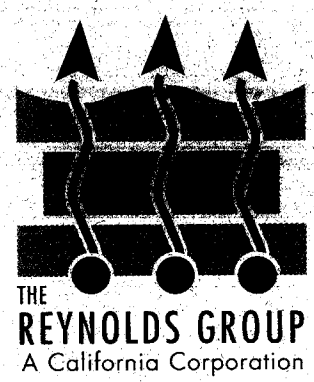


TRG-4879

Final Report

ARB GROUP AGREEMENT NO. 96-339

APPLICATION DEMONSTRATION OF DUAL STAGE BIOFILTER FOR PUBLICLY OWNED TREATMENT WORKS

Prepared For:

State of California
Air Resources Board
2020 L Street
Sacramento, CA 95814

Prepared By

F. Edward Reynolds, Jr., RCE
Derek Chitwood
The Reynolds Group
250 El Camino Real, Suite 204
Tustin, California 92780-3656
(714)730-5397

and

Dr. Joseph S. Devinny
University of Southern California
School of Engineering, OHE 200
Los Angeles, California 90080-1450
(213)740-9933

April 22, 1999

ACKNOWLEDGEMENTS

This study was conducted under ARB Group Agreement No. 96-339 by The Reynolds Group. The author would like to thank the Ojai Valley Sanitary District, especially David Burkhart, Ron Sheets and Shelli Perry. The staff at the Ojai Valley Sanitary District went out of their way to accommodate this project in their actively operating publicly owned treatment works (POTW). In addition, Ralph Propper of the California Air Resources Board (CARB) provided support and assistance that proved invaluable during the course of this contract.

ABSTRACT

Foul and odorous air emissions from wastewater plants, commonly known as Publicly Owned Treatment Works (POTW's), pump stations, and other industrial sources such as pulp and paper mills and refineries are common nuisances. The ingredients of the effluent air streams may contain a variety of volatile organic compounds (VOCs) that are subject to air pollution regulations. One of the key components of the odors is hydrogen sulfide gas (H_2S). Hydrogen sulfide is easily oxidized into sulfuric acid, but sulfuric acid creates havoc for conventional treatment methods. Sulfuric acids corrode thermal oxidation systems (conventional burner systems) and require high capital costs when treated chemically (typically using chlorine).

Biological treatment of air pollutants is appealing because biofilters are a benign and environmentally friendly technology. The primary barrier to adoption of biofilter technology at POTW's and other applications is the lack of operating experience. Plant managers are understandably reluctant to adopt new systems without a successful track record. Even the California Air Resources Board (CARB) was initially hesitant to support a system that did not work on traditional mechanical or chemical principles. This project was the first biologically based system that the CARB funded.

Under CARB sponsorship, The Reynolds Group, the University of Southern California and the Ojai Valley Sanitary District teamed to demonstrate that a two-stage biofiltration system can effectively treat H_2S. Conventional single-stage biofilters are subject to the accumulation of acids and early death.

Air pollution control (APC) by biofiltration is accomplished by passing contaminated air through a damp, porous medium that supports a vigorous mixed culture of microorganisms. The contaminants are biodegraded. Compost is commonly used as a support medium, although synthetic media and a variety of mixed media are also used.

Biofilters are an excellent technology for treating air emissions at POTW's if the difficulties caused by H_2S can be solved. Current biofilters at POTW's operate as single-stage open reactors. A single medium, usually compost, is expected to treat all of the compounds that must be removed. Some alkalinity may be added in the form of calcium carbonate minerals, but this is easily exhausted by sulfuric acid production. The spent minerals and acid-degraded compost often form small particles that contribute to biofilter clogging. The compost has a very limited lifetime.

The POTW biofilter for this project contained two stages. The first stage was an enclosed system with a lava rock support medium. The first stage was optimized for removal of H_2S, and utilized acidophilic autotrophic bacteria such as *Thiobacillus thiooxidans*. These strains are adapted to sulfide oxidation as an energy source, and survive well at low pH. This microbial ecosystem is relatively well known because it is responsible for the sulfuric acid corrosion of sewer piping. Because H_2S removal was confined to the first stage, there was no acid or inorganic sulfur production in the second stage compost bed. The acid produced in the carbon bed was drained and returned to the sewage flow. Only a small volume of liquid required handling.

Some oxidation of VOCs occurred in the lava rock bed. In this project, the first stage biofilter was sized only to remove the H_2S. This minimized initial costs and provided a dual phase system with maximum versatility.

This report summarizes the year-long full-scale demonstration of the two-stage biofilter at the Ojai Valley Sanitary District's newly modernized POTW. Topics presented in this report include a description of the demonstration, the sampling methods, and the results. The conclusions of this project are that:

a) a lava rock pre-stage biofilter can be a very effective means of removing H_2S and VOCs from the waste air flow stream at a POTW or other facility where H_2S is a component of the effluent,

b) the low-pH biofilter can effectively treat H_2S emissions at contact times as low as 12 seconds, which means that the pre-treatment unit can be very small and that current compost-based biofilters may be over designed,

c) lowering the pH in the first stage of the biofilter neutralized the pH in the second stage of the biofilter resulting in longer life of the second bed,

d) lava rock provides an excellent medium for a low pH biofilter,

e) VOCs can be removed in the low pH biofilter,

f) internet based instrumentation and software that can monitor and control the performance of the biofilter from remote locations have serious implications for the business model that will successfully compete in the industry, and

g) traditional problems associated with biofilters including acidification, flow heterogeneity, and measurement can be resolved with proper design and sufficient operating experience.

The environmental benefit of biofilters will be the improved treatment of POTW discharges, reduced odors, reduced neighborhood exposure to toxic chemicals, and the reduced generation of smog precursors. Economic benefits will accrue first to sanitary districts in California, which will have an inexpensive means of meeting their regulatory responsibilities. Industry will benefit as more installations are made, providing employment for engineers, contractors, and operators.

The primary barrier to adoption of biofilter technology at treatment plants, and particularly advanced technology, has been the lack of operating experience and dissemination of information regarding the use of biofilters at POTW's for the treatment of H_2S emissions. Plant managers are understandably reluctant to adopt new systems without a successful track record. This project with the support of the CARB directly addresses this problem.

COMMERCIALIZATION

The commercialization strategy for the biofilters is to allow the technology to spread throughout the industry as regulatory acceptance builds momentum. The success of the project and the support of the CARB have lent credibility to the biofiltration as an acceptable technology so that the technology can proliferate inside and outside of California. As the momentum builds, The Reynolds Group intends to capitalize on the growing market place and gain a prominent position as an industry leader. Inquiries regarding applications of biofilters on The Reynolds Group's web site continue to increase in volume.

As of the date of the completion of this project, there are at least three permanent jobs that have been created in Southern California. One of the jobs is in sales, one is in administration, and one is in technical engineering. There will be considerably more jobs created as biofiltration gains further acceptance in the United States. Furthermore, the use of biofiltration as a safe and effective non-chemical means of controlling odors will allow economic development to continue to encroach nearer to POTW's as population increases and real estate becomes more scarce.

As a direct result of this project, business negotiations are in progress for designing, constructing and operating biofilters in Baja California, Mexico. Several POTW's in California have expressed an interest in applying biofiltration as an alternative to their chlorine scrubber systems. In addition, several POTW's have initiated their own attempts in the last two years to construct and operate biofilters with limited success. The lessons learned in this ICAT project will add to the body of knowledge so that biofilters can be placed in service with an greater, even outstanding chance for success.

The Reynolds Group will continue to invest in biofiltration and as a result of this project will ramp up its investment significantly.

There are four different business models that seem to be evolving in the commercial marketplace for biofiltration. They are: 1) design/support services such as those provided by expert engineering firms, 2) niche product providers that build biofilters tailored to one specific application such as remediation systems at contaminated sites, 3) the "killer application" vendor who purports to have a technology that is better than all the rest, and 4) the turnkey, design, build, operate provider who provides all services.

The Design Support Services Business Model is structured as follows:

- Expert Design Advice Based On Experience
- License Technology/Patents
- Low Risk, Time Based Fees
- Owners Bear Risks
- Clients Like to Tinker/Do Their Own Work
- Professors/Engineers

The Niche Product Provider Business Model is built around the following:

- Standard or Modular Systems
- Need for Constant Improvement
- Risk of Obsolescence
- Risk Shifted More to Supplier
- Small Capitalized Companies

The Reynolds Group does not believe that a "killer application" yet exists in the industry or that such an application will ever exist. Rather, technological innovations in the biofilter industry will be driven entirely by experience and feedback from live operating systems.

The Turnkey Provider Business Model is built around the following:

- Risk Shifts Entirely to Supplier
- Significant Capital Requirements
- Projects Rely Upon Stand Alone Financing and Guarantees
- Financial Performance Relies on Cash from Individual Projects

The Reynolds Group believes that the biofilter business is:

- Still a Cottage Industry
- Too Small and Fragmented for Consolidation by a "Roll Up Financier"
- Significant Financial Rewards Not Available Yet
- May Fit as Part of a Suite of Complementary Services (e.g. Monsanto, US Filter) That Have a Substantial Market Coverage in the Waste Water Fields

The Reynolds Group believes that the successful business model for biofiltration will be to provide expert design consulting services from a single office location. To differentiate itself from the competition and to succeed, TRG must build operating experiences with biofilters that continue to incrementally build on previous generations. TRG's experience has grown rapidly over the last six years. The support of the CARB at this project for POTW's has greatly advanced the sales potential of biofilters industry-wide.

The Reynolds Group will provide design, permitting, procurement, construction management, and operational advice initially from a single office based in Tustin, California. Accessing the markets will be the key factor in succeeding in the biofilter business. The Reynolds Group intends to continue a full time marketing effort for the biofilters directed at POTW's with the support of full time business development staff and the technical staff who have gained from the firm's last six years of experience. Our goal is to sell two engineered biofilter systems by April of 2000 and to double our output each year for the next five years before stabilizing.

