1A, a *Pseudomonas Putida* (determined by fatty acid assay) was grown in a media with TOL as the sole carbon source. TOL1A was added at 10^6 cells per gram of filter medium.

Sampling and Analytical Methods

Gas samples were drawn through multi-sorbent glass tubes by universal flow pumps (SKC, model 224-PCXR7). The 4 mm I.D. glass tubes, manufactured by Supelco, contained a mixture of Carbopak®, synthetic carbonaceous spheres, and Carbosieve® III, a carbon molecular sieve. The tubes were connected to the sample ports by Teflon® tubing and stainless steel fittings. A stainless steel manifold allowed three samples to be taken at once for triplicate analysis. Flow through the sorbent tubes was determined with a bubble flow meter prior to sampling (SKC-West Inc., model 712). Sample volume was determined by multiplying the flow rate by the sampling time. Inlet samples were taken downstream of the orifice plates. Outlet samples were taken through each of the sample ports at the outlet vent. During the lab studies, samples were drawn continuously at a flow rate of approximately 30 ml/min for 12 minutes. During the JWPCP studies, samples were drawn for 10 minutes in one minute intervals over an hour sampling period.

A concentrating/capillary inletting system (Envirochem, model 810A) was used for sorbent tube sample desorption, pre-concentration and delivery. Samples were analyzed with a Hewlett Packard 5980A gas chromatograph utilizing a glass capillary column (J&W Scientific DB624) and Hewlett Packard 59970 mass spectrometer. Calibration standards were drawn into tubes from a tank of gas standard (Scott Marin, Riverside, Ca) containing TCM (chloroform), dichloromethane (methylene chloride), BZ, TOL, TCE, PCE, and o-XYL. Three calibration standards, a trip blank (unexposed tube) and an ambient blank (exposed to the ambient air at the treatment plant) were analyzed for each sample run.

During the field operation, grab samples were drawn twice daily by CSDLAC staff into clean 3 liter tedlar bags for analysis of aromatic compounds, H_2S, and VOCs. Bags were connected to the sample ports using Teflon® tubing. On the inlet side, the previously evacuated bags would fill due to the differential pressure in the duct. At the outlet of the

biofilter, a cloth plug was placed in the duct to partially seal the duct and the outlet flow was directed into the bag.

Grab samples were analyzed for aromatic compounds using a portable gas chromatograph (Sentex, Scentograph). The Scentograph uses an argon ionization detector system to determine organic molecule concentrations. A one point calibration was used with this system which can determine up to four organic compounds at once. A gas standard containing BZ, TOL, m+p-XYL, and o-XYL, was used to calibrate the GC. Samples were analyzed within one hour of collection.

Hydrogen sulfide analysis was accomplished using lead acetate tubes (Gastec). One hundred ml gas samples were drawn from the tedlar bags and injected through lead acetate tubes. Hydrogen sulfide in the sample reacts with the white lead acetate to produce brown lead sulfide. Hydrogen sulfide concentration is correlated with the length of the brown stain on the tube.

Total ionizable compound analysis was accomplished using another portable gas chromatograph (Photovac, model 10S plus). The sample was pulled through the photoionization detector (PID), bypassing the chromatography column. Because the chromatography column was bypassed, the column did not distinguish one compound from another but gave a number which represents the total amount of ionizable compounds within the sample. The instrument was calibrated using a one point calibration of a gas mixture of benzene, TOL, m+p-XYL, o-XYL, and EtBZ. This served as a surrogate for total ROG.

Grab samples were analyzed once a week by the CSDLA laboratory. The samples were collected in labeled 10 liter tedlar bags and taken to the CSDLA lab in cardboard boxes to minimize photochemical decomposition. The system used was a Varian 6000 gas chromatograph equipped with a 10.2 eV HNU model PI-52-02 PID in series with a Hall model 700A electrolytic conductivity detector (Tracor) operated in the halogen mode. The GC utilized a 2 m x 2 mm ID Pyrex column packed with 60/80 mesh Carbopak B coated with 1% SP 1000. Aliquots of gas were withdrawn from the sample bags and passed through a cryogenic trap then thermally desorbed onto a cooled gas chromatographic column. The gas chromatograph was temperature programmed to slowly heat the column to separate the components. Aromatics and unsaturated hydrocarbons were analyzed using the PID. The effluent from the PID was analyzed for hydrocarbons using the conductivity detector. The GC was periodically checked for accuracy using 10 point calibration curves for each detector. The

CSDLA's laboratory has an established quality assurance program and participates in the EPA audit cylinder program administered by the California Air Resources Board (CARB).

During the field tests, gas samples were tested for odorous compounds once a week. Two odor panels consisting of eight members each (male and female) were made up of local residents who had demonstrated odor sensitivity. Grab samples were collected in 2.5 liter Tedlar® bags. Analysis was performed as specified by the American Society of Testing Materials [1967] (ASTM designation D 1391-5). Odor concentrations were reported in odor units per standard cubic foot which represent the number of cubic feet that one cubic foot of sample would occupy when diluted to the odor threshold (odor just detectable). Analysis was done within six hours of collection.

Once each week, a sample of the filter media was removed and analyzed for pH and moisture content. Filter media samples were taken through one of two flanged fittings in the lid of the filter bed. A soil core sampler (Oakfield, model K) was used to extract four samples from varying bed heights from each side of the filter bed. The four samples were mixed together to make a composite sample. Samples were transported to the lab in plastic containers.

Filter media samples were weighed, then dried to constant weight at 103°C in a porcelain dish and weighed again. Moisture content was reported as the mass of water divided by the total mass filter media plus water. Filter media pH was determined using a standardized electrode pH meter (Beckman, model ϕ 10) using a mixture of 5 ml of distilled water and 5 grams of filter media. Leachate pH was determined in the field with pH indicator strips (Colorphast).

RESULTS

Results of the experimental program are presented in two segments. The intial segment of experiments began August 13, 1991 and extended through October 18, 1991. The work was conducted in the environmental engineering laboratories of the Department of Civil Engineering and included what might be considered start-up and shake-down periods for the pilot plant. Although the system operated with few problems there was a need to develop familiarity with the unit and its components, problems with sampling procedures, and to allow time for the cultures to develop. The second segment of experiments began when the pilot plant was brought on-line at the JWPCP on October 23, 1992 and extended through May, 1992. Experimental studies in the period March through May, 1992 were focused on system

response to higher concentrations of TCE. DCM and H_2S than had been observed at the primary screening station during the fall and winter period.

University of California, Davis Lab Experiments

In addition to unit start up, the U.C. Davis experiments were performed to determine appropriate loading rates and expected removal efficiencies for the field studies at the JWPCP. Compounds and inlet concentrations used in these experiments (Table 1) reflected typical concentrations reported at the primary effluent screening station at the JWPCP. During the first two weeks of operation, TOL alone was evaporated into the inlet gas and of flux rates of 3.1 and 4.7 ft/min (residence times, t_r, of 1 and 0.6 mins) for Biofilters I and II, respectively. After 6 days of operation samples were taken and it was found that little or no TOL removal was occurring in the reactor. After 7 more days of operation samples were taken again and toluene removal efficiency was found to be 63% for Biofilter I and 79% for Biofilter II. During the third week of operation, DCM was added to the gas stream. Samples were drawn after five more days of operation and no DCM activity was observed. During the second week of DCM addition the DCM removal efficiency was at 24% and 42% for Biofilters I and II, respectively. Lower removal efficiencies for TOL (48% and 33% for Biofilters I and II) were observed during this period. During the fourth week of operation the rest of the six VOCs (BZ, TCM, TCE, and PCE) were added.

Removal efficiencies for each of the six target VOCs versus gas flux rate through the biofilter bed are shown in Table 1 and Figures 4 through 9. Values reported represent the final removal efficiency determined for the period of operation at each flux rate, but these values should not be thought of as the steady state removal efficiencies. Increased removal efficiencies were observed with decreasing flux rates for TOL and BZ. The highest removal efficiencies observed, 77% and 78% for BZ and TOL respectively, occurred at a gas flux rate of 1.5 ft/min (t_r= 2 mins). Removal efficiencies for the four chlorinated VOCs and BZ are shown in Table 1. Highest removals, for the chlorinated compounds, were observed at flux rates of 2.3 and 5.5 ft/min (t_r = 1.3 and 0.5 mins) with lower removals occurring at both higher and lower flux rates. The presence of intermediate products of biotransformation was not observed in the outlet samples at any time during the laboratory studies.

TABLE 1:

Target Gas Inlet Concentrations Used in Lab Experiments and Removal efficiencies (% removal) for VOCs during laboratory studies

		% Removal gas flux (ft/min)			
compound	concentration (ppb)	1.5	2.3	5.5	5.9
chloroform	100	18	42	37	23
dichloromethane	100	23	36	42	19
trichloroethene	100	28	40	43	11
tetrachloroethene	100	25	49	38	12
benzene	500	77	48	51	9
toluene	500	78	61	39	14

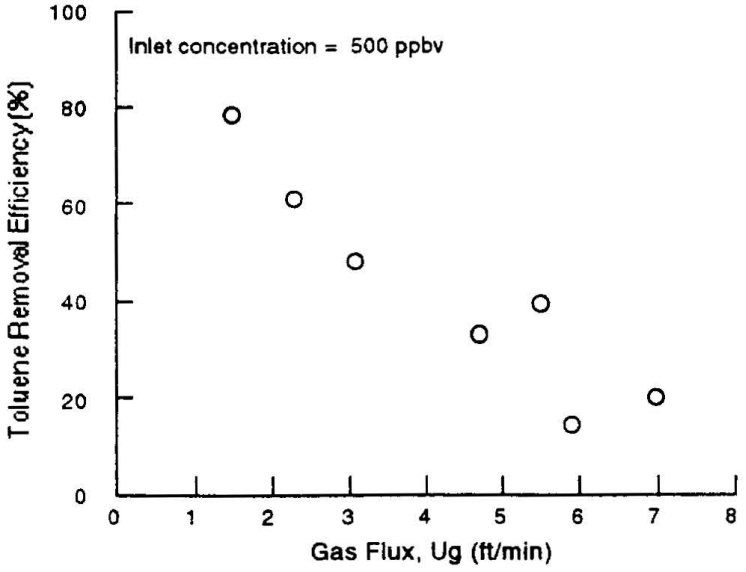


Figure 4. Toluene removal efficiency vs. gas flux during initial seven weeks of operation.

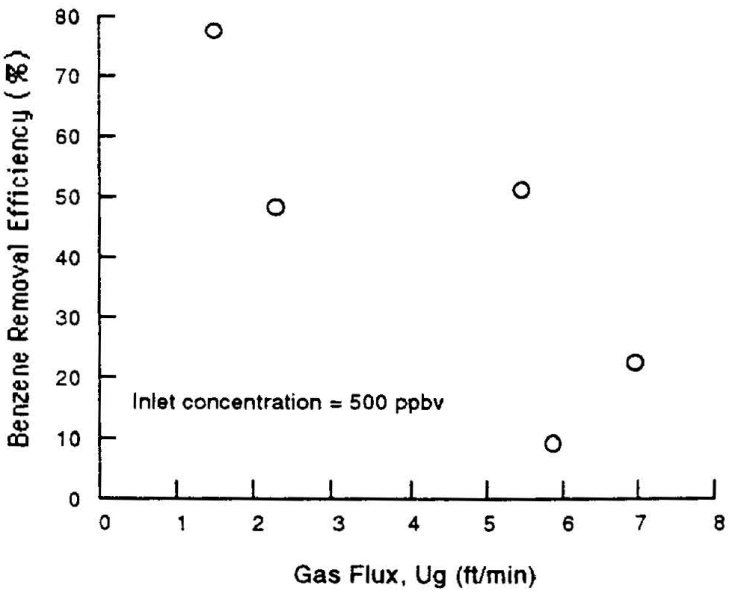


Figure 5. Benzene removal efficiency vs. gas flux during initial seven weeks of operation.

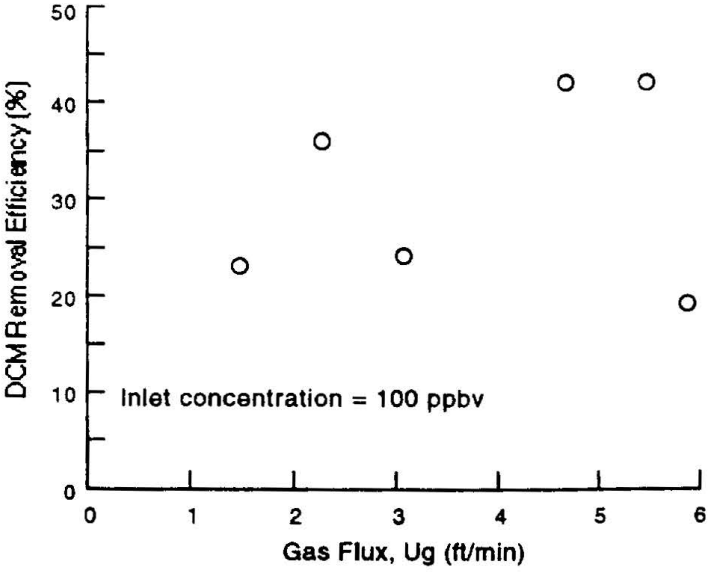


Figure 6. Dichloromethane removal efficiency vs. gas flux during initial seven weeks of operation.

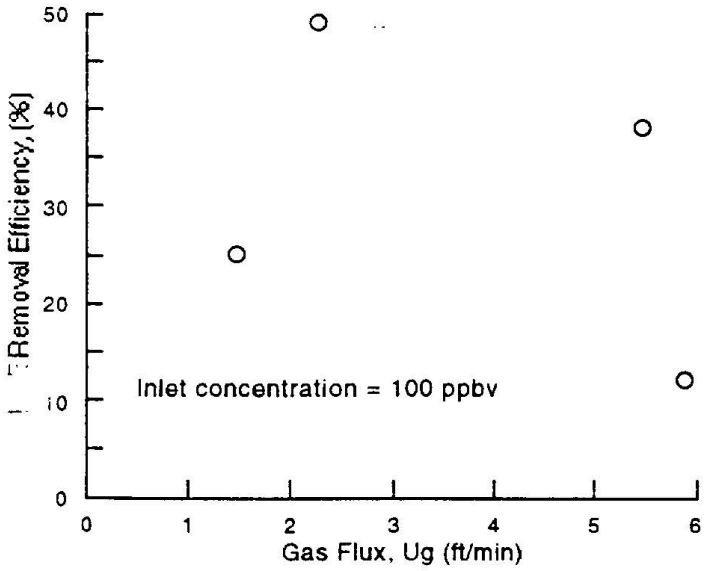


Figure 7. Tetrachloroethene (PCE) removal efficiency vs. gas flux during initial seven weeks of operation.

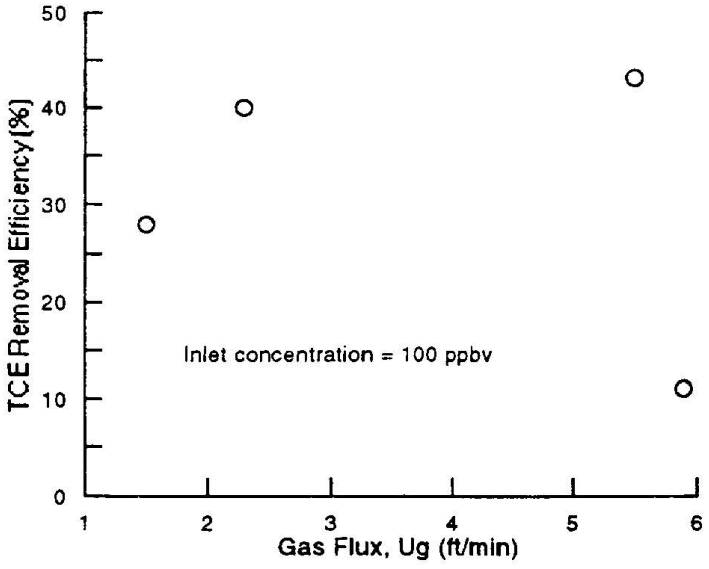


Figure 8. Trichloroethene removal efficiency vs. gas flux during initial seven weeks of operation.

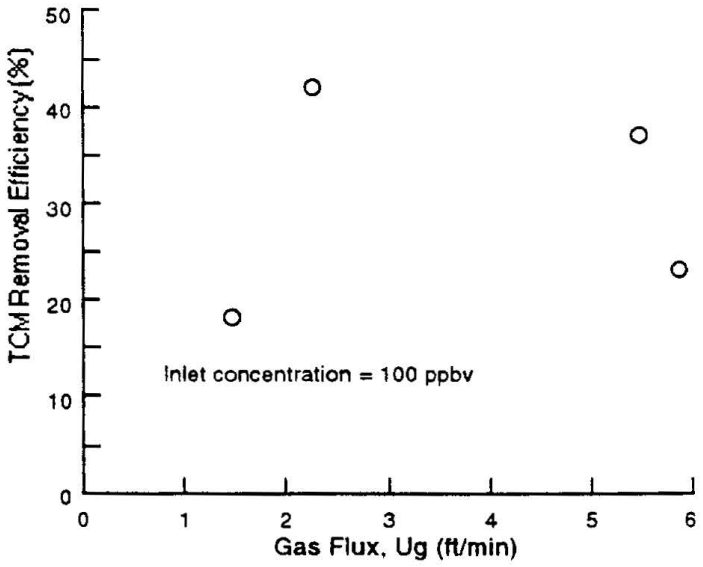


Figure 9. Trichloromethane (Chloroform) removal efficiency vs. gas flux during initial seven weeks of operation.

The results of the laboratory studies provided evidence that VOC removal by biolfitration would be possible. Substantial removal of the four chlorinated VOCs was particularly encouraging. Steady state conditions were not attained and there was not time during the laboratory segment of the experiments to establish optimal operating conditions. A factor that is expected in fixed film biological processes is that performance continues to improve until mass transport rate becomes limiting or the pores plug with microbial growth. It was hoped that continued improvement in process performance would occur during the field trials of the pilot plant.

JWPCP Field Experiments

In mid October, 1991, the biofilter pilot plant was transported to the JWPCP and installed at Traveling Water Screen Station No. 1. Screening Station No. 1 was selected for treatment because it was known to have significant emissions of VOCs. Volatile organic compound concentrations were higher at the headworks of the JWPCP, however, because the JWPCP services a large industrial component including several refineries, concentrations at the screening station were believed to be more representative of a typical POTW. Operation of the plant was begun at the JWPCP on October 24, 1991.

Approximately 50 fteet of 5 inch diameter flexible duct hose was used to connect Screening Station No. 1 head space air to the biofilter. A half inch drain was installed in the inlet ducting ten feett from the inlet to the biofilter so that accumulated water could be drained

regularly from the ducting. The biofilters were initially operated at flux rates of 1 and 3.5 ft/min (t_r = 3 and 0.9 mins) for Biofilters I and II respectively. On November 20th the flux rate in Biofilter II was increased to 4 ft/min (t_r = 0.75 mins)to determine the effect of higher loading.

During transport to the JWPCP the filter media partially dried out. Soaker hoses were placed on top of the filter media, the bed was saturated with water and then allowed to drain. After several hours of draining, bed samples were analyzed for moisture content and found to be 62 and 61% for Biofilters I and II respectively indicating that large volumes of water applied to the filter media would not increase the moisture content above an acceptable level. From November 16th to 19th and again from November 28th to December 2nd the biofilter was shut down due to problems with the humidification system. Although these were unplanned interruptions in normal operation, they provided an opportunity to observe how the system responded to such disturbances. The humidification chamber was deleted from the system flow train on December 2nd so that the blower could be used without the humidity chamber recirculation pump in operation. The influent air from the screening station is normally 95 to 100% relative humidity and weekly moisture content analysis showed no loss of moisture from the beds after the humidification system was taken off line. Mean moisture content throughout the study was 64± 3%. It was concluded that the mixture of materials (compost, perlite, and oyster shell) used in the filter bed had very good moisture retention and drainage properties for this application. The biofilter was in continuous operation throughout the winter and spring of 1991-92 in order to observe operation over the winter months and the long term performance and maintenance requirements.

VOC Removal: Averages of daily grab sample BZ, TOL, XYL (BTX), hydrogen sulfide, and total VOC concentrations for the period October 24th to November 20th are shown in Table 2. Hydrogen sulfide removal was consistently greater than 99% at all flux rates. Inlet and outlet concentrations for the aromatic compounds were highly variable, however removal efficiencies were consistently high with slightly higher removal efficiencies at lower flux rates (Biofilter I). The biofilters were able to maintain high removal efficiencies even at inlet concentrations up to 9 times the average. Due to the fact that these samples represent grab samples from a highly variable gas stream, occasional low removal efficiencies may indicate desorption of a previously adsorbed high loading of toluene. Removal efficiencies were lower than normal for several days after initial start up at the JWPCP and for one day after the system was restarted after shut down on days 26 and 39. Raising the gas flow rate in Biofilter II on day 27 did not appear to significantly change the system's performance. Outlet

concentrations of aromatic compounds dropped down to less than 100 ppb and stayed low after day 43, indicating some further acclimation of the microbial population. Because of the mild climate in the Los Angeles area and generally low variation in wastewater temperatures, gas inlet temperatures below 50°F were not measured during the study period. Removal efficiencies did not appear to be affected by temperature within the range encountered in this study, although a more controlled investigation might reveal such a relationship.

TABLE 2:

Average biofilter performance at the JWPCP from October 24, 1991 to November 20, 1991 for hydrogen sulfide, BTX, and total ionizable compounds.

	inlet	BF1 outlet	% removal	BF2 outlet	% removal
Hydrogen Sulfide (ppm)					
mean	17.72	0.04	99.92	0.16	99.65
standard deviation	19.04	0.24	0.35	0.84	1.41
benzene (ppb)					
mean	850	109	91	183	86
standard deviation	959	263	16	564	19
toluene (ppb)					
mean	925	68	95	117	91
standard deviation	1230	226	11	360	15
m & p-xylene (ppb)					
mean	244	27	91	42	88
standard deviation	256	65	19	119	20
o-xylene (ppb)					
mean	114	14	91	19	89
standard deviation	102	35	22	49	23
total ionizable compound					
mean	114	39	65	51	53
standard deviation	50	19	15	23	16

Sample chromatograms showing inlet and outlet concentrations for Biofilter I on November 12th are shown in Figure 10. These chromatograms indicate that the biofilter was removing a broad range of compounds from the gas stream including many of the higher molecular weight compounds. Peaks identified by mass spectrometry (1-chlorotetradecane, limonene, undecane, and dodecane) had removal efficiencies between 64 and 96 percent. The 1-chlorotetradecane peak is not supported by boiling point correlations and may have been the result of a problem in the GC-MS library. The presence of biological transformation products, i.e., new peaks not present in the influent sample, was not observed in any of the chromatographs of the biofilter samples.

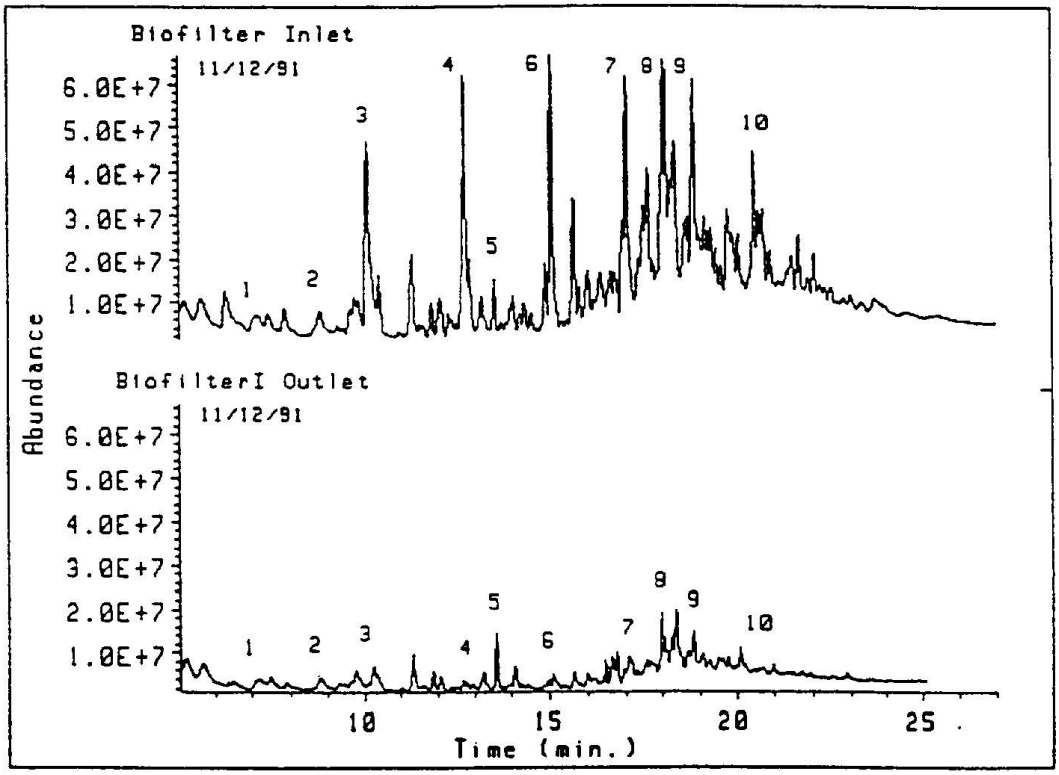


Figure 10: Example chromatogram compounds were identified by mass spectrometry (percent removals in parentheses) 1) dichloromethane (46), 2) chloroform (8), 3) benzene (98), 4) toluene (98), 5) PCE (0), 6) o-xylene (97), 7) unknown, 8) limonene (96), 9) undecane (64), 10) dodecane (76).

Results of one hour averaged samples taken on multi-sorbent tubes are shown in Table 3. Removal efficiencies for BZ, TOL, and XYL are consistent with the daily grab samples. In general, lower activity was seen for the chlorinated VOCs than the non-chlorinated aromatics both in the grab samples analyzed by the CSDLA lab (data not shown) and the averaged samples analyzed by the UC Davis lab. Exceptions to this were PCE, DCM, TCM, and m,o, and p-DCM which were significantly transformed on occasion although consistent removals were not observed. Removals of these compounds appeared to be correlated with higher inlet concentrations and possibly indicate mass transfer limitations at low inlet concentrations or analytical inaccuracies at low concnetrations. Removals of chlorinated compounds also appeared to increase with time and may indicate a longer acclimation period of the microbial population is required before significant degradation of these compounds can occur.

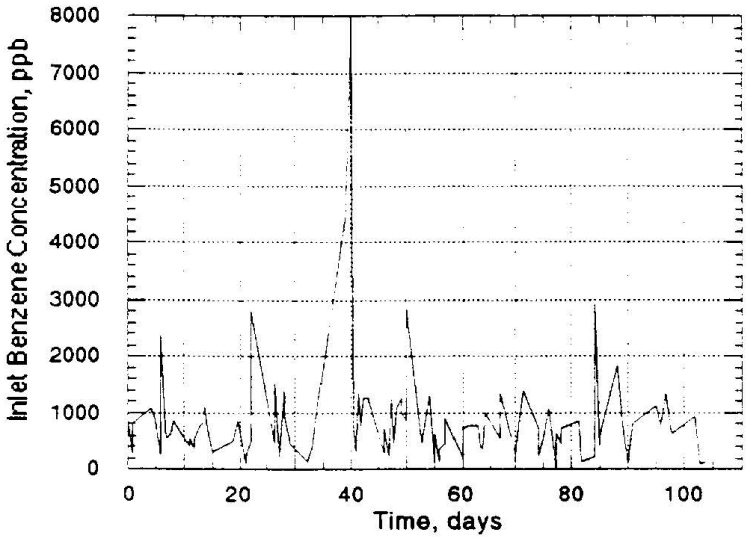
Samples were taken twice each day on a five day per week schedule by the staff of the JWPCP and analyzed for aromatic hydrocarbons with a PID as described in Section II. Results of these analyses are summarized in Figures 11 through 15.

TABLE 3:

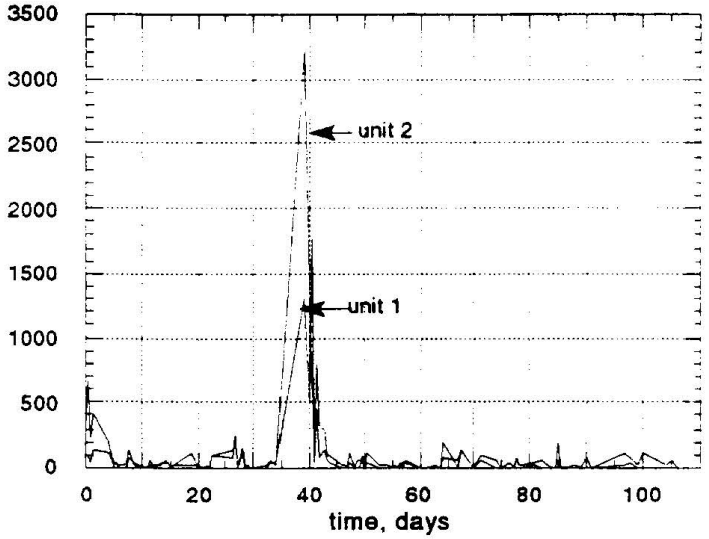
One hour averaged VOC concentrations and % removals at the JWPCP for the period October 24, 1991to November 20, 1991

		inlet	Biofilter I outlet		Biofilter II outlet	
compound	date	(ppb)	(ppb)	% removal	(ppb)	% removal
Dichloromethane	24-Oct	7	10	-	13	-
	31-Oct	16	13	19	19	-
	5-Nov	18	13	28	11	39
	12-Nov	50	27	46	34	32
	20-Nov	101	68	33	6	94
Chloroform	24-Oct	10	14	-	16	-
	31-Oct	18	13	28	20	-
	5-Nov	25	26	-	8	68
	12-Nov	71	65	8	53	25
	20-Nov	37	17	54	bd	100
Benzene	24-Oct	469	214	54	367	22
	31-Oct	304	10	97	27	91
	5-Nov	282	11	96	40	86
	12-Nov	355	8	98	47	87
	20-Nov	398	7	98	4	99
Trichloroethene	24-Oct	bd	bd	bd	bd	bd
	31-Oct	15	12	20	16	bd
	5-Nov	13	9	31	8	38
	12-Nov	bd	bd	bd	bd	bd
	20-Nov	bd	bd	bd	bd	bd
Toluene	24-Oct	473	195	59	343	27
	31-Oct	301	8	97	36	88
	5-Nov	294	7	98	52	82
	12-Nov	356	8	98	47	87
	20-Nov	376	3	99	8	98
Tetrachloroethene	24-Oct	27	41	-	46	-
	31-Oct	36	34	6	35	3
	5-Nov	32	31	3	24	25
	12-Nov	35	49	-	36	-
	20-Nov	62	16	74	bd	100
Xylene	24-Oct	360	233	35	312	13
	31-Oct	211	16	92	80	62
	5-Nov	218	16	93	75	66
	12-Nov	274	9	97	40	85
	20-Nov	284	2	99	45	84

bd-indicates sample concentration was below detection limit

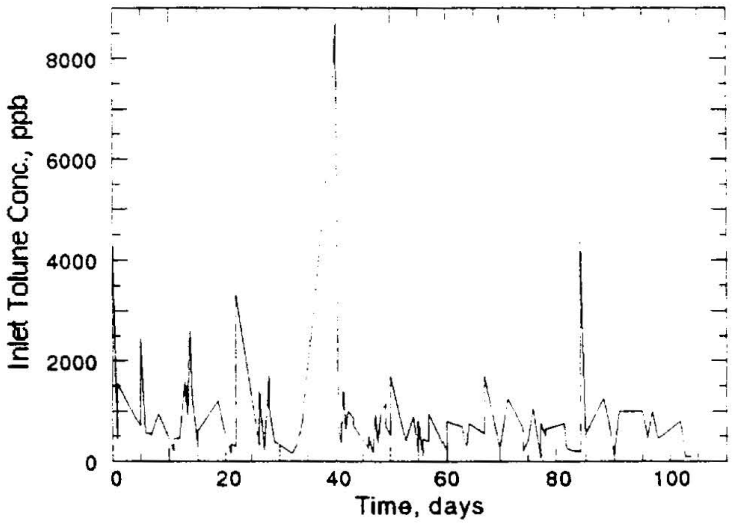


a. Daily inlet benzene concentrations during JWPCP segment of Study

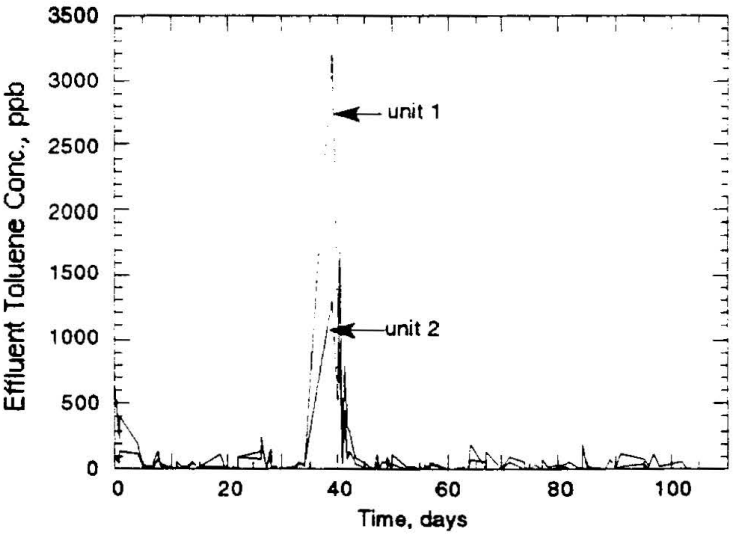


b. Daily outlet benzene concentrations during JWPCP segment of Study

Figure 11. Daily inlet and outlet benzene concentrations during JWPCP segment of study. Day 0 is October 24, 1991.