TABLE OF CONTENTS

1.0 INTRODUCTION

Biofiltration originated in California in the 1960's, and has blossomed in Europe for odor control where high density populations require very stringent regulations. Recently, due to improved biotechnology and controls, biofilter applications have expanded to include a variety of industrial discharges and treatment for control of toxic substances and smog precursors. No country has yet solved the issues that this project addresses at Publicly Owned Treatment Works (POTW's).

POTW's are facilities that treat sewage and wastewater. POTW's have always struggled with odor problems and efficient control of toxic substances and smog precursors. POTW's represent just a fraction of the number of potential emission sources for H_2S associated with wastewater. In many geographical locations throughout the United States, there are pumping stations that have to raise sewage in the pipelines so that the sewage can continue to flow by gravity to the POTW. For each POTW, there may be several pumping stations located near residential neighborhoods. There are about 55,000 public and private water entities that serve 90% of the United States. Approximately 30,000 are privately held with most of the rest owned by municipal governments. The United States Environmental Protection Agency estimates that about $140 billion need to be invested in water infrastructure in the next 20 years.

Water and waste-water systems are also being privatized and upgraded throughout the rest of the world. According to the World Bank, approximately $600 billion will be spent on building and upgrading the world's water and wastewater infrastructure in the next decade. In Latin America alone, there are substantial expenditures planned.

Currently, the worldwide market for biofilters is approximately $100 million per year, of which $50 million is in Europe, $30 million is in the Americas, and $20 million is in Asia. The entire market for scrubbers and adsorbers in 1996 was $3.6 billion and is expected to grow to $5.4 billion by 2001. The POTW market is expected to comprise 10% of the market place. The market for biofilters may grow at 10% to 20% per year for the forseeable future.

Emissions of foul-smelling hydrogen sulfide gas (H_2S), mercaptans, and other compounds have generated complaints from nearby residents. These complaints grow more serious as increasing residential development puts more homes near treatment plants. Recently, there has been talk at the United States Environmental Protection Agency that H_2S may be regulated.

Volatile organic compounds (VOCs) such as benzene and trichloroethylene are found in wastewater flows as a result of illegal dumping. Venting of air spaces, particularly aerobic biological treatment, release these compounds into the atmosphere. While concentrations are generally not high, the large amounts of water handled by POTW's means that total emissions can be significant.

Biofilters are benign air pollution control devices that use biological means to treat contaminated air streams. The filter medium is very inexpensive and readily available. When the filter material has exhausted its useful life, the material can be disposed without any special considerations. Biofilters for POTW's are clean, "green" and socially/politically acceptable.

Biofilters offer a superior alternative to conventional methods of treatment such as burning (oxidation) where fuel costs are high, absorption where contaminants are simply transferred to another medium, and chemical processes that consume large amounts of chemicals and generate another disposal problem.

2.0 BACKGROUND

A biofilter treats a contaminated air stream by biologically destroying the contaminants in the air stream. This biological activity is identical to other biological treatment processes such as aerobic treatment of wastewater and bioremediation of contaminated soils and groundwater. Aerobic treatment of wastewater is now an extremely mature treatment technology that is accepted worldwide. Bioremediation of soils and groundwater is also a proven technology that has grown in acceptance in the last two decades. Similarly, recent advances in biofilter technology and applications make biofiltration an extremely attractive alternative for environmental managers to consider when deciding among air pollution control (APC) alternatives.

2.1 OVERVIEW OF THE PROCESS

Biofilters treat effluent air streams that contain biodegradable volatile organic compounds (VOCs) and other odorous compounds. The effluent air stream passes through a natural, biologically active filter bed, referred to as a "biofilter". The filter bed does not trap the contaminants like carbon absorption, but rather consumes the contaminants so that the biofilter bed constantly regenerates itself.

Biofilters utilize natural microorganisms to convert organic contaminants to carbon dioxide and water. Biofiltration removes air pollutants by passing the contaminated air through a damp, porous medium that supports a vigorous mixed culture of microorganisms. Generally, these microorganisms are obtained from naturally occurring biological media such as sludge or other sources where an extremely diverse population of bacteria exists.

A bacterial culture (sludge or other sources) is applied to the biofilter bed. While most of the many species present in these inocula die away, those that are capable of degrading the contaminants under the conditions within the biofilter survive.

The successful microorganisms live in a layer of water and microbes referred to as a biofilm located on the surface of the biofilter packing material. The packing material is referred to as the biofilter "bed." The bed is housed in an enclosed or open vessel that is designed to meet the specific air flow demands, effluent air contaminants and applicable regulatory issues of a custom air pollution control device. Enclosed biofilter designs can range from small portable tank vessels to larger permanent structures the size of small buildings. Open biofilter beds where air is discharged directly to atmosphere can be up to one-half acre in size.

Contaminated air enters the biofilter and passes through the biofilter bed. The bed may be compost-based material, lava rock or some synthetic material. The metabolism of the contaminants occurs in the biofilm that accumulates as the bacterial culture grows. Passing through the bed, the air contaminants contact the microorganisms in the biofilm and are

consumed, much as people consume food for energy. The contaminants are transferred from the air phase to the water, then biodegraded. They are transformed into carbon dioxide and water.

Maintaining ambient temperature and moisture is crucial to the effectiveness of the biofilter. A blower is used to move the air across the biofilter bed and to maintain a supply of oxygen necessary for the metabolic activity in the biofilter bed. An air dispersion system ensures evenly distributed flow in the bed. Water is periodically injected into the bed to maintain the proper moisture level. The biofilter "bed" itself is non-hazardous and remains non-hazardous after use.

2.2 RECENT ADVANCES IN BIOFILTER TECHNOLOGY

Biofilters originated in Orange County, California in the 1960s. The technology has proliferated in Europe because energy costs and sophisticated odor regulations make biofiltration the viable economic alternative for waste air treatment. Conversely, biofiltration has not gained acceptance in the United States because of cheap energy prices and a lack of regulatory acceptance.

In the 1990s, interest in biofilter technology in the United States has grown rapidly. The number of research publications and funding in the last decade has grown at an exponential rate. Biofilters have become a staple topic within various conferences and exhibitions such as the Air & Waste Management Association's annual conference. The number of publications has expanded from virtually nil at the beginning of this decade to over 100 publications per year. For example, a bi-annual conference at the University of Southern California in Los Angeles dedicated to biofiltration attracts more than 40 papers on the subject from the international arena. Furthermore, the current biofilter market in the United States is estimated to be $20 million and growing.

Several well-capitalized companies including Envirogen, EG&G and Monsanto have made significant efforts to profit from the technology. Numerous small companies, including small consulting firms, have attempted to enter the market place. The momentum is building toward commercial acceptance of biofilter technology. However, new players in the market can be deluded into believing that biofiltration is a simple technology. Assuming that all one has to do is put "bugs in a box" and blow air across the beds to build a successful biofilter results mostly in failure. Failures of biofilters due to poor design and construction have retarded ability to penetrate the United States market.

Significant improvements have been made in the last decade in understanding how biofilters can treat contaminated air effectively for an extended period of time. A competent combination of design, construction, and operation will lead to very successful applications. The success of a biofilter depends on several factors including:

1) sustaining the active microbial culture,
2) buffering the biofilter from shocks that might inhibit microbial activity,
3) measuring biofilter performance, and
4) developing regulatory agency acceptance.

All of these factors have been considered in this ICAT Demonstration project.

1. Sustaining the active microbial culture

For a biofilter to operate at its peak performance, the biofilter bed must sustain its microbial population so that the biofilter performs at optimum efficiency for an extended period of time. The proper nutrients, water and temperature must be maintained for vigorous health of the bacterial culture.

Moisture systems have evolved using various proprietary spray and humidification devices so that today consistent moisture can be maintained continuously at all points in the biofilter bed.

In conventional compost biofilter beds, the compost provides a long-term nutrient supplement that sustains bacterial life. In synthetic beds, the proper mix of nutrients required to sustain microbial growth can be derived from simple bench scale studies. Filter bed materials are expected to last for many years without replacement.

The biofilter process is an exothermic reaction and generally if biofilters are insulated from temperature fluctuations, the microbes will thrive. Incremental design improvements have made biofilters immune from extreme external temperature fluctuations that may terminate the microbial activity.

2. Buffering the biofilter from shocks that might inhibit microbial activity

Many air effluent streams are cyclical in nature. For example, the effluent air streams from a publicly owned treatment works (POTWs) may spike at certain times during the day or contain acidic compounds such as H_2S which can kill the biofilter. By anticipating how biofilters react to such shock loads, designers can incorporate these extremes into the process. Modern biofilters can adapt to these shock loads if proper consideration is given during the design phase.

The contaminated air within a biofilter must cross over the entire biofilter bed. Early generation biofilters were hindered by channelization. Channelization occurs when air contaminants pass through a biofilter bed without contacting any microorganism in the biofilm. Improvements in airflow diffuser design and biofilter beds have greatly reduced the chances that channelization will occur in modern biofilters, thereby increasing the productivity of the biofilters and reducing their size.

3. Measuring biofilter performance

In the last decades, tremendous advances have been made in instrumentation to measure key biofilter parameters at minimal costs. In addition, the advent of the internet and

remote control monitoring allows biofilters to be monitored and adjusted continuously and remotely. This combination of low cost, improved technology and remote access improves the reliability of modern biofilters. For example, monitoring pH, temperature, head loss, moisture, biomass accumulation and destruction efficiency can all be performed in a real- time basis using inexpensive probes, load cells and other monitoring devices. The parameters can be adjusted using a touch screen computer system from a remote location. If necessary, a biofilter expert can be consulted on a real-time basis if any parameters are askew.

4. Barriers to regulatory acceptance/ developing regulatory agency approval

In general, regulatory agencies are more prone to accept a proven technology than an unproven one. Regulatory agencies have begun to open their minds to accepting biofilters now that they are aware of the modern biofilter strengths and weaknesses. Additionally, commercial interest in biofilter technology has steadily increased in the past decade. With all of the advances made regarding maintaining the homeostasis of the microbes, eliminating shock threats and monitoring flexibility, the number of successful biofilter applications has risen dramatically in the United States.