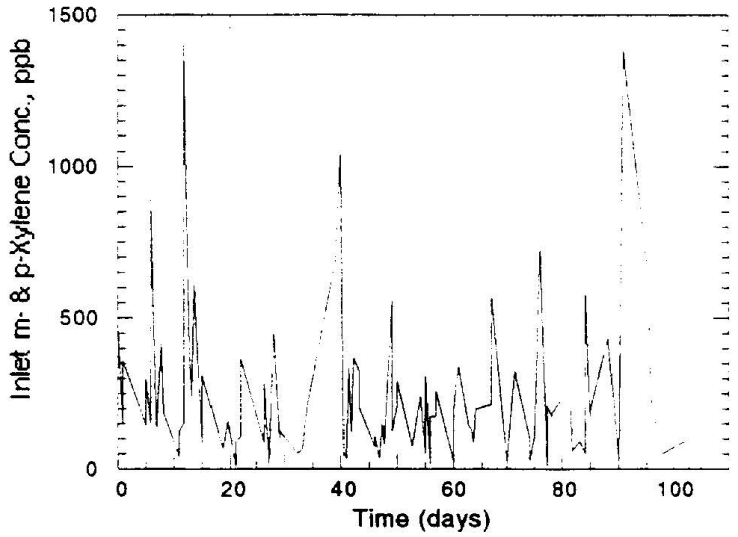


a. Daily inlet toluene concentrations during JWPCP segment of Study

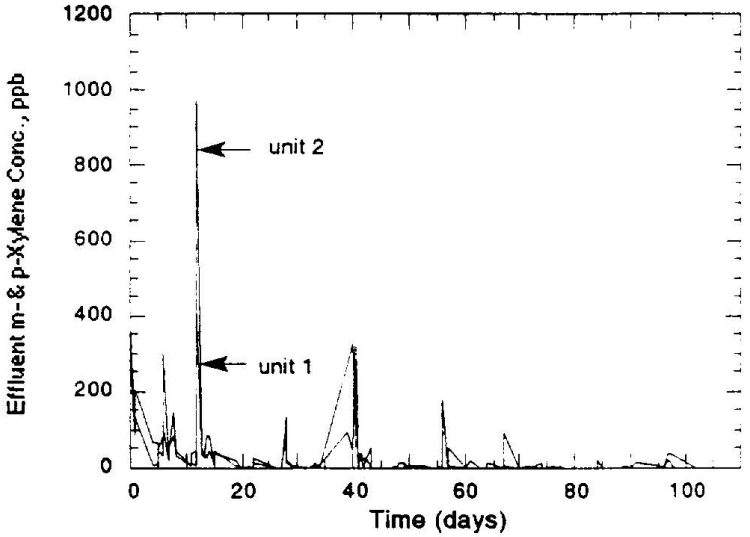


b. Daily effluent toluene concentrations during JWPCP segment of Study

Figure 12. Daily inlet and outlet toluene concentrations during JWPCP segment of study. Day 0 is October 24, 1991.

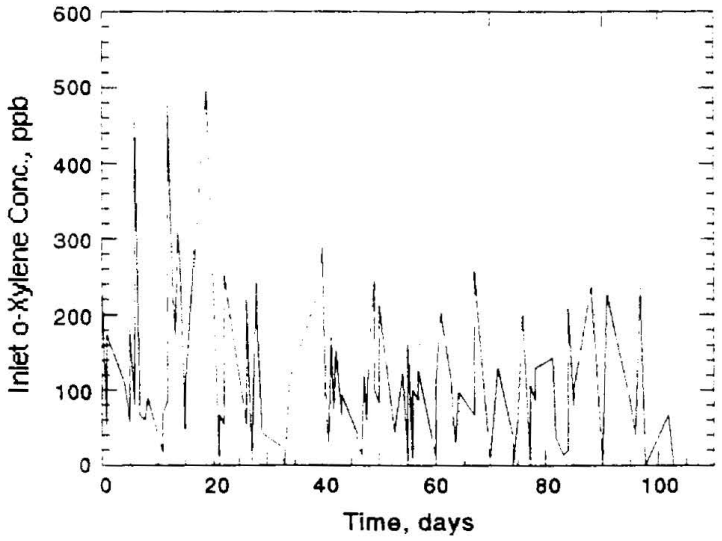


a. Daily inlet concentration of m- & p-xylene during JWPCP segement of study

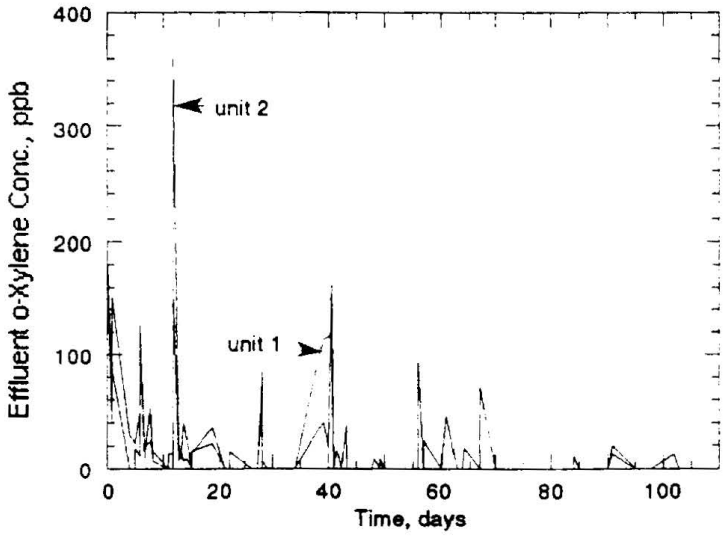


b. Daily Effluent concentration of m- & p-xylene during JWPCP segement of study

Figure 13. Daily inlet and outlet m & p xylenes concentrations during JWPCP segment of study. Day 0 is October 24, 1991.

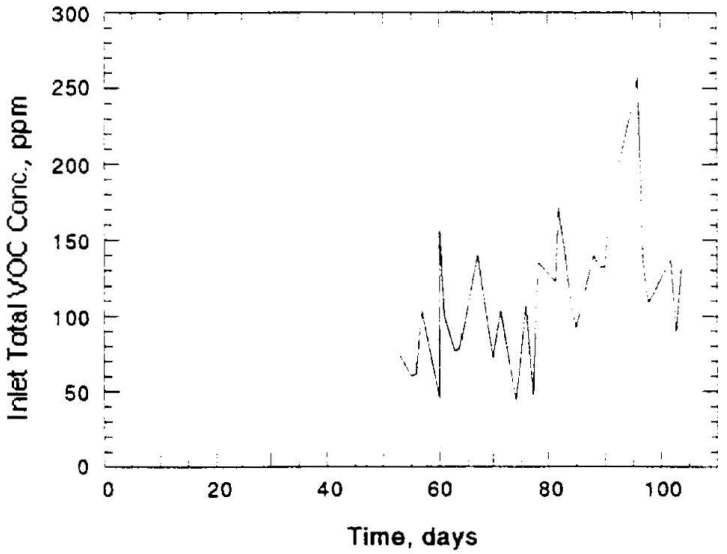


a. Daily inlet o-xylene concentrations during JWPCP segment of the study

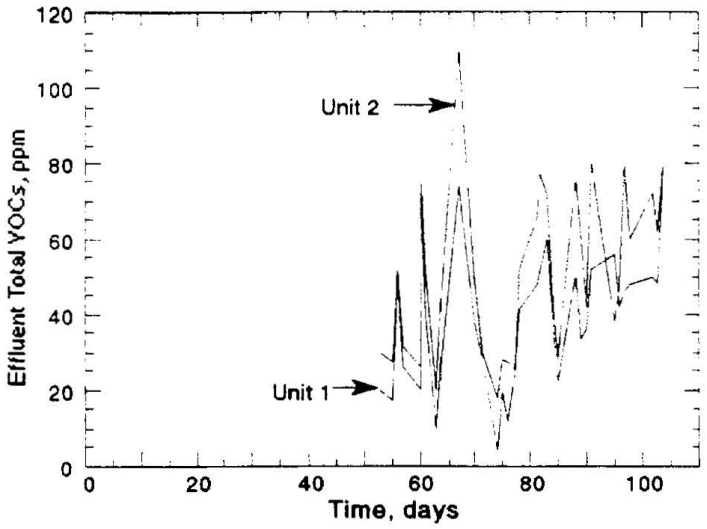


b. Daily outlet o-xylene concentrations during JWPCP segment of the study

Figure 14. Daily inlet and outlet o-xylene concentrations during JWPCP segment of study. Day 0 is October 24, 1991.



a. Daily inlet total VOC concentration during JWPCP segment of study



a. Daily effluent total VOC concentration during JWPCP segment of study

Figure 15. Daily inlet and outlet total VOCs concentrations during JWPCP segment of study. Day 0 is October 24, 1991.

Odor Removal: Weekly odor tests were performed on biofilter inlet and outlet gases and ambient air. The results of these tests are shown in Table 4. In general, performance of the biofilter pilot plant as an odor control system was excellent. With only one exception (12/25 BF I), odor measurements were all in the slight to moderate range even at very high inlet concentrations (1/21). In addition, odor panelists reported that biofilter had a "woodsy" smell that was not unpleasant. Inlet H_2S concentrations ranged from 1 to 80 ppm with a mean of 18 ppm. Outlet H_2S concentrations ranged from below the detection limit of 0.1 ppm to 8 ppm. Only 6 of 210 samples had H_2S concentrations above 1 ppm.

TABLE 4:

JWPCP Biofilter Odor Test Results

date	odor obser-vation	H_2S ppm	OU/ SCF	odor obser-vation	H_2S ppm	OU/ SCF	odor obser-vation	H_2S ppm	OU/ SLF	odor obser-vation	OU/ SCF
11/12	mod	6	380	sli	0	8	sli	0	6	sli	1
11/18	mod	0	100	sli	0	6	sli	-	trace	ali	1
11/25	str	6	2200	str	0	1300	mod	0	70	sli	6
12/2	str	4	130	mod	0	70	sli	0	15	sli	2
12/9	mod	4	1800	sli	0	3	sli	-	trace	sli	trace
12/16	str	20	1800	sli-mod	0	30	sli	0	7	sli	trace
12/23	mod	3	350	sli	0	14	sli	0	90	sli	10
12/30	mod	4	400	mod	0	150	leak	-	-	sli	24
1/6	str	6	1700	sli	0	9	sli	0	7	sli	1
1/21	str	15	20,000	mod	0	220	mod	0	100	sli	1

Operating pH: Daily pH readings of the drain water from the biofilter showed a steady decline from 6.5 to 1.5 pH units over the first two months of operation. Composite samples of filter bed pH however, stayed at approximately pH 7 throughout the study period. On November 20th cores were taken of the filter bed and pH measurements were made every 5 inches throughout the depth of the bed. The range of pH values for the two beds was 6.5 to 7.3 pH units with a mean of 6.9 ± 0.3 pH units and no clear distribution of pH with depth. It was felt that the low drainage water pH indicated the presence of sulfur oxidizing bacteria in the plenum chamber under the filter bed and that the the calcium carbonate in the filter media was sufficient to neutralize any acidity that was formed in the bed itself. The pH data indicate that acidification of the bed is not a concern under these conditions, however there is a high potential for corrosion of the filter chamber and other equipment which are in contact with the drainage water.

DISCUSSION

The verification phase work has provided a good bit of very positive information, as summarized below:

1. Removal efficiencies of greater than 95 % of aromatic VOCs known to be biodegradable appear to be readily attainable at acceptable gas flux values. For example, benzene, toluene, and m- and p-xylene are being removed at the 95 % level with a gas flux of 3 ft/min.

2. Removal efficiencies of some compounds known to be biodegradable (e.g. dichloromethane) have not been clearly established. The results of the laboratory studies were (Table 1) indicated that good removals were possible, and that the values similar to those for toluene and benzene could be expected. Possible reasons for the lower than expected removals in the field include lack of time available to establish the microbial cultures, low concentrations in the gas feed, or variation in concentrations in the gas feed.

3. Removal of compounds thought to be nonbiodegradable except by co-metabolism (e.g. TCE and PCE) was observed in both the laboratory and field segments of the study. Removals in the laboratory segment were more consistent and greater than in the field. The controlling parameters are not understood at this time. However, the low concentrations of these compounds in the field segment of the study and the amount of feed concentration variation may have contributed to the results. Of considerable interest is the response to 1,1,1-trichloroethane in the field studies. This compound was not included in the laboratory experiments but was present in relatively large concentrations (30 to 90 ppbv) in the off-gas from the screening station. Removal of 1,1,1-trichloroethane occured in the biofilter but the results were not consistent. Controlled laboratory experiments would be helpful in estimating the potential for microbial degradation of 1,1,1-trichloroethane .

4. Sulfide and odor removal appears to be very satisfactory at the loading rates used in the field studies. Corrosion of facilities will be a problem because of the low pH of the drainage but pH control within the biofilter medium appears to be satisfactory.

A large number of questions have been raised during the verification phase. These have been categorized into three groups: Biofilter Operations, Fundamental Parameters, and Biological Factors.

Biofilter Operations

1. Gas Loading Rates: A limited range of gas loading rates have been used in the verification phase. The highest flux used was 7 ft/min during the start up in the UCD Civil Engineering laboratories. Steady state conditions were not established and therefore the limiting removal efficiencies are unknown at this time. Removal of more recalcitrant compounds (e.g. TCE and PCE) may also have increased over a long period of time.

2. Organic Loading Rates: The verification phase studies were set up to reflect conditions at an unusual plant; the JWPCP. Plants treating principally domestic wastewaters will be subjected to regulatory limits and it would be good to know if biofilters will perform satisfactorily and be economical at the expected lower and more variable VOC concentrations.

3. Loading Rate Variation: All of the data taken to date indicates that response to load variation will be good. However, controlled variation studies will be required to determine if short term breakthroughs due to high concentration transients can be expected.

3. Humidification: Our pilot plant system has manual humidification controls. At least one commercial unit uses load cells to determine moisture content and insulation and gas inlet heaters to maintain constant temperature. Some further analysis is required to determine the effect of moisture content, the relationship between moisture content and performance and the impact of cyclic variation of moisture content on performance. However, the success of the field segment of the study suggests that sophisticated controls are unnecessary, at least in temperate climates.