2.3 ADVANTAGES OF THE TECHNOLOGY

Admittedly, biofilters are not a perfect technology. It is true that for some compounds such as odorous hydrogen sulfide destruction efficiencies can be as high as 99.98%. However, at extremely high concentrations of hydrogen sulfide a biofilter cannot sustain itself. Similarly, biofilters can effectively and consistently treat VOCs such as benzene, acetone, ketones and other VOCs at efficiencies exceeding 95%. Many times these "imperfect" efficiencies are sufficient to allow a regulated facility to operate under its permitted conditions. In several regulated geographical areas, total elimination of VOCs is not necessary for a facility to continue it's commercial activities.

For example, a printing company in Los Angeles was subject to an annual limit of discharging ten tons per year of methyl iso-butyl ketone (MIBK). The permit restriction forced the printing facility to operate only forty hours per week. By operating the biofilter with only a 50% guaranteed destruction efficiency, the emissions were reduced by half and the printing facility was able to operate for eighty hours per week. The actual efficiency exceeded 90%. This resulted in doubling the printing plant's output and profit. It eliminated the need to relocate the facility to another state with less rigorous air pollution control restrictions.

As a result of competitive capital and low operating costs, biofiltration may have significant economic advantages over other air pollution control (APC) technologies if applied to air streams that contain low concentrations (typically less than 2,500 ppm) of readily biodegradable pollutants. Consistent control efficiencies of greater than 90 percent have been achieved for many common air pollutants. Advantages of biofilters include:

- Very low operating / energy costs.
- Low capital cost compared to other air pollution control equipment
- Removal efficiencies over 90%. (Some manufacturers guarantee more!)
- Operation at ambient temperature, and with a pressure drop of only several inches.
- Byproducts are harmless CO_2 and H_2O.

Biofilters are suitable for high flow rates when the concentrations are relatively low. One disadvantage of the biofilter is that it may take up a large amount of space.

Several projects have tested biofilters for use at POTW's. Generally, the devices have been single stage conventional compost biofilters, which are attractive because of their simplicity and low cost. The microorganisms involved in the composting process constitute an excellent inoculum, so that the medium rapidly becomes effective at removing air pollutants. However, difficulties arise because of the H_2S, which is commonly present in parts-per-million concentrations. Common species of microorganisms can readily oxidize H_2S to sulfuric acid. But the acid accumulates, lowering the pH of the biofilter, ultimately inhibiting microbial activity, and causing the biofilter to fail. The acid also degrades the compost, which causes increasing pressure loss. High concentrations of H_2S may lead to accumulation of elemental sulfur. Elemental sulfur is an intermediate in the oxidation process, and is also inhibitory to microorganisms.

3.0 DESCRIPTION OF FIELD DEMONSTRATION

3.1 BIOFILTERS

3.1.1 Ojai Valley Sanitary District Biofilter

The Ojai Valley Sanitary District operates a 3 million gallon-per-day wastewater treatment plant that includes a 3000 ft^2 below-grade, open bed-biofilter. The biofilter uses wood chips from lumber waste as the medium. They are strips from 1 inch to 12 inches long. The biofilter is designed to treat 8000 cubic feet per minute (cfm) of waste air removed from the plant's headworks, grit chamber and grit classifier. Air is driven by a centrifugal blower designed to deliver 8000 cfm at a pressure of 5 inches of water column (in. H_2O). Air is humidified by passing it through a spray humidification chamber and then is passed through fourteen 10-inch diameter schedule 80 PVC laterals beneath the wood chips. Each lateral is 50 ft long and has a pair of 5/8-inch diameter holes drilled every 6 inches along its length. Pairs of holes were drilled at 90 degrees from each other and the pipe was laid so that each hole is 45 degrees from the center bottom. The air is thus directed outwards and downwards from the pipe. The laterals are 4 ft apart and are covered with 6 inches of ¾ inch diameter acid resistant, smooth river rock. The depth of the medium above the rock is 3 feet. Six inches of chipped bark was added for aesthetic value. Six garden type sprinklers controlled by a timer provide irrigation of the biofilter. No nutrients were added because the organic medium provided necessary nutrients. Operation of the biofilter began in August 1997. The biofilter was not inoculated.

3.1.2 Acid Gas Biofilter

A pilot-scale biofilter was designed and constructed for this project. It was the first stage of a two-stage biofilter. It was called an acid gas biofilter (AGB) because it was designed to remove H_2S from waste air and protect the second stage, organic medium biofilter.

The AGB was constructed of three polyethylene tanks in parallel using PVC piping and valves for the delivery of air and water. Each tank was 92 inches in diameter and 46 inches tall. Air was driven by a small centrifugal blower designed to deliver 580 cfm at 5 in. H_2O. Valves on the inlet and outlet air piping allowed the system to operate with all the air passing through one tank, through two tanks in parallel, or through three tanks in parallel. Air entered through the side of each tank in the headspace above the lava rock medium. After passing through the medium, air exited from the bottom center of each tank. The tanks and piping sat on a 26 ft long, 6 foot wide two-layer steel skid with two control boxes for the monitoring and control equipment (Figure 3.1).

The medium in the AGB was lava rock with a median diameter size of 5/16 inches (Sunburst Decorative Rock, Inc. Irwindale, CA). The medium was relatively uniform in shape and size, and fines were removed before installation by washing. Lava rock is inert and is not damaged by acid. Its alkalinity was determined to be less than 10 mg/l as $CaCO_3$. Because it is a porous rock, it has a relatively large surface area. Others have found it an effective medium (Morton

and Caballero 1997). Each filter bed was 30 inches deep with an empty bed volume of 115 cubic feet. Above the medium, there was 10 inches of headspace, and there was 6 inches of air space below the medium.

Water and nutrients were added by a sprinkler system in the headspace above the medium. Each bed was wetted with 14 sprinklers to achieve complete and even coverage. The sprinklers were full cone whirl type sprinklers with 120° spray angle constructed of PVC from Bete (Greenfield, MA). During irrigation, the water flowrate was approximately 5 gallons per minute. Leachate drained from the bottom of the each tank through the same PVC pipe as the air. A leachate dropout box allowed collection of leachate. Level switches and a valve controlled the level of the leachate, assuring that the water did not back up into the air line.

The AGB was inoculated with influent wastewater from the headworks of the plant. Initially, approximately forty gallons of influent were applied through the sprinkler system. Two weeks later another 30 gallons per tank were applied directly with a garden hose. This provided nutrients to the system for startup.

Nutrients were also added to the AGB through the sprinkler system. Harrison (Harrison 1984) used a basal mineral salt solution for *Thiobacillus* species that contains 0.042 percent weight per volume of solution (%W/V) nitrogen, 0.0045 %W/V phosphorus, and 0.011 %W/V potassium. Initially, two commercial fertilizers were blended to obtain this ratio: Ammonium sulfate (J.R. Simplot Company, Lathrop, CA) and "Citrus Food" (Dexol Industries, Torrance, CA). Later, Miracle Grow Lawn Food was used at the nutrient source. A concentrated nutrient solution was stored in the nutrient reservoir. Nutrients were added to the water line by a metering pump at a rate of approximately 50 milliliters per minute. The final nitrogen, phosphorus and potassium concentrations in the blended water were approximately the same as the basal mineral salt solution.

3.2 SYSTEM OPERATION

For this experiment, the valve on the final lateral (lateral 14) of the wood chip biofilter was closed, and the air was drawn off by a small blower and passed through the AGB, then returned to the lateral. The wood chips above this lateral served as a second-stage organic medium biofilter. A small portion (7.5%) of the air was passed through two stages (the AGB and the wood chip biofilter). The balance of the air passed only through the wood chip biofilter. The wood chips above lateral 13 served as a one-stage conventional biofilter for comparison. Flows were equalized through all 14 laterals (Figure 3.2). This allowed comparison of the treatment efficiency and bed life of the wood chip biofilters while one was preceded by the AGB.

There were three different phases of the experiment. During Phase 1 the AGB was operated with three tanks in parallel. During Phase 2 it was operated with two tanks in parallel, and in Phase 3 all the air passed through one tank (Tank 1). The goal in operating in this manner was to determine the effect of the change in air retention time on AGB performance while keeping the flow through the entire system approximately 600 cfm (Table 3.1)

3.3 CONTAMINANT ADDITION

After an initial period of experimentation, H_2S from a compressed gas cylinder (Technical Purity, Matheson Gas Products, Rancho Cucamunga, CA) and a number of VOCs were added continuously to both the two-stage and one-stage biofilters because the wastewater system discharge contaminant concentrations were too low for experimental purposes. H_2S was added so that the concentration was approximately 5 ppmv at the inlet of both biofilters.

Concentrations were also supplemented for methylene chloride, chloroform, methanol, acetone, toluene, ethylbenzene, xylenes, 2-methyl-butane, and methyl tert-butyl ether (MtBE). The goal in adding these chemicals was to have at least one representative of as many classes of VOCs and odor causing chemicals common at POTWs as possible. Aldehydes, though important, were not added because of the extra cost associated with their analysis.

The VOCs were added to the inlet piping of the biofilters in liquid form. Stock solutions of the VOC mixture were combined in the laboratory. The mixture was transferred to 4 liter glass containers used in the delivery system. Addition of the liquid mixture to the air stream was controlled by a pressure source, flowmeters, and needle valves (Figure 3.3).

The inlet concentration of most of the compounds was between 0.1 and 1 ppmv, which is typical at POTWs (Ergas, et al. 1995; Webster 1996). The methanol inlet concentration was approximately 5 ppmv. Table 3.2 lists the principal characteristics of the compounds used in this study (Montgomery et al., 1996). The predicted removal efficiency is based on the model by Choi, et al. (1996) and for a biofilter with a one-minute empty bed retention time (EBRT) where the inlet concentrations are between 1 ppb and 10 ppm.