4. Temperature: Operational effects at temperatures lower than experienced in Los Angeles should be determined. Collection system and treatment plant off-gases will always be relatively warm and insulation of biofilters in cold climates is possible. The issue is the sensitivity of the process to temperature. Normally biological reaction rates increase by a factor of 1.5 to 2 for each 10°C rise in temperature. Some reactions appear to shut down completely outside of particular temperature ranges.

5. Sulfide Control: Plant operators will be interested in the sulfide and odor control aspects of biofiltration and the questions raised with respect to VOC removal will need to be answered for these problems as well.

Fundamental Parameters

1. Mass Transfer Rate: In the simplest conceptual model, biofilters can be considered problems of mass transfer with chemical reaction. One of the reactants, the bacteria, increase with time and this means that the reaction rate should also increase with time. The net result will be that mass transfer will be the rate limiting parameter for easily biodegradable materials. However, the reaction surface is not well defined. Transfer may be directly to the microbial cells or may be to the sorbed water and then to the cells. Differences in mass transfer rates for the two models are not known. In process operation and design the question of the controlling transfer rate will arise as part of the optimal moisture content determination.

2. Minimum VOC Concentration: Available models for biodegradation often predict that a minimum concentration exists below which the system will not function. For the most commonly used model, the Monod equation, this limiting concentration is:

$$C_{min} = \frac{Kk_d}{Yk - k_d} \qquad (1)$$

Where C_{min} = minimum VOC liquid phase concentration, mg/L

K = saturation coefficient, mg/L

kd = microbial maintenance energy rate constant, d^{-1}

Y = microbial yield coefficient, g cells produced/g VOC removed

k = biodegradation rate constant, d^{-1}

The conceptual development for Equation 1 assumes that biodegradation is part of the microbial growth process. Thus, the model probably does not apply to cometabolism. The applicabilty of the model to attached growth processes, a class to which biofilters belong, is also questionable.

3. Stoichiometry of Cometabolism: A number of chlorinated VOC's (e.g. TCE and PCE) are believed to be oxidized through cometabolism, a process in which nonspecific enzymes produced for the breakdown of other metabolites (e.g. methane or toluene) catalyze the degradation of materials without benefit to the cell. Presumably there will be a necessary feed ratio of the primary metabolite to the cometabolite (e.g. toluene/TCE) required for complete cometabolite degradation. There is no information available in the literature on this subject.

4. Verification of Biodegradation: The verification phase results, and the literature, have abundant data on VOC removal in biofilters. There is considerably less information on fate of the compounds. Based on the general loss of peaks and lack of addition of new peaks in the GC-MS scans we believe that biodegradation is occurring. However, verification of biodegradation using labeled compounds and CO_2 traps is needed.

5. Spatial Variation of Activity: Microbial growth should be related to the mass transfer limits on the food supply. Thus the activity of the biofilter should decrease from the bottom of the biofilter upward in a somewhat exponential fashion. This conceptual spatial variation in activity has implications related to system resiliency to loading variation, limits on organic concentration related to oxygen transfer rate, and total unit capacity.

6. Loading Rate Variation: One approach to managing negative impacts of sharp VOC concentration transients (which have been shown to occur) would be to place a sorbent in the bed, either as a layer or mixed through the medium. Chang et al. [1991] noted that the JWPCP odor control carbon adsorption beds functioned in this fashion. If a high concentration transient of a specific VOC occurred sorption would provide a damping effect and allow biodegradation to occur. The need for such an approach will become apparent following loading rate variation studies. Current results seem to indicate that the most probable benefit would be in controlling biodegradation of compounds subject to cometabolism.

6. Nutrient Requirements and The Importance of Compost: Compost is used in biofilters because the material is a nutrient source and a reservoir of microorganisms. Nutrients necessary for microbial growth (nitrogen, phosphorus, ...) will generally be absent from the gas phase and must be provided from some other source. Two options exist: (1) to use a support, such as compost, that contains the necessary nutrients, and (2) use a film flow system (physically similar to a scrubber) to bring the nutrients to the microorganisms. The nutrients in the support method have a finite life, although some replenishment might be possible by soaking the compost with a nutrient solution. Film flow nutrient systems are more sophisticated, require more controls, may be wasteful of water, and force liquid phase absorption thereby reducing mass transfer rates (although there might be a possibility of using intermittent feeding).

7. pH Control: Essentially complete conversion of H_2S to SO_4^{-2} has been achieved at the loading rates used in the field segment of the study. Drainage from the beds is at less than pH 4 but the last measurements of pH in the medium gave values of about 7. This needs to be investigated further, but the next stage is probably best done using the pilot unit in the field. Corrosion problems could be very serious with these units where significant sulfides are present. Additionally, we may develop low pH values in the medium over time. Finally, we believe that three approaches might be taken toward pH control in operating systems: (1) blowing in carbonate or bicarbonate aerosols, (2) feeding buffer into the bed (through the top with the soaker system would appear to be the best method), and (3) adding a layer of calcium carbonate below the compost medium.

Biological Factors

1. Microbial Processes Occurring: At present only circumstantial evidence exists that biodegradation is occurring. Tracer studies using radio labeled compounds are the most obvious method of tracking the fate of feed compounds. This work can only be done in the laboratory.

2. Mass Transfer/Biooxidation Rate: Determination of the rate limiting step needs to be made. Mass transfer rate was noted under Fundamental Parameters but the biooxidation rate may be controlling as well. Measurements of biooxidation rates can be conducted both in the films and in laboratory cultures to establish actual and potential values. These studies will involve some labeled compound work.

3. Microorganism Identification: The microorganism population should be investigated and predominant groups of organisms identified. This will allow establishment of a conceptual model of the ecology of the process. Such information will provide a basis for analyzing operating processes, particularly those that are functioning poorly.

RECOMMENDATIONS

The purpose of the Phase I studies was to establish the possible roles of biofiltration in controlling VOC emissions from wastewater treatment plants. The technology is not limited to this application and in actuality is appropriate for any source of VOCs. What has been established is that biofiltration is a viable process for low concentration VOC sources such as wastewater treatment plant off-gases. Other possible applications include lanfills and soil remediation operations, as well as industrial sources (e.g. bakeries). Because these studies were limited in scope a number of questions remain to be answered. Some of these questions should be addressed prior to large scale application of biofiltration. Among the most important concerns are the impact of gas and VOC loading rates on performance, the potential for biodegradation of VOCs by cometabolism, and mass tranfer rate evaluation. The experiments suggested below are related to these priorities.

1. Experiments with laboratory scale units (6" diameter, 3' deep beds) that allow operation of several systems in parallel over a wide range of loading rates.

2. The laboratory scale experiments should be run for at least 12 months to allow establishment of performance potentials and quasi-steady state conditions.

3. Labeled compound studies should be run using the six compounds we have been following in the Phase I work (toluene, benzene, methylene chloride, chloroform, TCE and PCE) to determine (a) mass transfer rates, (b) fate, and (c) biooxidation rates.

4. Microorganisms should be identified and the compound biooxidation rates of the pure cultures should be established as references.

5. Stoichiometry of cometabolism needs to be established if there is to be any hope of predicting performance with respect to removal of chlorinated solvents and pesticides.

6. Adsorption capacity of the medium should be established.

7. Impact of wetting/drying cycles should be studied.

8. Shock or transient loading response should be studied. This work should include sudden increases from moderate loadings and response to operation after shut downs of one to two weeks.

Modifying the biofilter technology for application to landfills appears to be a highly appropriate direction for the research to take, as well. A conceptual approach that would apply to landfills without gas collection and recovery systems has been developed. This approach would involve two types of treatment system: (1) a soil filter incorporated into the cover, and (2) a modified vacuum process for systems unable to produce enough gas to be economical as a recovery operation.

REFERENCES

Alexander, Martin, "Biodegradation of Chemicals of Environmental Concern", *Science*, Vol 211, January 9, 1981

American Society for Testing and Materials, *Standard Method for Measurement for Odor in Atmospheres*, American National Standards Institute, 1967

Bell, J.P.,Osinga, I and Melcer, H, Investigation of Stripping of Volatile Organic Contaminants in Municipal Wastewater Treatment Systems, Ontario Ministry of the Environment, Wastewater Technology Center, Burlington, Ont., 1988

Bishop, W., Witherspoon,J., Card, T., Chang, D., and Corsi, R., *VOC Vapor Phase Control Technology Assessment*, Water Pollution Control Federation Research Foundation, RP No. 90-2, 1990

Bohn, Hinrich L.,"VOC Removal by Soil Biofilter Beds", *Proceedings of Hazmacon '89*, Hazardous Materials Management Conference and Exhibition, Vol. 2, Association of Bay Area Governments, April 18-20, 1989

Brauer, H., "Biological Purification of Waste Gases", *International Chemical Engineering*, Vol. 26, No. 3, July 1986

California Air Resources Board, *The Impact of Toxic Air Quality Regulations on California Publicly Owned Treatment Works*, Kris P. Lindstrom and Farouk T. Ismail eds, October 1988

Carlson, D.A. and C.P. Leiser, "Soil Beds for the Control of Sewage Odors", *Journal of the Water Pollution Control Federation*, Vol 38, No 5, May, 1966

Chang , D.P.Y, Schroeder, E.D., and Corsi, R.L., *Emissions of Volatile and Potentially Toxic Organic Compounds from Sewage Treatment Plants and Collection Systems*, California Air Resources Board A5-127-32, 1987

Chang, D.P.Y, et al., *Emissions of Volatile and Potentially Toxic Organic Compounds From Wastewater Treatment Plants and Collection Systems* (Phase II), California Air Resources Board, A732-085, 1991

Eitner, D and Gethke, H. G., " Design, Construction, and Operation fo Biofilters for Odour Control in Sewage Treatment Plants", in *Proceedings* 80th annual Meeting of APCA, Air Pollution Control Association New York, NY,1987

Eitner, D., "Biofilter in Flue Gas Cleaning: Biomasses, Design, Costs, and Applications", *Brennst.-Waerme-Kraft*, Vol. 41, No. 3, 1989

Environmental Protection Agency, *Report to Congress on the Discharge of Hazardous Wastes to Publicly Owned Treatment Works*, EPA/530-SW-86-004, Office of Water Regulations and Standards, Washington, D.C., 1986

Ergas, S. J., E.D. Schroeder, and D.P.Y. Chang,"VOC Emission Control at Wastewater Treatment Facilities Using Biofiltration", Presented at the 84th annual meeting of the Air and Waste Management Association, Van Couver, British Columbia, June, 1991

Hartenstein, H. U. and Allen, E. R., *Biofiltration, an Odor Control Technology for a Wastewater Treatment Plant* Report to Department of Public Works, City of Jacksonville,FL 1986

Kampbell, D. H., J T. Wilson, H. W. Reed, and T T. Stocksdale, "Removal of Aliphatic Hydrocarbons in a Soil Bioreactor", *Journal of the Air Pollution Control Association*, Vol 37, No. 10, October, 1987

Kersting, U, "Biofilter Units in the Area of Sewage Treatment: Application Areas, Construction, Costs", *Verein Deutscher Ingenieure Berichte*, NR. 735, 1989

Kosky, K. and C. R. Neff, "Innovative Biological Degradation System for Hydrocarbons Treatment", *Biofilter Technology for Air Toxics Emissions and POTWs*, Biofiltration, Inc., Gainesville, Fl

McCarty, P., "Bioengineering Issues Related to In Situ Remediation of Contaminated Soils and Groundwater", in *Environmental Biotechnology* , Edited by Gilbert S. Omenn, Plenum Publishing Company, 1988

Meikle, R.W. "Decomposition: Qualitative Relationships", in *Organic Chemicals in the Soil Environment*, Goring, C. and Hamaker, J.W. eds., Marcel Drekker Inc, 1972

Neff, C. R. "Biofilter Technology for Odor Control" *Biofilter Technology for Air Toxics Emissions and POTWs* Biofiltration, Inc,Gainesville, FL

Ottengraf, S. P. P. and Van den Oever, A.H.C., "Kinetics of Organic Compound Removal from Waste Gasses with a Biological Filter", *Biotechnology and Bioengineering*, Vol 25, 1984

Ottengraf, S. P. P., J.J.P. Meesters, A.H.C. Van den Oever and H.R. Rozema, "Biological Elimination of Volatile Xenobiotic Compounds in Biofilters", *Bioprocess Engineering*, Vol 1, Eindhoven Univ. Technol., 1986

Ottengraf, S. P. P., Van den Oever, A. H. C., and Kempenaars, F. J. C. M., "Waste Gas Purification in a Biological Filter Bed", *Prog. Ind. Microbiol.*, Vol 20, 1984 International Process Systems "Odor Control, Compleating the Composting Process" Glastonberry, CT,1990

Ottengraf, S. P. P., "Exhaust Gas Purification", in *Biotechnology*, H.J. Rehm and G. Reed (editors), Vol 8, 1986

Spain, J.C.,"Microbial Adaptation in Aquatic Ecosystems", in *Enhanced Biodegradation of Pesticides in the Environment*, Racke, K.D. and J.R. Coats eds. American Chemical Society Symposium Series 426, 1990Harder, W. and L. Dijkhuizn, "Strategies of Mixed Substrate Utilization", Phil. Trans. R. Soc. Lond., Vol B 297, pp 459-480, 1982

Utgikar, V. and Govind, R., "Biodegradation of Volatile Organics in a Biofilter", Dept of Chemical Engineering, University of Cincinnati, Cincinnati, OH, 1990

Vogel, T.M., and McCarty, P.L., "Biotransformation of Tetrochloroethylene, to Trichloroethylene, Dichloroethylene, Vinyl Chloride, and Carbon Dioxide Under Methanogenic Conditions", *Applied and Environmental Microbiology*, May, 1985

APPENDIX A

University of California, Davis Department of Civil Engineering
Pilot Scale Biofilter Operations and Maintenance Manual

October, 1991

Table of Contents

Principle of Operation

The biofilter consists of a filter bed of compost mixed with other amendments, a gas intake system, a humidification system, and a gas flow measurement system as shown in figure 1. The filter medium serves as a support for microbial cultures that remove and degrade gaseous contaminants. Gases are blown through the bed where the pollutants are sorbed onto the media and or biologically degraded by the microbial population. Favorable conditions with regard to temperature, pH, nutrients, oxygen, and moisture are provided for growth and maintenance of the microbial population.

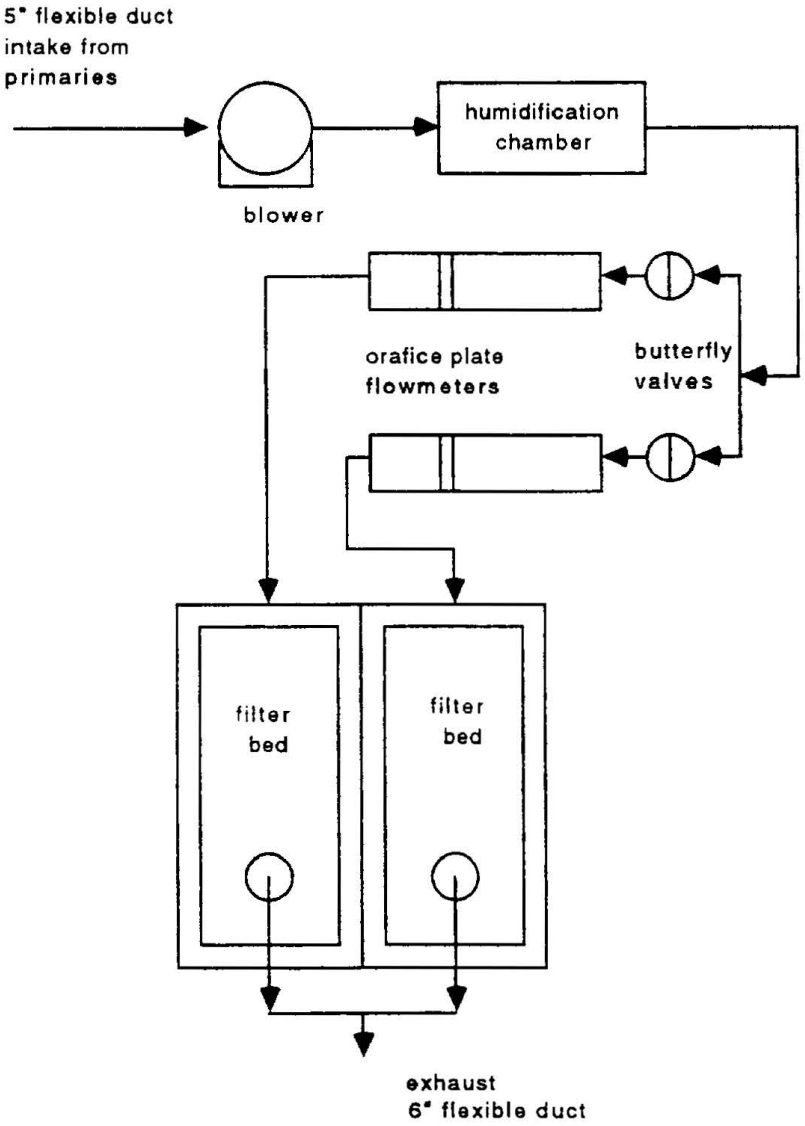


Figure 1 Biofilter Gas Flow Schematic

Gas Intake System

The gas intake system consists of a 9 inch radial blower, 1/3 horsepower, single phase motor, and 5 inch neoprene impregnated, wire reinforced, cotton ducting. The gas intake system draws air from the head space above the primary sedimentation basins to the biofilter.

Humidification System

Control of humidity in the filter medium is critical to maintaining removal efficiencies. Too little moisture results in dry zones and loss of microbial activity. Too much moisture results in the development of anaerobic zones and consequently in poor effluent quality and the production of odors.

In this system, moisture is provided by humidifying the influent gases. The gases flow through a fiberglass tank (the humidification chamber) which is equipped with a spray nozzle as shown in figure 2. A float valve maintains a constant water reservoir in the bottom of the tank. The float valve is connected by a hose to the water supply. Water is circulated from the reservoir to the spray nozzle by a positive displacement pump and variable speed motor. The pump is equipped with a screen at the intake to protect the pump and spray nozzle from large particles. A pressure gauge and pressure switch are located at the pump outlet. The pressure gauge allows the operator to set the pump speed at a good operating pressure for the spray nozzle (20-40 psi) and to help in trouble shooting the system. The pressure switch shuts off the entire system (pump and blower) and turns on the light if the pressure at the pump outlet is too high or too low (60 psi or 6 psi respectively). A high pressure at the pump outlet can indicate a clogged spray nozzle a low pressure may mean the water level in the reservoir is low or the pump is clogged. Three tubing connections allow water which collects in the pipes or bottom of the biofilter to drain back to the humidification chamber.

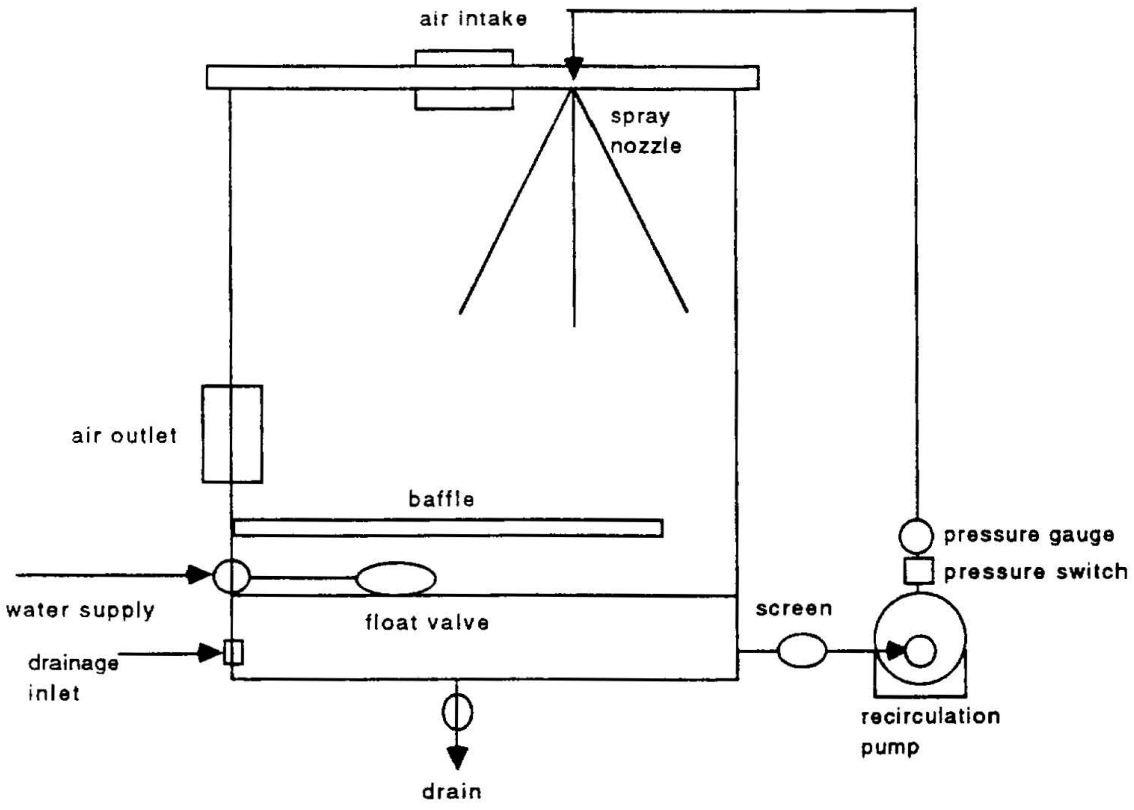


Figure 2. Humidification system

Gas Flow Measurement

After leaving the humidification chamber, the flow is split and the gases flow through an orifice plate system. Two six inch diameter eccentric orifice plates measure flow between 50 and 185 scfm. The relationship between pressure drop and air flow is the following:

$$Q = 131 \sqrt{\Delta h}$$

where Q is the flow rate in standard cubic feet per minute (scfm) and Δh is the pressure drop in inches of water. The pressure drop across the orifice plates is measured by two zero to two inches of water range magnihelic pressure gauges. These pressure gauges can also be configured to measure pressure drop across the filter bed. For flow rates outside the range of the orifice plates or for a check on the orifice plate calibration two bored through tube fittings are located in a straight length of pipe upstream of the orifice plates.

These fittings allow the insertion of a pitot tube or hot wire anemometer into the pipe for measuring the air velocity directly. The gas flow is controled by two butterfly valves upstream of the orifice plates. Sample ports are located downstream of the orifice plates.

Filter Bed

The gases flow from the orifice plates through flexible ducting into two eight foot by four foot filter beds. An eight inch high plenum chamber below the filter bed serves to distribute the gases evenly through the bed. The filter bed is supported by steel reinforced diamond mesh sheets. All interior metal surfaces are coated with epoxy paint. Above the diamond mesh is a four inch layer of coarse wood bark which serves to keep the fine particles of compost from sifting through the mesh. Above that, is three feet of filter medium consisting of compost mixed with perlite, and crushed oyster shell. Perlite is an expanded volcanic material and serves as an inert material which decreases the pressure drop across the bed. The crushed oyster shell is a source of calcium carbonate, a pH buffer. Urethane coated plywood covers seal the top of the filter bed. The covers are vented to six inch diameter ducts which are equipped with sample ports for the outlet gases.

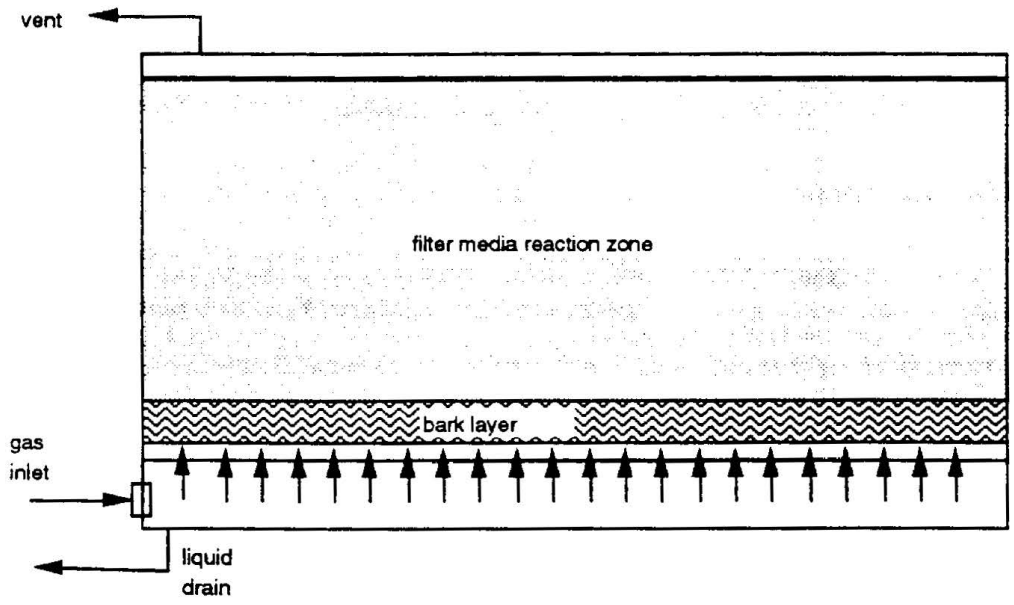


Figure 3. Filter Bed

Maintenance Schedule

Daily:

Check Gas Flow Rates

Biofilter I magnihelic pressure drop _____ inches water.

Biofilter II magnihelic pressure drop _____ inches water.

Check humidification system

Pressure at nozzle _____ psi.

Clean filter at pump inlet if necessary.

Verify that water is draining from orifice section back to humidification chamber.

Look over area check for leaks, holes in ducting, etc.

Weekly:

Sample inlet and outlet gases (see sampling procedure)

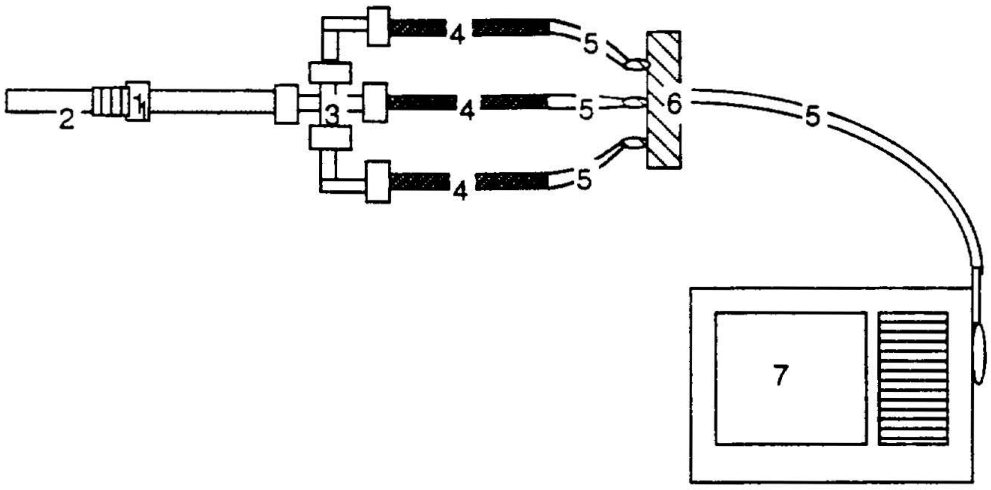
Sample filter medium for moisture content and pH determination (see sampling procedure)

Trouble Shooting

Problem	Possible Cause	Solution
System off, light on	pressure too high or too low in pump	see below.
Pump pressure too high	clogged spray nozzle	remove lid of humidification chamber, unscrew nozzle and clean.
Pump pressure too low	float valve stuck	remove lid of humidification chamber, tap float valve.
	water supply off	turn on water supply.
	inlet filter clogged	clean filter, drain and clean humidification chamber.
Water not draining to humidification chamber	tubing clogged	clean or replace tubing and fittings.

Sampling Procedure

Gas sampling will normally be done once a week. Three inlet samples are taken through either sample port downstream of the orifice plate. Three outlet samples are taken through each of the sample ports at the outlet vent. A schematic showing the sampling arrangement is shown in figure 4.



1. Tube fitting
2. 1/4" teflon tubing
3. tube manifold
4. sample tubes
5. tygon tubing
6. low flow manifold
7. sampling pump

Figure 4. Sampling Set Up

Set Up

- Insert a length of 1/4" Teflon tubing (2) through the thermocouple fitting. The Teflon tubing should go a few inches into the duct. Tighten fitting.

- Attach the stainless steel tube manifold (3) to the Teflon tubing. Tighten fitting.

- Note: This step should not be done until you are ready to sample. Take the stainless steel end caps off the sorbent tubes (4). Be careful not to lose the red ferrules that are under the end caps. The tubes must be inserted so that the red arrow on the side of the

tube points away from the tube manifold (in the direction of flow). Attach the Tygon tubing that is connected to the low flow manifold to the tubes (5) by pushing it onto the ends of the the tubes. The numbers on the manifold must go to the correct tube. Attach the tube to the tube manifold using the stainless nuts with the red ferrules. Tighten down the nuts only finger tight.

- Make sure that there are no crimps anywhere in the tubing.

Pump Operation

Pump number 1 is for sampling at the biofilter inlet and pump number 2 is for the outlet. The following should be done before the pump is attached to the tubes:

- Turn the pump on with the ON switch. You should hear the pump running, if not turn the pump on and off a few times until it starts.

- Press the START/HOLD key.

- Press the SET UP key. "Delayed Start" will display on the LCD as well as a flashing digit. The value of the flashing digit will be incremented each time the DIGIT SET key is pressed. Using the DIGIT SELECT and DIGIT SET keys, enter the desired number of minutes delay before the sample period is to begin.

- Once the correct number of minutes is displayed, press the MODE key. "Sample Period" will now be displayed. Using the DIGIT SELECT and DIGIT SET keys, enter the desired number of minutes for the total sample period. _____mins.

- Press the MODE key again. "Pump Period" will now display. Again, using the DIGIT SELECT and DIGIT SET keys, set the pump period for the amount of time the pump should run during the sample period._____mins.

- You can scan the program by repeatedly pressing the MODE key.

To start sampling:

- Press the START/HOLD key. The "Delayed Start" indicator will flash and the "Time" indicator will display the amount of time remaining until the sampling cycle starts. At the end of the sample period the pump will shut off automatically.

Tubes

The tubes have been calibrated so that they need to be placed in the right holder in the manifold. The tubes and the manifold holders have numbers on them. If the tubes are mixed up or if one is broken and an alternate tube is used just let me know what was done and I can recalibrate the tubes after the analysis. The tubes will come with a sheet telling the tube numbers and corresponding manifold numbers. There will also be a trip blank, ambient blank, and extra tube included in addition to the sampling tubes. The trip blank should accompany the other tubes at all times but not be opened. The ambient blank should be opened for the same length of time as it takes to install and take apart the sample tubes. It's purpose is to see how much contamination is picked up in handling the tubes. The extra tube is in case one breaks.