3.4 MONITORING AND DATA COLLECTION SYSTEM

A system was developed to automate control and data collection from the biofilters. Data acquisition hardware, relays and programming software were obtained from National Instruments (Austin, TX) for the development of the monitoring, data collection and control system. The monitoring system included: (1) 6 thermocouples for temperature measurements; (2) pitot tubes to measure flow rates into each tank; (3) four load cells to measure the weight of the first of the three tanks (Tank 1) that made up the AGB; (4) a pH probe and transmitter for measurement of leachate pH, (5) a 631-X Jerome Meter (Arizona Instruments, Jerome, AZ) for H_2S; (6) an SRI (Torrance, CA) flame ionization detector (FID); and (7) a CO_2 transmitter (Vaisala, Inc., Woburn, MA).

Air samples were regularly taken from four points: system inlet, outlet of acid gas biofilter, outlet of second stage (wood chip) biofilter, and outlet of one-stage (wood chip) biofilter. Air samples from each of these points were analyzed for concentration of H_2S, and total volatile organic compounds (VOCs). Three other air sampling points were located at the quarter point,

half point and three-quarter point depth in the medium of the AGB's first tank (Tank 1). The air sampling system included 1/4" flexible PVC tubing attached to the sampling ports, a solenoid array designed to allow sequential sampling of the four sampling ports, and a diaphragm pump to pull the air to the measurement devices (Figure 3.4).

Air was drawn through each sample port for 5 minutes at a rate of approximately 2 liters per minute. Blank air was sampled between each of the sampling points to continually verify the base line of the detectors. Needle valves distributed the air at appropriate rates to the measurement devices. The computer control and data acquisition system ignored the first 4.5 minutes of VOC data and CO_2 data and averaged the last 30 seconds of the sequence. H_2S data were also obtained during the last 30 seconds of each sequence. In this way, each of the four sampling ports was analyzed once every 40 minutes.

Water levels in the leachate dropout box were controlled by two level switches and an electric ball valve. Water addition to the biofilters was controlled in response to changes in the weight of Tank 1 of the AGB. When the weight fell below the lower set value, the sprinklers were turned on. After the weight reached the upper set value, the sprinklers were shut off. Water addition and leachate removal times were automatically recorded.

3.5 PERIODIC MEASUREMENTS

The pH of the media, the pressure across the beds, and concentrations of individual organic air contaminants were measured.

3.5.1 Medium pH

Medium from the acid gas biofilter was sampled by a 6 foot long brass grain probe with ten isolated sampling sections (Seedburo, Chicago, IL). Horizontal profiles were obtained by inserting the probe through side sampling ports located at the medium ¼ and ½ points. (Sampling at the ¾ point and bottom of the medium could not be accomplished because the weight of the rock above the sampling port height made insertion difficult.) Vertical profiles were obtained by inserting the probe vertically into the medium after opening the access cover to the biofilter. After extraction, medium pH was measured using pH paper and recorded in the field logbook.

3.5.2 Pressure Measurements

The pressure difference across the bed of the AGB and the wood chip bed was periodically measured by an inclined liquid manometer. Sampling ports directly above the medium and directly below the medium were used. The pressure difference across the headspace of the medium was also measured. Sampling ports were located directly above the medium. One was under the inlet while the other was on the wall facing the inlet.

3.5.3 Volatile Organic Compound Concentrations

Air samples were taken periodically and analyzed using EPA Method 18 (for 2-methyl-butane), EPA Method 308 (for methanol) and TO-14 (for air toxics, smog precursors, acetone and MtBE). Initiation of sampling began only after the leachate pH had stabilized at approximately 4. During most sampling events, five locations were sampled: system inlet, AGB outlet, two-stage biofilter outlet, single stage biofilter outlet, and blank air.

Samples for EPA Method 18 and TO-14 were collected in 6-liter Summa canisters (Figure 3.5). An orifice was attached directly to each Summa canister to control the inlet flow rate so that the canisters were filled in approximately one hour. This allowed a one hour average concentration. The goal was to minimize fluctuations in the results. A 4" long, ¼" diameter Teflon tube was connected to each orifice. For sampling the system inlet and AGB outlet, the end of the Teflon tubing was inserted directly into the air stream through a small hole in the PVC piping. For sampling the two-stage and single stage outlets, the end of the Teflon tubing was connected to the side of a "Tee" made from nylon located directly after the sampling hood. One end of the Tee was connected to the hood and the other was connected to ¼" PVC tubing. Air was drawn through the PVC tubing at a rate of approximately 1 liter per minute (lpm) by a diaphragm pump and discarded. A side stream of air (0.1 lpm) was pulled into the Summa canister. Sampling of the field blank was achieved by connecting the Teflon tube to the regulator outlet on the blank air cylinder.

Samples for EPA Method 308 were collected by an impinger method (Figure 3.6). For sampling the system inlet and AGB Outlet, air was drawn directly off the PVC air pipes as with the Summa canister method. A ¼" PVC tubing was inserted into the flow stream. Sampling of the second stage and single stage effluent was conducted similarly to the Summa canister method. Air was drawn into the impinger through the same sampling hood. In this sampling procedure, all the air passed through the impinger. A battery operated pump (a personal pump usually used to collect samples for human exposure assessment) was used to draw air through a 25 ml impinger, filled with 15 ml of distilled and deionized water. The impinger was fitted with a 100 µm fritted glass diffuser to minimize the bubble size. The air was bubbled through the water at a rate of 0.75 lpm for approximately 6 hours. (The actual rate and time was recorded for each sampling event.) To minimize evaporation, the impinger was kept in an ice bath. The total volume of air that passed through the water and the final water volume were recorded and submitted to an analysis company. They were necessary for calculation of the air concentration.

3.5.4 Pulse Tests

Pulse tests were conducted to determine empty bed residence time (EBRT), lava rock porosity, and actual time of travel measurements. 1-liter pulses of methane were used as the tracer. Pulses were injected into the inlet piping and were then measured at various locations. The same sampling line was used for all pulses to assure that no variations in time occurred because of

different travel length. Pulses were measured using the on board FID. Results were recorded every 2 seconds by a subroutine of the automated sampling system for later analysis.

3.5.5 Liquid Phase Measurements

AGB irrigation water, AGB leachate, and leachate from the wood chip biofilter were periodically analyzed for concentrations of alkalinity, ammonia, nitrate, nitrite, orthophosphate, and sulfate. Alkalinity, ammonia, nitrite, orthophosphate, and sulfate were analyzed by methods approved by Standard Methods (1995). Ammonia was analyzed by the ion selective electrode method.

Alkalinity was determined by titration of 0.2 N H2SO4 to pH=4.5 as measured by a pH electrode. Nitrite, orthophosphate, and sulfate were analyzed by a Hach method. Nitrate was analyzed by a Hach method, similar to the methods used for nitrite, orthophosphate, and sulfate (Hach, 1992). All methods used were the standard operation procedures for the Ojai Valley Sanitary District.

3.5.6 Air Phase Ammonia Concentrations

A short-term experiment was conducted to determine the effectiveness of the biofilters for removing ammonia from the air. Industrial grade compressed ammonia was added to the inlet of the two-stage and single stage systems at a constant rate so that the inlet concentrations were approximately 50 ppm. The impinger method described above was used for sampling air phase ammonia. The pH of the distilled and deionized water was adjusted to 2 by addition of sulfuric acid to assure maximum solubility of ammonia. The time and flowrate of the air through the impinger was recorded. The water phase concentration of ammonia was analyzed by the method described above. The air phase concentrations were then calculated from the water concentration, sampling time, and flowrate by the equation

$$[NH_{3(gas)}] = \frac{1.44[NH_{3(aq)}]V_{H_2O}}{V_{air}}$$

where $[NH_{3(gas)}]$ is the gas phase concentration of ammonia in parts per million by volume, $[NH_{3(aq)}]$ is the aqueous phase concentration of ammonia, V_{H2O} is the volume of water used for the analysis of aqueous phase ammonia in milliliters, V_{air} is the volume of air that passed through the water during sampling in liters, and the value 1.44 is the conversion factor.

3.6 MEDIA CHARACTERS

3.6.1 Field Capacity

Laboratory experiments were conducted to determine the water contents of lava rock, compost, granular activated carbon, and wood chips at field capacity. The wood chips were obtained from the conventional biofilter. The media were flooded for one hour and allowed to drip drain for another hour for determination of field capacity. The media were weighed again after drying in

an oven at 103°C for 24 hours (Table 3.3). The field capacity results for compost and GAC compare well with those of other investigators (Hodge 1993; Yang and Allen 1994).

3.6.2 Water Content and Volatile Organics

Periodic measurements were made of the water content and volatile organic material on the biofilter media. Samples were extracted from the AGB using the grain probe mentioned previously and others were removed from the wood chip biofilter by excavation. After removal, samples were immediately placed on weighed tin plates. Samples and tins were weighed and then dried for 24 hours at 103°C. After cooling in a zero humidity chamber, the samples were again weighed. The water content was determined by the equation

$$\%W.C. = \frac{m_{wet} - m_{dry}}{m_{wet} - m_{filter}} \times 100\%$$

where %W.C. is the percent water content, m_{wet} is the wet mass of the sample, and m_{dry} is the dry mass of the sample. The dry samples were then placed in a muffle furnace for 30 minutes at 500°C. After cooling in a zero humidity chamber to ambient temperature, the samples were again weighed. The volatile organic content on the lava rock was calculated by the equation

$$\%VOM = \frac{m_{dry} - m_{ash}}{m_{dry} - m_{filter}} \times 100\%$$

where %VOM is the percent of volatile organic material on the samples and m_{ash} is the mass of the sample after the volatile organic material was burned off.

3.6.3 Characterization of Organic Medium at Project End

At the completion of the project, a large section of the wood chip biofilter was excavated and samples were obtained at various locations for characterization purposes. Samples were obtained for three vertical profiles: directly above lateral 14 (which served as the second stage biofilter of the two-stage system), directly above lateral 13 (which was used as the single stage biofilter for comparison purposes), and directly above lateral 12, which was used as a control. At each of these vertical profiles, four samples were obtained: at the bottom of the medium, 1 foot above the bottom, 2 feet above the bottom, and at the top of the medium (3 feet above the bottom). Samples were collected by hand and placed in 1-gallon "Ziploc" bags. Samples were immediately placed in a refrigerator for later analysis.

Samples were analyzed for water content of total volatile organic material as described above and for alkalinity, ammonia, nitrate, and sulfate concentrations. 200 g of each sample was placed in a 500 ml plastic jar and 300 ml of distilled and deionized water was added. Sealed samples jars were agitated and placed in a refrigerator. After 3 days, the sample jars were opened and the water was filtered through clean glass filter paper. The sample water was then

analyzed for alkalinity, ammonia, nitrate, and sulfate as described above. The pH of the water was also determined using a pH electrode.

The volatile organic content of the biofilm around the wood chips was estimated by filtering 25 ml of unfiltered sample water immediately after vigorous agitation of the sample jars. The filter paper and the collected solids were dried for 24 hours at 103 °C and then weighed. The dried samples were then placed in a muffle furnace for 30 minutes at 500°C and weighed again after cooling. The percent volatile organic content of the biofilm was estimated using Equation 1.3 above.

Table 3.1 System Parameters for Each Phase of Operation

	Phase 1	Phase 2	Phase 3	Wood Chip Biofilter
Empty Bed Residence Time	32.6 sec	22.2 sec	12.1 sec	67 sec
Surface Area of Bed	138 sq ft	92.3 sq ft	46.1 sq ft	3000 sq ft
Bed Volume	345 cu ft	230 cu ft	115 cu ft	9000 cu ft
Average Flowrate	635 cfm	620 cfm	570 cfm	8000 cfm
Loading Rate	4.60 cfm/ft^2	6.72 cfm/ft^2	12.4 cfm/ft^2	2.67 cfm/ft^2

Table 3.2 Contaminant Properties

	Molecular Weight	Solubility in Water (mg/l)	Vapor Press. (mm of Hg)	Henry's Const. (atm-m^3/mol)	Log K_{ow}	Predicted R.E.
Acetone	58.1	481,098	230	3.67×10^{-5}	-0.24	75.8%
Chloroform	119.4	7950	246	4.35×10^{-3}	1.97	22.5%
Ethylbenzene	106.2	140	10	6.28×10^{-3}	3.15	94.1%
Isopentane	72.2	48	689	1.25	2.30	50.2%
Methanol	32.0	Miscible	127	4.44×10^{-6}	-0.77	88.6%
Methylene chloride	84.9	13000	435	2.69×10^{-3}	1.25	39.9%
Methyl tertiary butyl ether	88.2	51,000	245	5.58×10^{-4}	0.94	93.5%
Toluene	92.2	535	28.4	5.97×10^{-3}	2.73	86.4%
m-xylene	106.2	146	8.3	7.68×10^{-3}	3.17	91.5%
p-xylene	106.2	156	8.7	7.68×10^{-3}	3.17	91.5%
o-xylene	106.2	175	6.6	5.10×10^{-3}	3.12	100%

Table 3.3	Media Water Contents at Field Capacity		
Medium	Dry Bulk Density (kg/l)	Water Content at Field Capacity (wt/wt)	Water Content at Field Capacity (vol/vol)
Lava Rock	0.794	0.155	0.146
Compost	0.215	0.588	0.306
GAC	0.364	0.484	0.342
Wood Chips	0.178	0.647	0.326

Figure 3.1 **A profile of the the Acid Gas Biofilter. The vertical white pipes are the air inlet pipes. Outlet pipes cannot be seen. The edge of the wood chip biofilter can be seen in the foreground.**

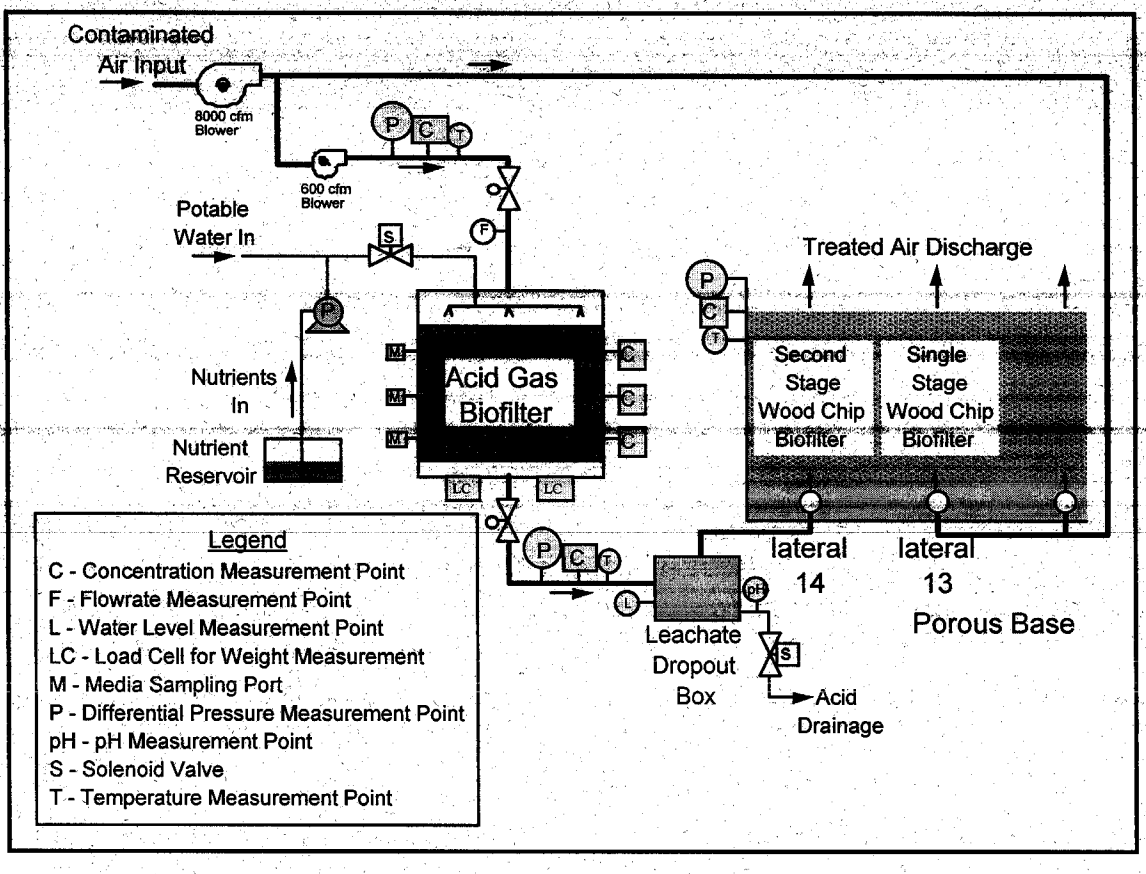


Figure 3.2 Biofilter Schematic

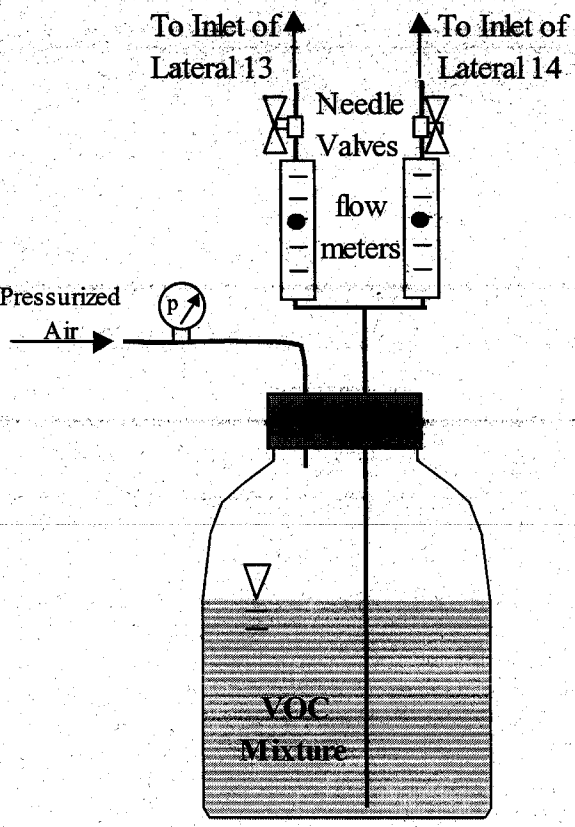


Figure 3.3 Method used to add the VOC Mixture to the inlet of both lateral 13 and 14.