Moisture Content Sampling and Analysis Procedure

Samples may be taken either from the flange fittings in the lids of the filter beds or through the outlet duct. A core through the bed is removed either with a core sampler or a length of pipe. Place samples in sealed plastic bags or containers with tight fitting lids to prevent loss of moisture. Determine the tare weight of the drying pan. Place approximately 3 grams of the filter media in the drying pan. Weigh the samples immediately. Place the sample in a drying oven and dry to constant weight. Place in a desiccator containing active desiccant to cool. Weigh again. Compute the moisture content by the following formula:

$$\theta = \frac{\text{(weight of wet soil + tare) - (weight of dry soil + tare)}}{\text{(weight of wet soil + tare) - (tare)}}$$

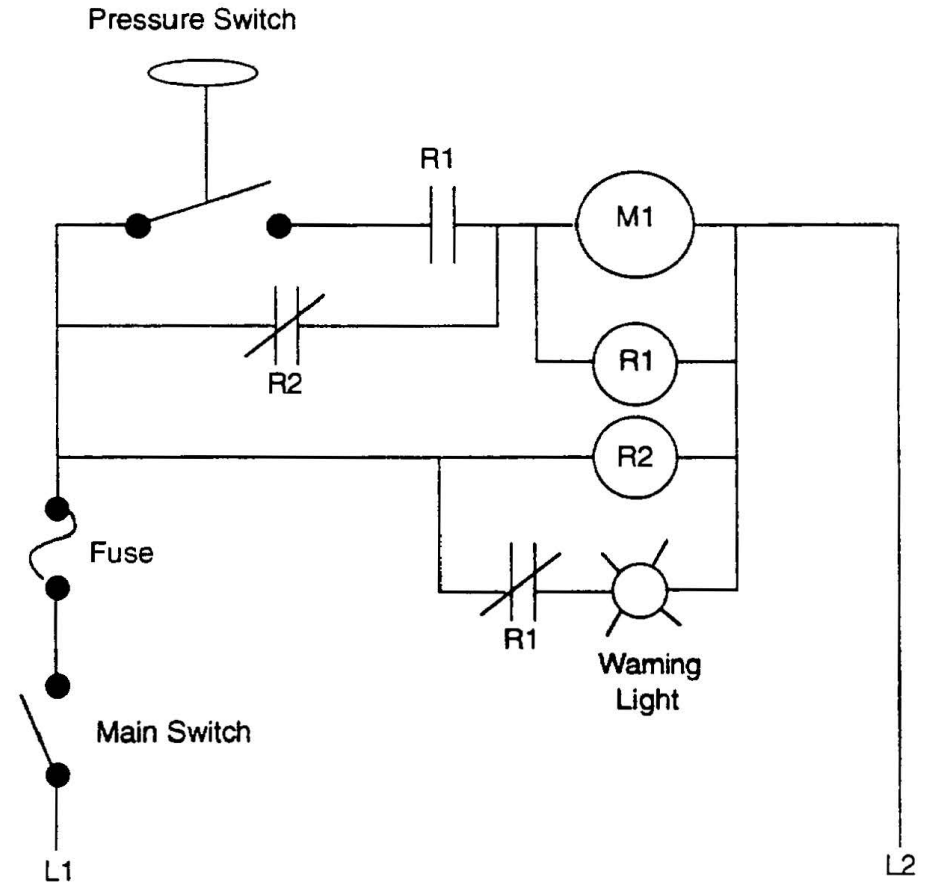
pH Analysis Procedure

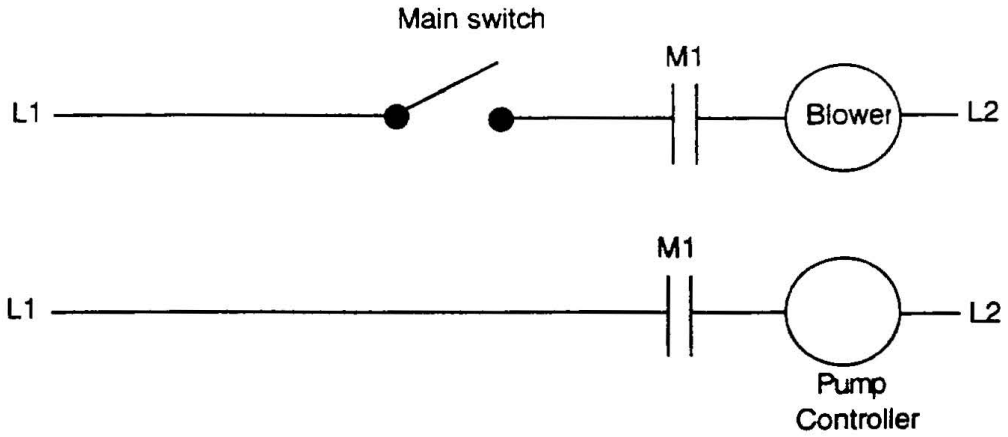
Place approximately 5 grams of filter media in a beaker with 5 ml of distilled water. Determine the pH with a calibrated pH meter.

APPENDIX I SAFETY INFORMATION

APPENDIX II ADDITIONAL INFORMATION
WIRING DIAGRAM, PRODUCT INFORMATION, ORDERING INFORMATION, OPERATING INSTRUCTIONS, AND PARTS MANUALS FOR MAJOR COMPONENTS OF THE PILOT SCALE BIOFILTER

Motor Control Wiring Diagram





APPENDIX B
UC DAVIS LABORATORY PILOT STUDIS DATA

	Toluene					Dichloromethane				
		Unit 1		Unit 2			Unit 1		Unit 2	
	Inlet	Outlet	%	Outlet	%	Inlet	Outlet	%	Outlet	%
Date			Rem		Rem			Rem		Rem
21-Aug	598	588	2							
28-Aug	847	313	63	182	79					
5-Sep	734	202	72	383	48	115	114	1	126	-10
11-Sep	618	322	48	415	33	71	54	24	41	42
17-Sep	654	350	46	525	20	98	102	-4	82	16
25-Sep	652	254	61	562	14	90	58	36	73	19
2-Oct	553	244	56	440	20					
15-Oct	817	182	78	502	39	120	92	23	70	42

	Trichlormethane					Benzene				
		Unit 1		Unit 2			Unit 1		Unit 2	
	Inlet	Outlet	%	Outlet	%	Inlet	Outlet	%	Outlet	%
Date			Rem		Rem			Rem		Rem
17-Sep	122	121	1	109	11	559	306	45	454	19
25-Sep	183	107	42	141	23	529	275	48	481	9
2-Oct						567	323	43	443	22
15-Oct	113	93	18	71	37	914	214	77	449	51

	Trichloroethene					Tetrachloroethene				
		Unit 1		Unit 2			Unit 1		Unit 2	
	Inlet	Outlet	%	Outlet	%	Inlet	Outlet	%	Outlet	%
Date			Rem		Rem			Rem		Rem
17-Sep	122	121	1	109	11	559	306	45	454	19
25-Sep	183	107	42	141	23	529	275	48	481	9
2-Oct						567	323	43	443	22
15-Oct	113	93	18	71	37	914	214	77	449	51

APPENDIX C
JWPCP PID DATA

Date	Time	BENZENE CONC (ppb)					TOLUENE CONC (ppb)				
		INLET	OUT 1	%REM	OUT 2	%REM	INLET	OUT 1	%REM	OUT 2	% REM
10/24	9:30	862	252	71	473	45	1097	90	92	304	72
10/24	14:00	855	172	80	398	53	4519	95	98	664	85
10/25	7:40	247	76	69	189	23	398	45	89	227	43
10/25	12:20	810	168	79	323	60	1569	141	91	414	74
10/28	8:00	1083	107	90	258	76	848	113	87	184	78
10/29	8:00	860	13	98	54	94	669	9	99	26	96
10/29	13:30	800	23	97	24	97	2433	42	98	29	99
10/30	8:30	226	20	91	8	96	558	14	97	0	100
10/30	14:00	2345	252	89	337	86					
10/31	8:30	551	16	97	0	100	556	21	96	0	100
10/31	12:00	533	42	92	0	100	492	37	92	0	100
11/1	8:00	642	192	70	117	82	786	126	84	84	89
11/1	13:15	856	32	96	30	96	944	24	97	37	96
11/4	8:30	384	42	89	20	95	185	0	100	7	96
11/4	14:00	547	30	95	73	87	461	21	95	59	87
11/5	7:45	361	19	95	22	94	447	7	98	27	94
11/5	12:30	548	248	55	300	45					
11/6	8:10	765	33	96	45	94	1571	23	99	21	99
11/6	12:30	791	40	95	16	98	874	35	96	15	98
11/7	9:00	1093	43	96	64	94	2622	35	99	62	98
11/7	13:00	724	26	96	56	92	1256	29	98	32	97
11/8	8:30	284	4	99	0	100	245	0	100	0	100
11/8	12:10	301	18	94	0	100	611	15	98	15	98
11/12	8:30	500	37	93	15	97	1201	120	90	27	98
11/13	8:00	844	27	97	39	95	697	6	99	23	97
11/14	8:20	77	0	100	0	100	155	2	99	0	100
11/14	14:30	236	6	97	17	93	332	6	98	15	95
11/15	7:50	473	0	100	16	97	314	0	100	0	100
11/15	13:30	2802	456	84	287	90	3371	105	97	94	97
11/19	8:30	446	214	52	322	28	313	72	77	142	55
11/19	13:30	1519	538	65	593	61	1400	249	82	246	82
11/20	8:00	226	9	96	13	94	171	0	100	0	100
11/21	8:00	1367	145	89	236	83	1720	122	93	149	91
11/21	12:00	956	20	98	49	95	1039	0	100	18	98
11/22	7:40	503	55	89	58	88	348	14	96	20	94
11/22	12:10	431	38	91	20	95	407	0	100	4	99
11/25	8:10	150	12	92	26	83	133	7	95	14	89
11/26	8:10	392	54	86	74	81	365	40	89	52	86
11/27	7:45	1092	122	89	76	93	769	31	96	12	98
12/2	15:00	4444	1929	57	3135	29	6438	1304	80	3223	50
12/3	8:00	7804	977	87	4707	40	8807	487	94	1241	86
12/3	14:30	692	1173	0	665	4	580	1770	0	679	0
12/4	8:30	316	71	78	120	62	338	44	87	78	77

Date	Time	BENZENE CONC (ppb)					TOLUENE CONC (ppb)				
		INLET	OUT 1	%REM	OUT 2	%REM	INLET	OUT 1	%REM	OUT 2	% REM
12/4	13:30	1318	663	50	855	35	1425	447	69	797	44
12/5	8:00	760	130	83	421	45	657	71	89	326	50
12/5	13:30	1226	292	76	514	58	1000	142	86	282	72
12/6	8:00	1230	151	88	246	80	865	62	93	89	90
12/6	12:30	1210	130	89	302	75	700	35	95	105	85

12/9	8:20	285	9	97	42	85	233	4	98	19	92
12/9	11:50	716	19	97	106	85	512	3	99	28	95
12/10	7:50	235	2	99	11	95	165	0	100	1	99
12/10	13:20	1235	81	93	179	86	922	43	95	109	88
12/11	8:00	453	16	96	25	94	353	3	99	6	98
12/11	14:00	1077	65	94	103	90	960	0	100	65	93
12/12	8:00	1268	16	99	116	91	1120	7	99	65	94
12/12	12:00	977	161	84	123	87	669	86	87	44	93
12/13	8:15	852	0	100	39	95	473	0	100	11	98
12/13	12:00	2836	319	89	607	79	1703	32	98	118	93
12/16	8:20	454	6	99	14	97	384	1	100	10	97
12/17	14:00	1305	0	100	36	97	905	0	100	21	98
12/18	8:00	69	0	100	0	100	134	0	100	0	100
12/18	14:00	623	8	99	38	94	812	0	100	17	98
12/19	8:00	117	0	100	0	100	117	0	100	0	100
12/19	13:00	367	18	95	19	95	443	38	91	0	100
12/20	8:00	443	11	98	99	78	386	0	100	34	91
12/20	12:30	894	160	82	78	91	950	64	93	45	95
12/23	8:30	196	0	100	0	100	181	0	100	0	100
12/23	14:00	724	0	100	0	100	787	0	100	0	100
12/24	8:00	748	0	100	14	98	725	0	100	6	99
12/26	8:00	738	0	100	18	98	677	0	100	9	99
12/26	14:00	419	70	83	5	99	396	0	100	2	99
12/27	8:00	341	0	100	0	100	311	0	100	0	100
12/27	12:00	984	759	23	109	89	764	189	75	72	91
12/30	8:00	521	0	100	46	91	548	0	100	57	90
12/30	14:00	1328	57	96	79	94	1692	136	92	129	92
1/2	7:50	288	0	100	0	100	224	0	100	0	100
1/3	8:00	1392	86	94	112	92	1232	62	95	88	93
1/6	8:20	701	0	100	68	90	633	0	100	54	91
1/6	12:00	209	0	100	9	96	188	0	100	12	94
1/7	7:50	542	0	100	14	97	418	0	100	6	99
1/8	7:50	1068	0	100	33	97	1054	6	99	42	96
1/9	8:00	23	0	100	0	100	44	0	100	0	100
1/9	12:00	634	0	100	61	90	721	0	100	77	89
1/10	7:50	452	0	100	13	97	497	0	100	16	97
1/10	12:00	734	0	100	23	97	660	0	100	13	98
1/13	13:20	830	55	93	72	91	745	22	97	42	94
1/14	8:15	154	13	92	33	79	230	0	100	56	76
1/15	8:30	173	0	100	8	95	216	0	100	12	94
1/16	7:45	225	0	100	0	100	214	0	100	0	100

Date	Time	BENZENE CONC (ppb)					TOLUENE CONC (ppb)				
		INLET	OUT 1	%REM	OUT 2	%REM	INLET	OUT 1	%REM	OUT 2	% REM
1/16	12:00	225	0	100	0	100	214	0	100	0	100
1/17	8:00	2943	50	98	203	93	4384	0	100	200	95
1/17	13:00	398	0	100	6	98	407	0	100	5	99
1/20	8:45	586	14	98	20	97	568	0	100	28	95
1/21	7:50	1840	25	99	0	100	1223	0	100	0	100
1/22	8:10	793	12	98	118	85	801	5	99	77	90
1/23	8:00	101	0	100	0	100	110	0	100	4	96
1/27	8:00	787	21	97	76	90	1010	16	98	119	88
1/28	7:45	1128	72	94	128	89	978	44	96	83	91
1/29	8:00	773	0	100	68	91	425	0	100	22	95
1/30	7:45	1354	4	99	172	87	997	0	100	115	88
2/3	7:45	605	0	100	30	95	459	0	100	22	95
2/4	7:30	926	0	100	86	91	799	0	100	63	92
2/5	8:00	113	0	100	0	100	79	0	100	0	100

Date	Time	M&P - XYLENES CONC (ppb)					O - XYLENE CONC (ppb)				
		INLET	OUT 1	%REM	OUT 2	%REM	INLET	OUT 1	% REM	OUT 2	% REM
10/24	9:30	252	129	49	132	48	139	108	22	98	29
10/24	14:00	472	270	43	370	22	236	179	24	189	20
10/25	7:40	150	87	42	119	21	53	42	21	71	0
10/25	12:20	357	130	64	203	43	173	86	50	151	13
10/28	8:00	189	8	96	63	67	108	0	100	28	74
10/29	8:00	143	12	92	65	55	56	0	100	23	59
10/29	13:30	301	46	85	48	84	181	17	91	23	87
10/30	8:30	147	34	77	88	40	80	10	88	49	39
10/30	14:00	891	108	88	309	65	456	108	76	126	72
10/31	8:30	134	19	86	24	82	103	8	92	8	92
10/31	12:00	128	39	70	50	61	66	14	79	20	70
11/1	8:00	420	143	66	84	80	61	52	15	24	61
11/1	13:15	186	30	84	44	76	88	7	92	16	82
11/4	8:30	45	9	80	8	82	16	0	100	0	100
11/4	14:00	123	10	92	42	66	66	0	100	14	79
11/5	7:45	153	7	95	43	72	86	0	100	13	85
11/5	12:30	1401	424	70	1014	28	478	158	67	361	24
11/6	8:10	384	30	92	53	86	224	7	97	21	91
11/6	12:30	244	41	83	27	89	174	15	91	9	95
11/7	9:00	605	29	95	86	86	311	6	98	39	87
11/7	13:00	445	47	89	84	81	265	9	97	29	89
11/8	8:30	83	5	94	8	90	34	0	100	0	100
11/8	12:10	305	41	87	47	85	104	13	88	16	85
11/12	8:30	67	16	76	3	96	500	36	93	23	95
11/13	8:00	162	1	99							
11/14	8:20	10	0	100	0	100	0	0	100	0	100
11/14	14:30	91	0	100	3	97	65	0	100	0	100
11/15	7:50	106	0	100	0	100	52	0	100	0	100