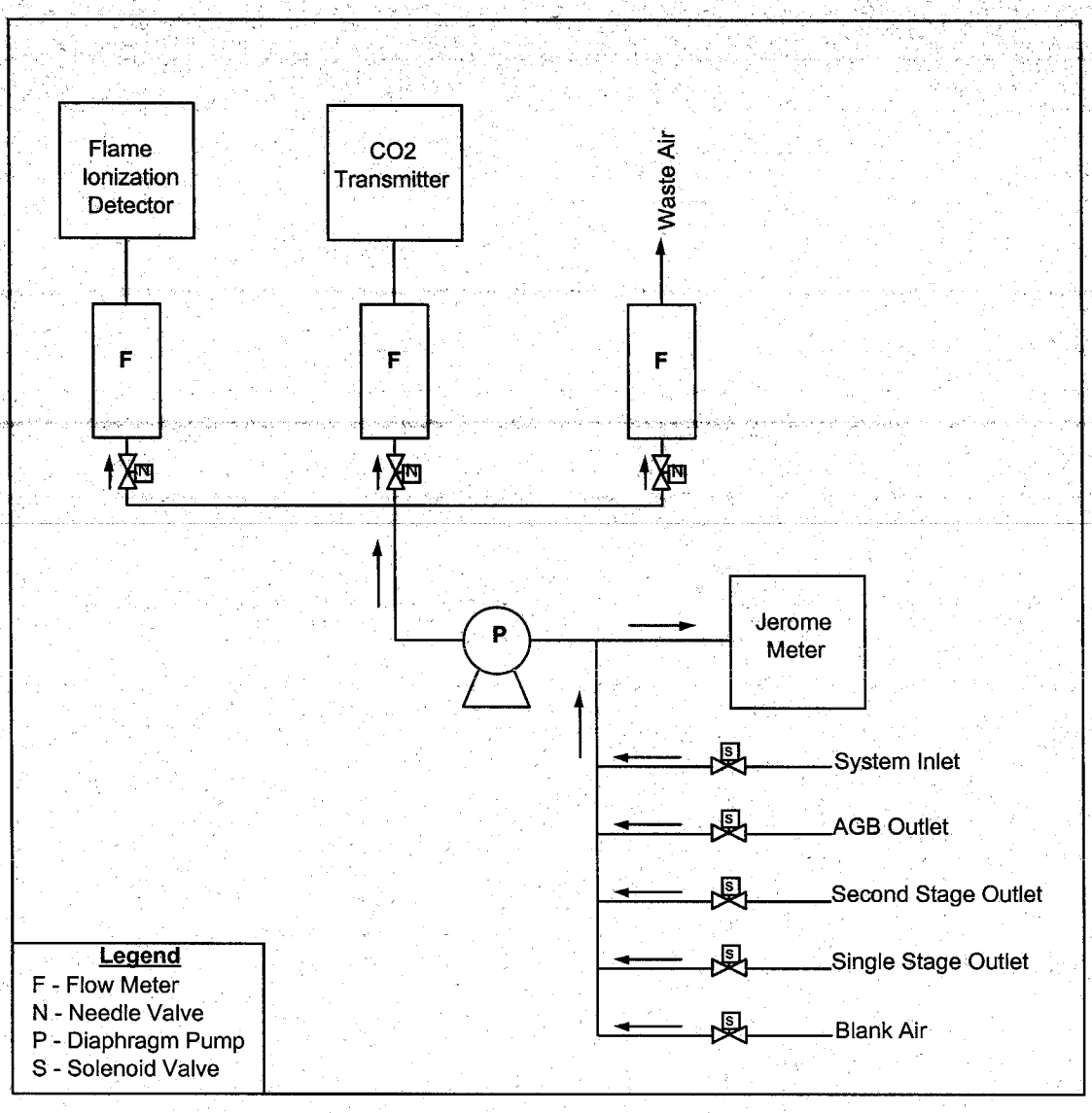
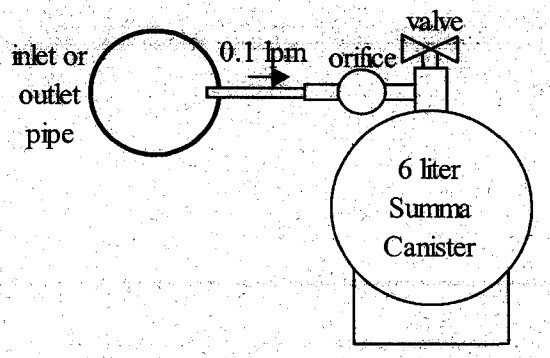
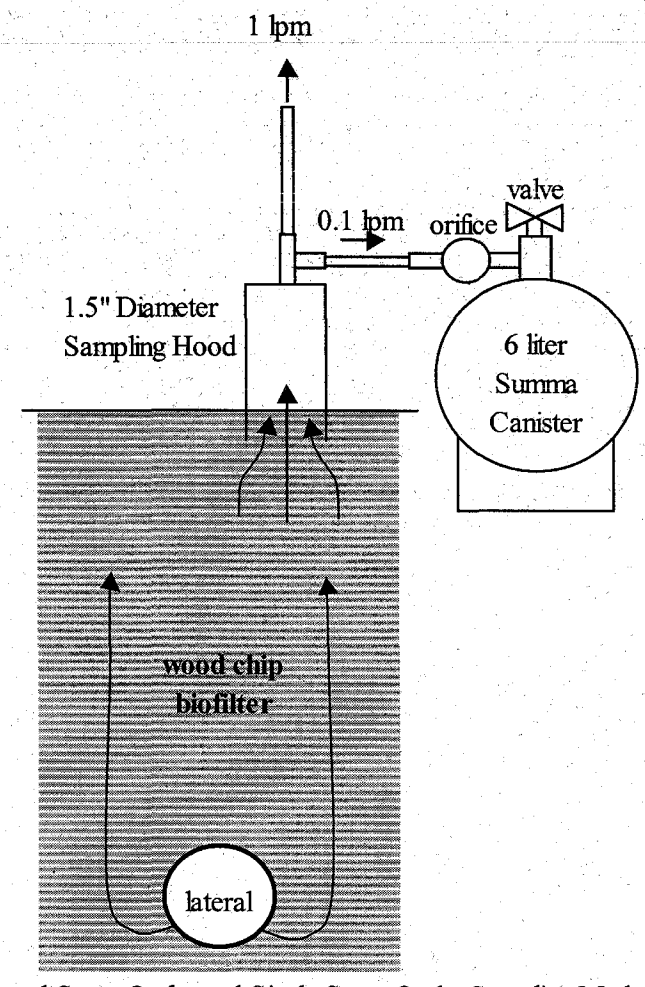


Figure 3.4 Sampling Network for Monitoring CO2, VOCs and H2S from Various Points In the System

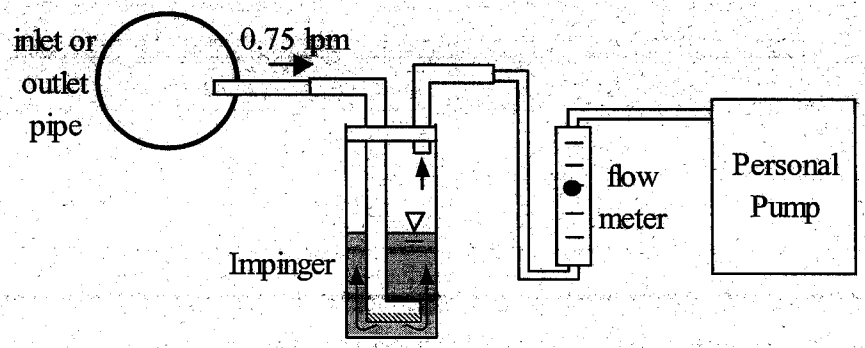


System Inlet and AGB Outlet Sampling Method

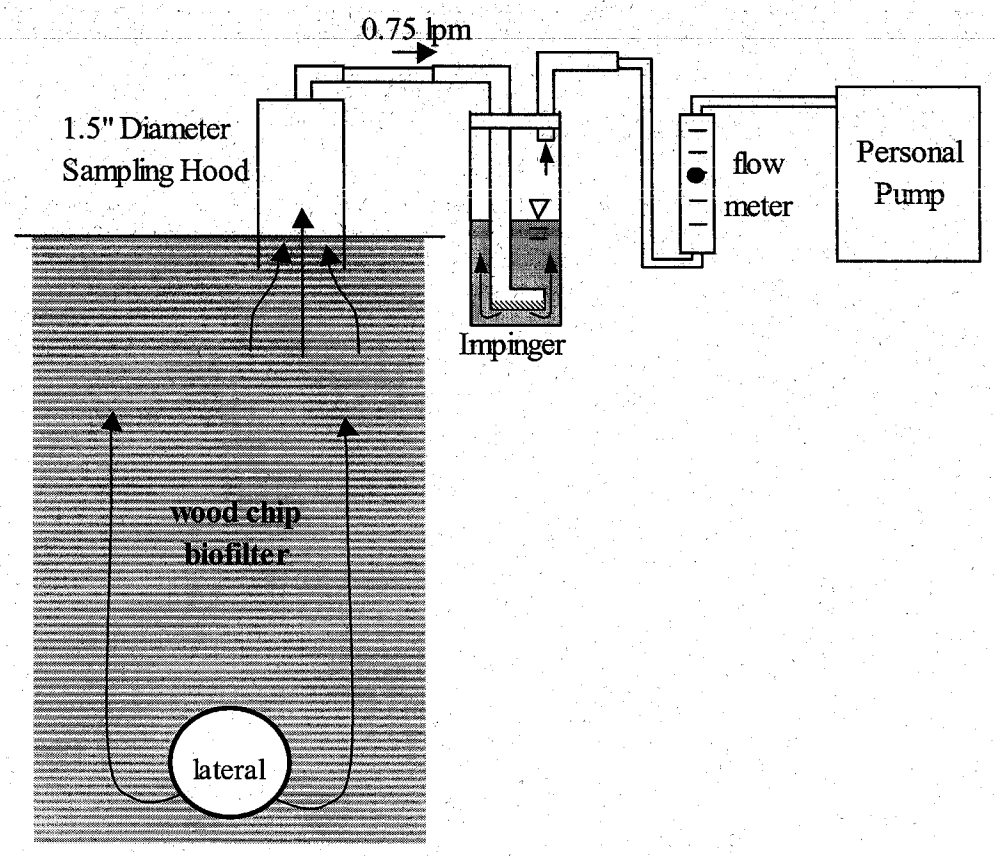


Second Stage Outlet and Single Stage Outlet Sampling Method

Figure 3.5 Schematic of sampling methods for EPA Method 18 and TO-14



System Inlet and AGB Outlet Sampling Method



Second Stage Outlet and Single Stage Outlet Sampling Method

Figure 3.6 Schematic of impinger sampling methods for EPA Method 308

4.0 LESSONS LEARNED FROM ANALYTICAL TESTING EXPERIENCE

Initially, air samples were analyzed by EPA Methods 8015 and 8240 at the suggestion of our analytical company. These methods are, in their original form, for water samples. The analytical company modified these methods for use with air samples. However, these methods were either not properly followed or the methods themselves are completely inappropriate. The results from the analytical company were consistently blank for all compounds though we were adding VOCs to the system and knew the inlet concentration to be on the order of 1 ppm for each contaminant added. Samples were collected in Tedlar bags, which is a commonly employed sampling method. Because of the relatively low concentrations, it is possible that some adsorption to the walls occurred. However, this was expected to have only a minor effect on the analytical results. After switching to EPA Methods 18 (for Isopentane and methanol), and TO-14 for the remaining VOCs, results obtained were on the order expected for most compounds. However, problems persisted with analysis of methanol and isopentane.

The detection limit for isopentane and methanol by EPA Method 18 is 0.2 ppmv. Therefore, with a design inlet concentration of 1 ppmv for isopentane, the maximum measurable removal efficiency (R.E.) was 80%. The expected R.E. was only about 50% (Figure 5.3). However, when the actual inlet concentration was less than the design, problems did occur. In fact, in the first sampling event, the inlet concentration was only 390 ppbv. Therefore, our analytical company attempted a concentration procedure to decrease the detection limit. This was effective for isopentane. However, methanol was not detected in these samples. Apparently, the concentration system caused water droplets to form. Because methanol is miscible in water, the methanol completely dissolved in the water.

In an attempt to obtain reasonable results for methanol, EPA Method 308 was implemented. After initial attempts to trap methanol on silica gel failed, an impinger method was used to trap methanol (as discussed in the methods section). The method proved to be effective, and it was used until the completion of the project.

It is difficult to reconcile the variability of the data. After the first few sampling events, there is no indication of analytical error. The analytical companies we used were diligent to run laboratory blanks and calibration standards in a timely manner. We suspected that variability in the data occurred because of fluctuations in the inlet concentration. The contaminant addition system described previously was susceptible to fluctuations with change of temperature. During sampling the system was watched carefully to minimize these fluctuations, but they could not be eliminated.

In summary, it appears that the use of summa canisters and TO-14 was an effective method for obtaining representative samples of most of the biofilter contaminant concentrations in this study. Contaminants that have a very high solubility in water should be collected in water using an impinger method. EPA Method 18 is effective for analyzing isopentane and other common components of gasoline, but difficulties arise from the high detection limit.

5.0 RESULTS AND DISCUSSION

VOC removal efficiency (R.E.) for the AGB alone and the two-stage biofilter are compared with the R.E. of the single stage biofilter in Tables 5.1 and 5.2 and also in Figures 5.1, 5.2 and 5.3. Hydrogen sulfide removal efficiency is presented in Figure 5.5.

Removal efficiency in the biofilters is both a function of the biofilter's empty bed residence time (EBRT) and the acclimation period of the biofilter. In AGB removal efficiency is relatively poor in Phase 1 with an EBRT=32.6 seconds in comparison to Phase 2 (EBRT=22.2 sec). Some compounds (e.g. methylene chloride and chloroform) have removal efficiencies greater in Phase 3 (EBRT=12.1 sec) than in Phase 1. Clearly the biofilter ecosystem was developing and was not at steady-state during the demonstration.

Slow development of the culture may be a result of the acidic conditions. Sampling was not initiated until the leachate pH was approximately 4. Throughout the study the leachate pH was approximately constant accept during periods of system upset. Under acidic conditions heterotrophs, responsible for consuming VOCs, may have been stressed. Consequently, degradation of complex compounds was expected to be suppressed. However, removal efficiency for all but the aromatics was in the range expected (Compare Predicted R.E. in Table 3.2 with the results in Table 5.4). Aromatics may have been poorly removed because of their relatively low solubility in water, the complexity of their structure may have inhibited degradation, and transfer rate limitation especially in Phase 3.

The results were used to predict the treatment that would occur at an EBRT of 60 sec. The calculation was done by assuming an exponential decline in concentration as describe in the model of Hodge and Devinny (1995).

$$R.E. = \exp(-bK_m EBRT) \times 100\%$$

where bK_m is the product of the biological degradation coefficient and the contaminant air-to-liquid mass partitioning coefficient. The constant bK_m was derived for each average efficiency, and used to calculate the expected treatment efficiency at an EBRT of 60 sec. Results are shown in Table 5.3. The results from Phase 1 were much lower than for Phase 2 and 3. However the data were also highly variable and should be viewed with caution. In general, the results of the model predict very good removal efficiency for most compounds. Interesting, methylene chloride, chloroform, and MtBE each have a trend of increasing removal with respect to time. This indicates that the microbial culture was adapting for these compounds even towards the end of the project.

The two-stage biofilter had results similar to the AGB alone. The first stage (the AGB) effectively removed a majority of the H_2S (Figure 5.5) from the air stream, preventing acidification of the wood chip medium. The lower section of the single stage biofilter experienced very low pH conditions (Table 5.6), which presumably will enhance the degradation of the medium.

The second stage of the two-stage biofilter only modestly increased the removal efficiency of the biofilter system. This may have been a factor of the medium chosen. The wood chips were relatively large, limiting the surface area on which VOC-degrading microbes live. Pulse tests indicated that the porosity of the medium was low (~30%), thereby limiting the passage way of the air and decreasing the actual contact time of the air in the medium. Wood chips were chosen because of their size. POTWs have experienced difficulties with the use of compost in acidic conditions (Reyes, 1998). Large wood chips were expected to have greater longevity and reduced head loss across the medium.

The results given and the results from the model assuming 60 second detention time indicate that adequate removal may be accomplished by a single low-pH biofilter with an inert medium such as lava rock. Specification of lava rock is straight forward and it can be sieved to any required size. Compost and wood chips are difficult to specify by a design engineer because there are too many variables and there is no standard classification system. This alone has led many engineers to not use biofilters at POTWs and other applications (Stevenson, 1999).

Table 5.1 **Removal efficiency in Acid Gas Biofilter during the project. Each value for the AGB is an average of three samples. Results for the single-stage biofilter are an average of nine values**

	R.E. for AGB at EBRT of 32.6 sec	R.E. for AGB at EBRT of 22.2 sec	R.E. for AGB at EBRT of 12.1 sec	R.E. for Single-Stage Biofilter Average
Methylene Chloride	30.3%	27.5%	39.1%	51.8%
Chloroform	14.4%	40.8%	32.3%	27.8%
Toluene	60.4%	91.5%	56.9%	71.4%
Ethylbenzene	45.3%	65.6%	39.9%	59.7%
m- & p- Xylenes	33.9%	84.1%	40.8%	61.2%
o- Xylenes	44.0%	84.2%	41.4%	56.1%
Acetone	82.2%	99.3%	79.4%	98.0%
MtBE	19.8%	51.4%	52.1%	46.8%
Methanol	96.2%	81.5%	84.8%	97.3%
Isopentane	42.6%	37.4%	65.4%	63.5%

Table 5.2 **Removal efficiency in the two-stage biofilter during the project. Each value for the two-stage system is an average of three samples. Results for the single-stage biofilter are an average of nine values**

	Phase 1 (3 Tanks)	Phase 2 (2 Tanks)	Phase 3 (1 Tank)	R.E. for Single-Stage Biofilter Average
Methylene Chloride	51.5%	26.6%	56.4%	51.8%
Chloroform	14.2%	35.4%	51.4%	27.8%
Toluene	54.4%	92.1%	59.1%	71.4%
Ethylbenzene	56.4%	97.6%	55.1%	59.7%
m- & p-Xylenes	49.7%	92.6%	45.2%	61.2%
o- Xylenes	55.6%	87.2%	46.9%	56.1%
Acetone	92.5%	99.3%	99.5%	98.0%
MtBE	20.2%	45.2%	54.7%	46.8%
Methanol	96.2%	81%	99.0%	97.3%
Isopentane	79.2%	41.1%	78.4%	63.5%

Table 5.3 Predicted percent removal efficiency in AGB if EBRT was 60 sec.

	Predicted % R.E. at EBRT=60, Data from Phase 1	Predicted % R.E. at EBRT=60, Data from Phase 2	Predicted % R.E. at EBRT=60, Data from Phase 3
Methylene Chloride	33.7	64.0	91.2
Chloroform	28.1	76.7	86.4
Toluene	80.6	99.8	95.6
Ethylbenzene	64.9	93.1	90.9
m- & p-Xylenes	44.1	99.2	86.1
o- Xylenes	68.7	99.2	91.4
Acetone	99.4	100.0	99.3
MtBE	27.4	86.9	95.9
Methanol	99.9	98.8	99.9
Isopentane	92.2	72.2	95.4

Table 5.4 pH of wood chip medium at end of project. Bottom samples are nearest the inlet. Lateral 12 is the control. Lateral 13 is the single-stage biofilter and lateral 14 is the second stage of the two-stage biofilter

	Lateral 12	Lateral 13	Lateral 14
3 feet above bottom	7.83	8.02	8.01
2 feet above bottom	7.53	8.02	7.98
1 foot above bottom	7.54	7.84	8.14
Bottom	7.44	2.49	7.89