Date	Time	M&P XYLENES CONC (ppb)					O XYLENE CONC (ppb)				
		INLET	OUT 1	%REM	OUT 2	%REM	INLET	OUT 1	% REM	OUT 2	% REM
11/15	13:30	363	14	96	29	92	254	0	100	15	94
11/19	8:30	81	0	100	0	100	54	0	100	0	100
11/19	13:30	281	0	100	0	100	225	0	100	0	100
11/20	8:00	20	0	100	0	100	7	0	100	0	100
11/21	8:00	479	98	80	130	73	256	83	68	61	76
11/21	12:00	447	10	98	20	96	210	0	100	6	97
11/22	7:40	98	5	95	7	93	59	0	100	0	100
11/22	12:10	125	0	100	4	97	44	0	100	0	100
11/25	8:10	47	0	100	0	100	27	0	100	0	100
11/26	8:10	64	7	89	13	80	0	0	100	0	100
11/27	7:45	206	3	99	0	100	114	0	100	0	100
12/2	15:00	686	95	86	268	61	228	40	82	113	50
12/3	8:00	1061	47	96	328	69	289	17	94	115	60
12/3	14:30	48	320	0	143	0	70	165	0	119	0
12/4	8:30	37	0	100	0	100	26	0	100	0	100
12/4	13:30	332	38	89	39	88	170	0	100	15	91
12/5	8:00	128	0	100	19	85	74	0	100	11	85
12/5	13:30	364	18	95	25	93	154	0	100	0	100
12/6	8:00	328	54	84	0	100	65	38	42	0	100
12/6	12:30	199	0	100	0	100	93	0	100	0	100
12/9	8:20	74	0	100	0	100	43	0	100	0	100
12/9	11:50	108	0	100	0	100	28	0	100	0	100
12/10	7:50	35	0	100	0	100	13	0	100	0	100

12/10	13:20	147	0	100	9	94	124	0	100	0	100
12/11	8:00	85	0	100	0	100	60	0	100	0	100
12/11	14:00	279	0	100	13	95	150	0	100	9	94
12/12	8:00	562	0	100	11	98	250	0	100	0	100
12/12	12:00	127	15	88	7	94	100	8	92	5	95
12/13	8:15	208	0	100	0	100	83	0	100	0	100
12/13	12:00	295	0	100	3	99	213	0	100	0	100
12/16	8:20	75	0	100	4	95	42	0	100	0	100
12/17	14:00	238	0	100	0	100	123	0	100	0	100
12/18	8:00	51	0	100	0	100	10	0	100	0	100
12/18	14:00	306	4	99	0	100	164	0	100	0	100
12/19	8:00	20	0	100	0	100	8	0	100	0	100
12/19	13:00	177	177	0	0	100	101	98	3	0	100
12/20	8:00	179	0	100	0	100	85	0	100	0	100
12/20	12:30	261	55	79	9	97	126	24	81	0	100
12/23	8:30	26	0	100	0	100	11	0	100	0	100
12/23	14:00	199	0	100	0	100	109	0	100	0	100
12/24	8:00	345	18	95	1	100	203	47	77	0	100
12/26	8:00	142	0	100	0	100	114	0	100	0	100
12/26	14:00	130	0	100	0	100	55	0	100	0	100
12/27	8:00	83	0	100	0	100	25	0	100	0	100
12/27	12:00	201	0	100	15	93	98	0	100	17	83
12/30	8:00	215	0	100	0	100	68	0	100	0	100

Date	Time	M&P XYLENES CONC (ppb)					O XYLENE CONC (ppb)				
		INLET	OUT 1	%REM	OUT 2	%REM	INLET	OUT 1	% REM	OUT 2	% REM
12/30	14:00	573	8	99	91	84	259	0	100	71	73
1/2	7:50	22	0	100	0	100	7	0	100	0	100
1/3	8:00	329	0	100	7	98	130	0	100	0	100
1/6	8:20	97	14	86	0	100	37	0	100	0	100
1/6	12:00	24	0	100	0	100	0	0	100	0	100
1/7	7:50	106	0	100	0	100	61	0	100	0	100
1/8	7:50	748	0	100	6	99	207	0	100	0	100
1/9	8:00	8	0	100	0	100	0	0	100	0	100
1/9	12:00	212	0	100	5	98	106	0	100	0	100
1/10	7:50	173	0	100	0	100	85	0	100	0	100
1/10	12:00	185	0	100	0	100	129	0	100	0	100
1/13	13:20	276	0	100	0	100	142	0	100	0	100
1/14	8:15	61	0	100	0	100	35	0	100	0	100
1/15	8:30	88	0	100	0	100	12	0	100	0	100
1/16	7:45	53	0	100	0	100	20	0	100	0	100
1/16	12:00	53	0	100	0	100	20	0	100	0	100
1/17	8:00	600	0	100	18	97	210	0	100	10	95
1/17	13:00	173	0	100	0	100	80	0	100	0	100
1/20	8:45	190	0	100	0	100	101	0	100	0	100
1/21	7:50	431	0	100	0	100	237	0	100	0	100
1/22	8:10	240	0	100	8	97	126	0	100	0	100
1/23	8:00	14	0	100	1	100	0	0	-	0	-
1/27	8:00	1382	0	100	10	99	225	13	93	19	92
1/28	7:45	683	0	100	5	99	87	0	100	0	100
1/29	8:00	215	0	100	0	100	41	0	100	0	100
1/30	7:45	141	40	72	17	88	235	0	100	0	100
2/3	7:45	51	35	31	0	100	0	0	-	0	-
2/4	7:30	88	0	100	0	100	65	13	80	0	100
2/5	8:00	0	0	-	0	-	0	0	-	0	-

Date	Time	TOTAL VOC CONC (ppb)

		INLET	OUT 1	% REM	OUT 2	% REM
12/16	8:20	75	20	73	30	60
12/17	14:00					
12/18	8:00	60	17	72	27	55
12/18	14:00					
12/19	8:00	62	50	19	52	16
12/19	13:00					
12/20	8:00					
12/20	12:30	103	26	75	31	70
12/23	8:30	44	20	55	26	41
12/23	14:00	158	74	53	76	52
12/24	8:00	100	39	61	51	49
12/26	8:00	77	10	87	20	74
12/26	14:00					

Date	Time	TOTAL VOC CONC (ppb)				
		INLET	OUT 1	% REM	OUT 2	% REM
12/27	8:00	78	28	64	45	42
12/27	12:00					
12/30	8:00	140	74	47	110	21
12/30	14:00					
1/2	7:50	72	38	47	50	31
1/3	8:00	103	28	73	30	71
1/6	8:20	43	4	91	18	58
1/6	12:00					
1/7	7:50	70	19	73	28	60
1/8	7:50	108	12	89	27	75
1/9	8:00	45	24	47	25	44
1/9	12:00					
1/10	7:50	135	41	70	52	62
1/10	12:00					
1/13	13:20	121	48	60	66	46
1/14	8:15	172	51	70	77	55
1/15	8:30	138	60	57	71	49
1/16	7:45	106	36	66	43	59
1/16	12:00	106	36	66	43	59
1/17	8:00					
1/17	13:00	92	22	76	28	70
1/20	8:45					
1/21	7:50	140	50	64	75	46
1/22	8:10	132	33	75	61	50
1/23	8:00	132	36	73	42	68
1/27	8:00	173	52	70	80	54
1/28	7:45	240	56	77	38	84
1/29	8:00	256	42	84	48	81
1/30	7:45	136	46	66	80	41
2/3	7:45	108	48	55	60	44
2/4	7:30	136	50	63	72	47
2/5	8:00	88	48	45	62	30
		131	79	40	81	38

APPENDIX D

QUALITY ASSURANCE - QUALITY CONTROL

On September 5, 1991, the sensitivity and linearity of response of the gas chromatograph mass spectrometer (GC/MS) was tested using a certified gas standard containing 20 VOCs which was obtained from the California Air Resources Board. Of the twenty compounds in the gas standard, the response of the GC/MS to the six compounds shown in Table D.1 was determined. Triplicate standards were run for each of three volumes of standard, 150, 750, and 1500 ml. A comparison of the response (peak area for the primary ion for each compound) between the triplicate samples of gas standards run on the GC/MS is shown in Table D.2. Mean concentrations are in parentheses next to the compound name. The greatest deviation between standards was 15% of the mean. The results of regressions of the average mass of standard for the three samples at each volume vs the response of the GC/MS are shown in Figures D.1 through D.6. Results justified the use of a single point calibration in subsequent sample runs.

TABLE D.1: Six Compounds Introduced into the Biofilters During UC Davis Tests

Compound	molecular weight	density (g/ml)
chloroform	119.38	1.49
dichloromethane	84.93	1.34
trichloroethene	131.39	1.47
tetrachloroethene	165.83	1.63
benzene	78.11	0.88
toluene	92.13	0.87

Table D.2: Comparison of Standard Response for GC/MS 9/5/91

sample volume (ml)	response 1 ppb	response 2 ppb	response 3 ppb	std dev ppb
dichloromethane (94 ppb)				
150	81	86	115	13
750	83	87	112	11
1500	91	95	96	2
toluene (104 ppb)				
150	95	95	122	11
750	100	91	122	11
1500	104	103	105	1
chloroform (100 ppb)				
150	84	94	121	14
750	84	91	125	15
1500	96	100	103	3
benzene (99 ppb)				
150	85	96	117	11
750	88	87	123	15
1500	101	98	99	1
trichloroethene (105 ppb)				
150	92	98	125	12
750	96	93	126	13
1500	107	101	106	2
tetrachlorethene (104 ppb)				
150	86	107	119	12
750	100	87	125	14
1500	104	101	106	2

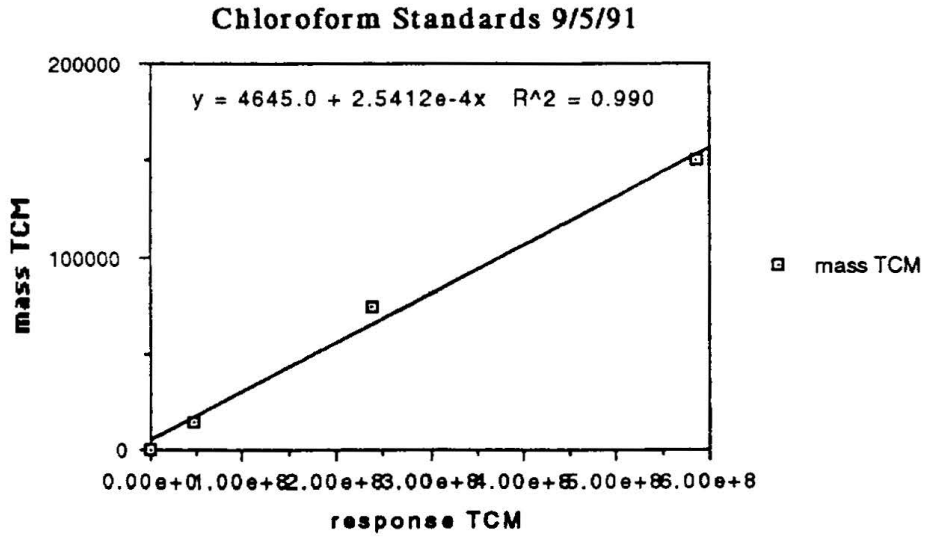


Figure D.1 : Calibration Curve for Chloroform

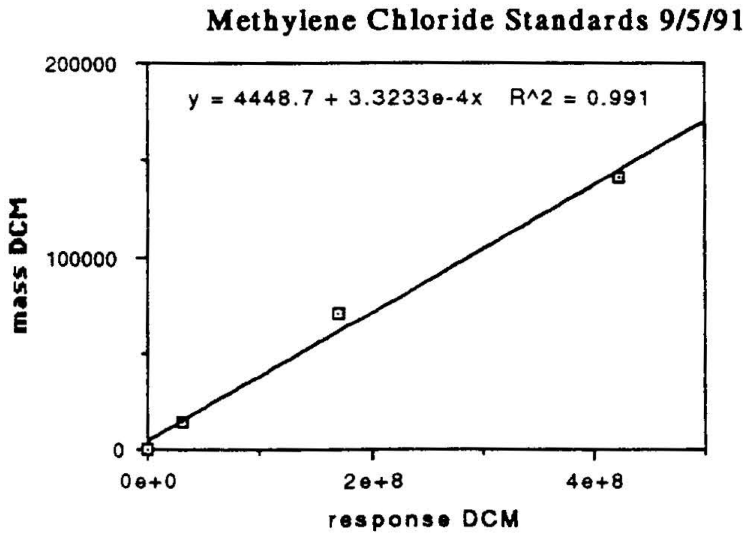


Figure D.2: Calibration Curve for Dichloromethane

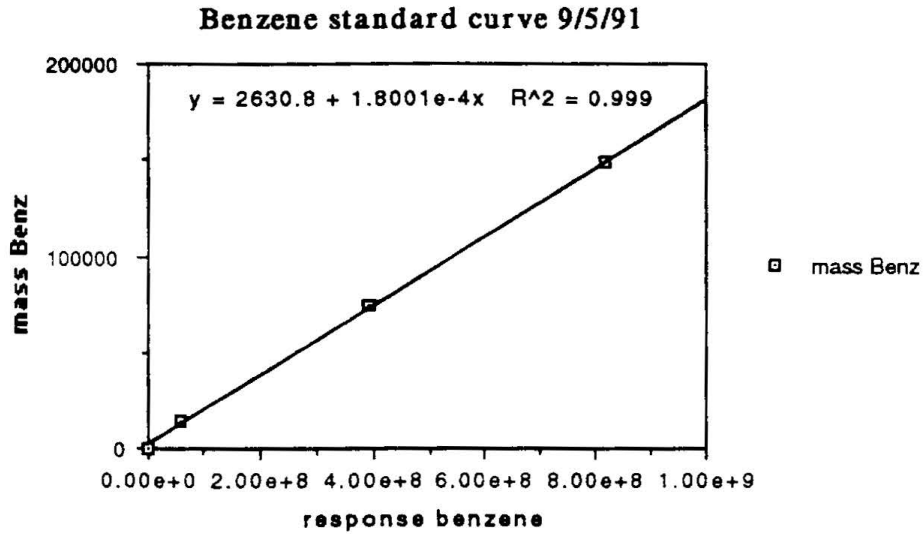


Figure D.3: Calibration Curve for Benzene

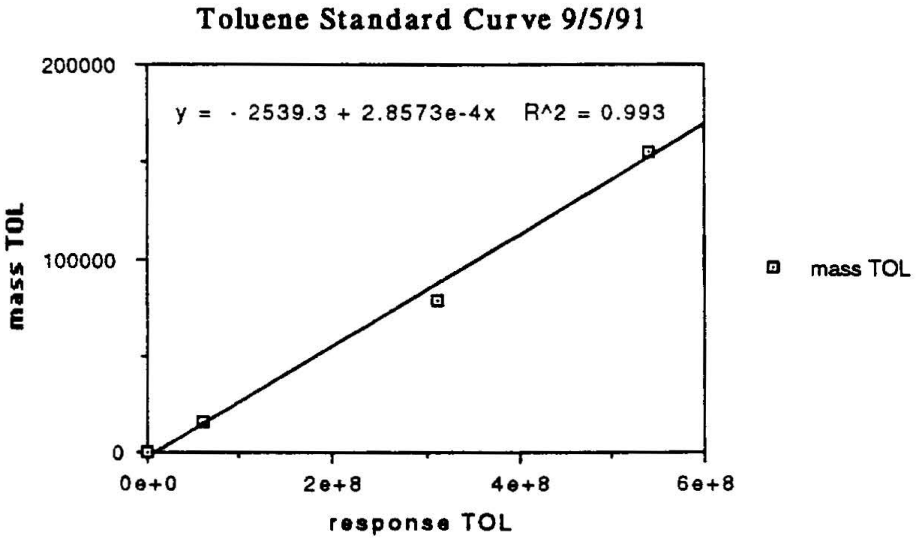


Figure D.4: Calibration Curve for Toluene

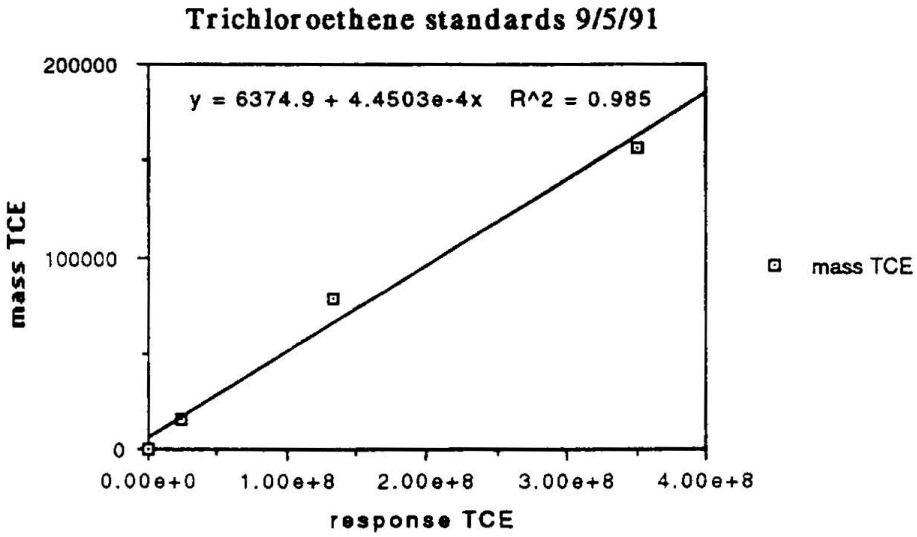


Figure D.5: Calibration Curve for Trichloroethene

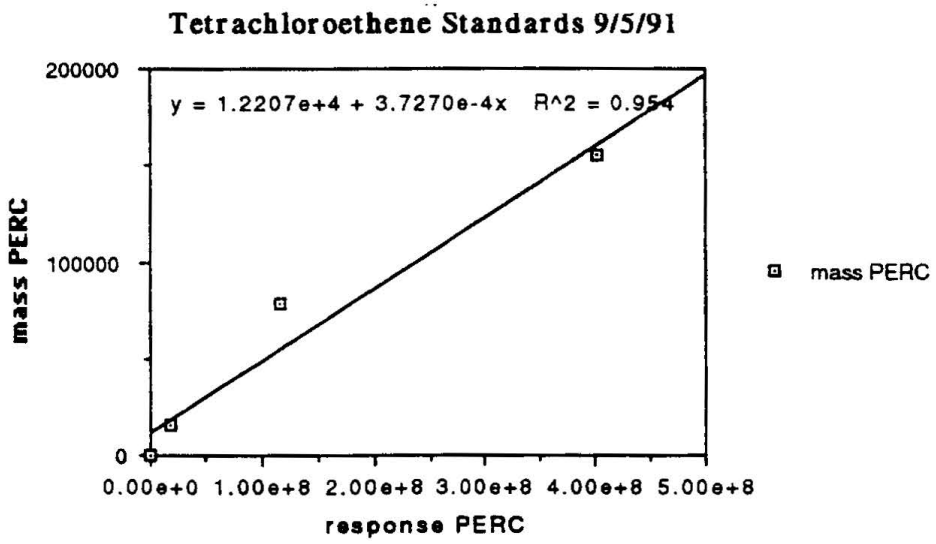


Figure D.6: Calibration Curve for Tetrachloroethene

PERMEABILITY STUDY

Air permeability of the filter media was determined using the aparatus shown in Figure D.7. A two inch diameter, three foot long, PVC pipe was filled with the filter media. Gas flow through the pipe was controlled with a needle valve, pressure drop across the column was determined with a mercury manometer, and the gas flow rate was determined using a dry gas meter (Singer) and a stop watch. All media mixtures were at 60% moisture content. The air permeabilities for the three mixtures tested, pure compost, 20% perlite and compost, and 50% perlite and compost, were 9.2, 1.6, and 27 m/min respectively. Addition of 20% perlite to the compost made the filter media less permeable, increasing the energy requirements to overcome pressure losses across the bed. Addition of 50% perlite to the compost increased the air permeability, decreasing the energy requirements and favoring more even gas distriburtion through the bed. Results of the permeability studies are presented in Figure D.7.

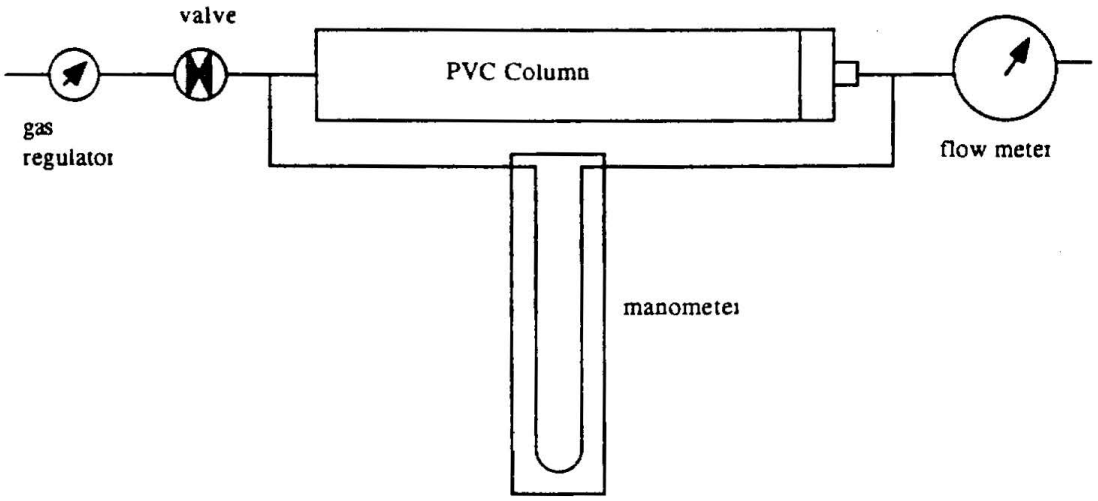
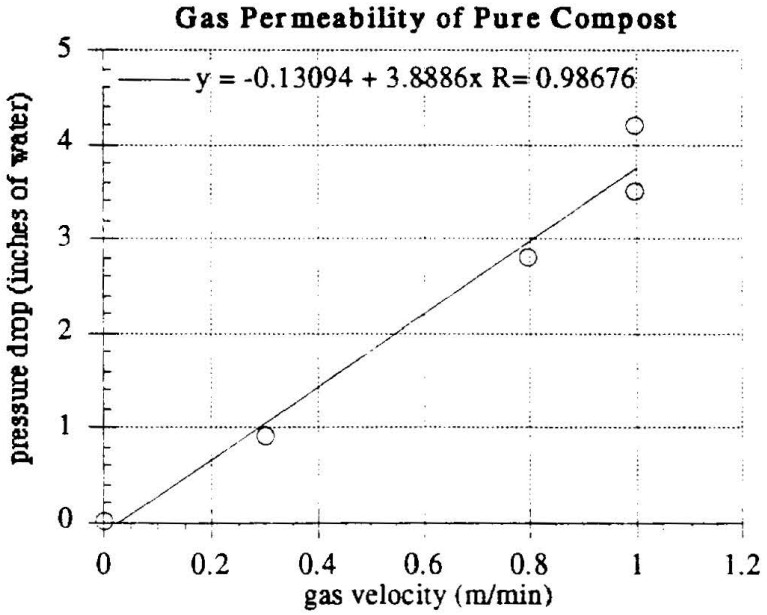
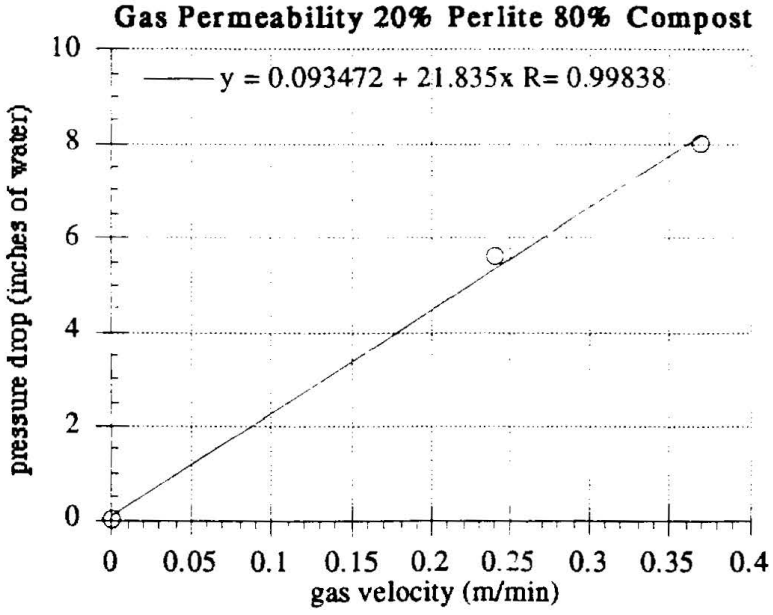


Figure D.7: Aparatus for Determining Pressure Drop Through Filter Media


Gas Permeability of Pure Compost
y = -0.13094 + 3.8886x R= 0.98676
pressure drop (inches of water)
gas velocity (m/min)
0
1
2
3
4
5
0
0.2
0.4
0.6
0.8
1
1.2


Gas Permeability 20% Perlite 80% Compost
y = 0.093472 + 21.835x R= 0.99838
pressure drop (inches of water)
gas velocity (m/min)
0
2
4
6
8
10
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

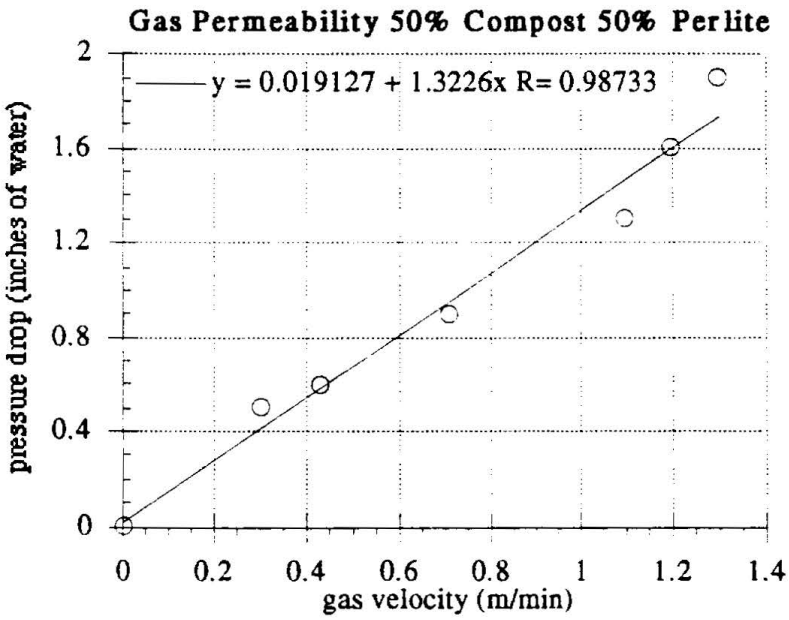


Figure D.8: Pressure Drop Across a Three Foot Column of Compost with Varying Amounts of Perlite.

DEGRADABILITY STUDY

Batch experiments were done with carbon 14 labeled toluene to determine whether microorganisms present in the JWPCP compost were able to mineralize toluene. Ten gram samples of the air dried compost were put into biometer flasks (Figure D.8) along with six mililiters of distilled water and ten µg of toluene. Carbon 14 labeled toluene was added to bring the activity of each flask to 66,960 DPM/ flask. The volume of labeled toluene was not significant enough to increase the concentration of the toluene in the biometer flasks. Each flask was equipped with a small vial of base (3 ml of 0.1 N NaOH) which served as a trap for any CO_2 that was formed in the flask as a result of biodegradation. Flasks were stoppered with teflon covered silicone stoppers and a canula was inserted through the stopper into the vial of base. A syringe needle was also inserted through the stopper to allow gases to enter when a sample was being withdrawn. Both canula and needle were stoppered with teflon seals when sampling was not in progress. At regular intervals, the base was removed from the vial through the canula, mixed with scintillation fluid, and counted using a scintillation counter , and replaced with fresh base.

The results of this experiment are shown in Figure D.9. The data shown are mean values of two replicates. Recovery of labeled toluene was less than 15% of the $C^{[14]}$ added. Subsequent destruction of the samples and use of a methanol extraction technique to recover any labled toluene left in the soil showed that this may have been due to volatilization and leakage through the stoppers in the flasks. The compost gave comparable results, however, to a positive control which contained a ringe soil known to have organisms in it which degrade toluene. The compost samples also showed a poitisitive response compared with a sterileized control which did not show significant evolution of CO_2.

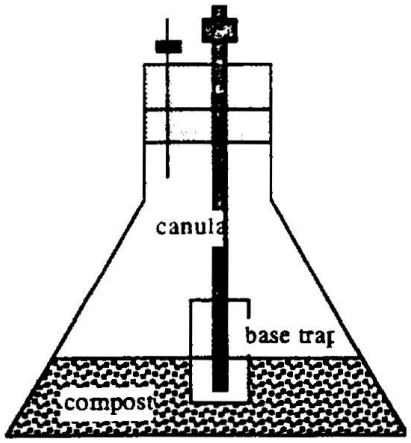


Figure D.8: Biometer Flask Set-up

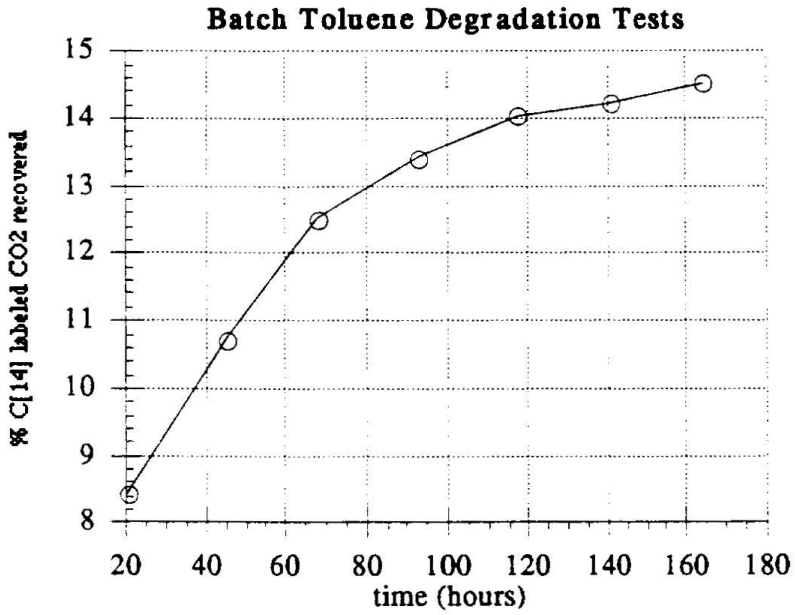


Figure D.9: Results of Batch Toluene Degradation Tests

BUFFER & pH STUDY

Two types of buffer were considered for use in the biofilter media, hydrated limestone ($Ca(OH)_2$ and oyster shell ($CaCO_3$). The use of dolomite limestone was suggested, however staff at the Buckman St. Wastewater Treatment Plant in Jacksonville Fla. had experienced solidification of the filter media in their biofilter when dolimite was used as a buffer and discouraged it's use. Experiments were performed to determine the effect of the different types of buffer on the filter media pH. Varying amounts of hydrated lime and oyster shell were added to five gram portions of both the compost and the compost and perlite mixture. Five mililiters of distilled water were added and the mixture was allowed to equilibrate for twenty four hours. The pH was determined using a standardized electrode pH meter. Results are shown in Table D.3; oyster shell was found to provide buffer capacity without increasing the pH of the filter media.

Table D.3: Affect of Buffer on Filter Media pH

$Ca(OH)_2$ meq/ g	compost pH	compost + perlite pH	$CaCO_3$ meq/g	compost pH	compost + perlite pH
0.0	7.3	7.2	0.0	7.3	7.2
0.05	7.9	8.2	0.05	7.3	7.2
0.1	8.0	8.2	0.1	7.2	7.1
0.2	8.4	8.5	0.2	7.3	7.1
0.4	8.9	9.1	0.4	7.3	7.4
2.0	9.6	10.5	2.0	7.2	7.1