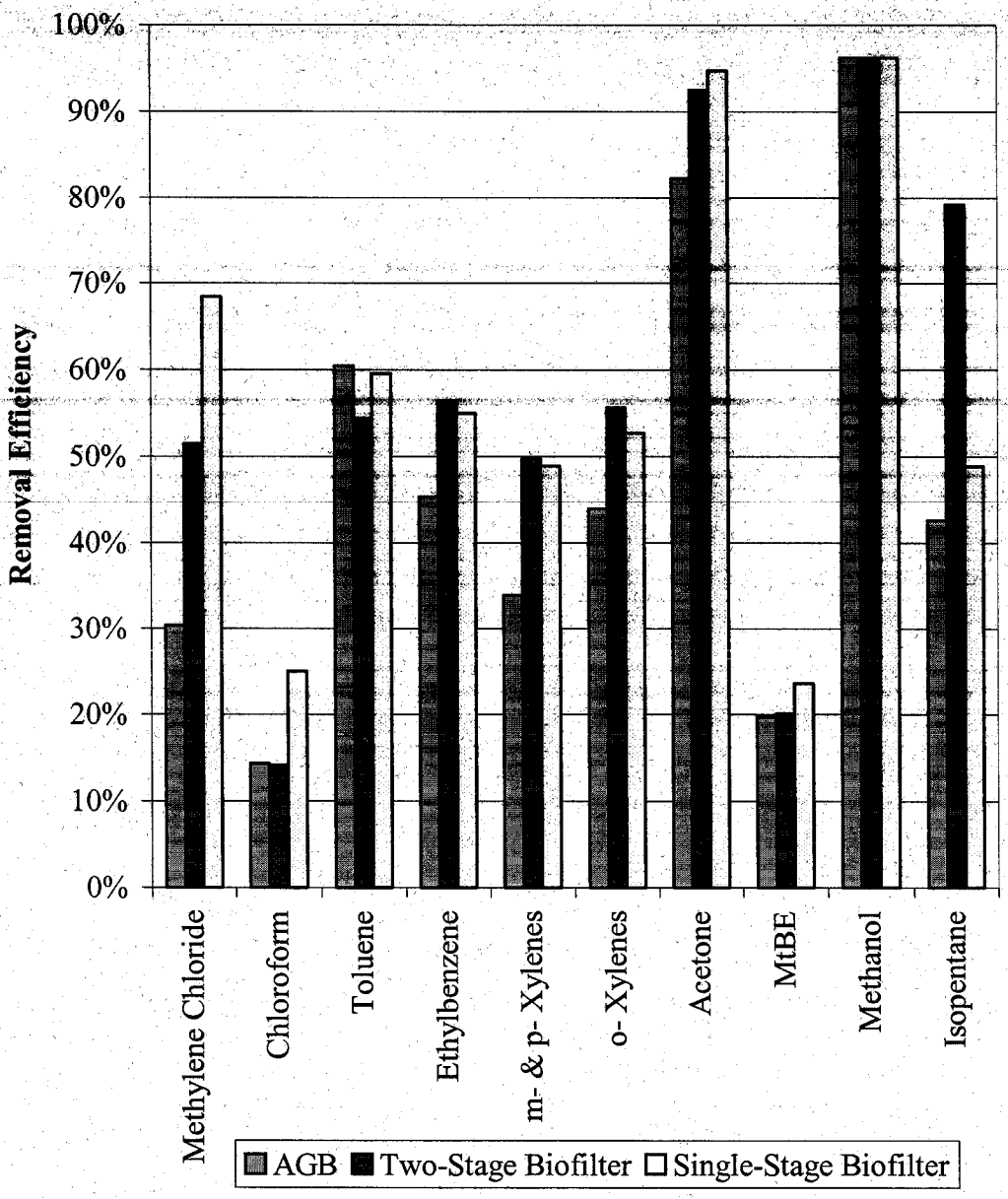


Figure 5.1 **Removal efficiency of organic contaminants in biofilters during Phase 1 of the demonstration.**

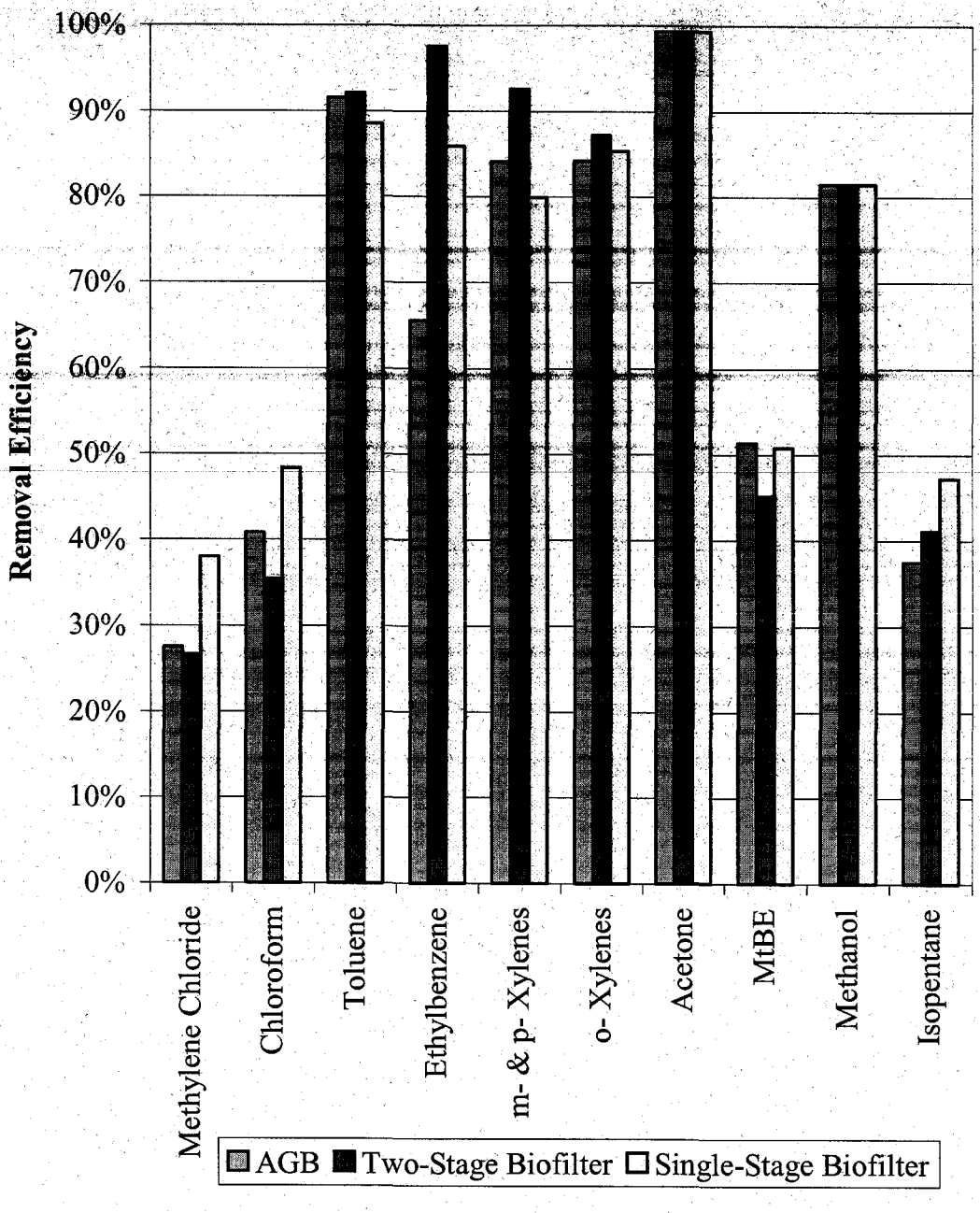


Figure 5.2 **Removal efficiency of organic contaminants in biofilters during Phase 2 of the demonstration.**

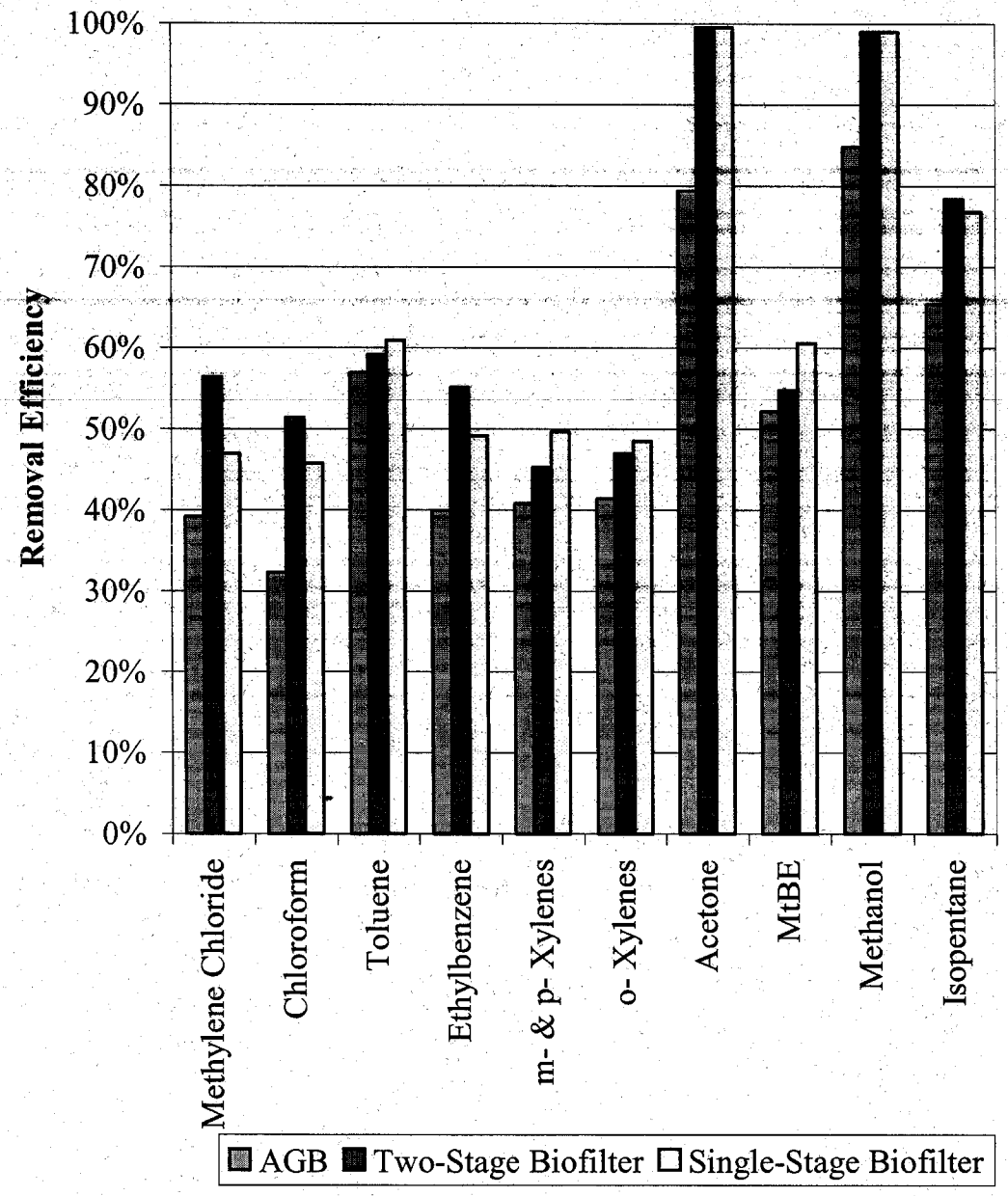


Figure 5.3 **Removal efficiency of organic contaminants in biofilters during Phase 3 of the demonstration.**

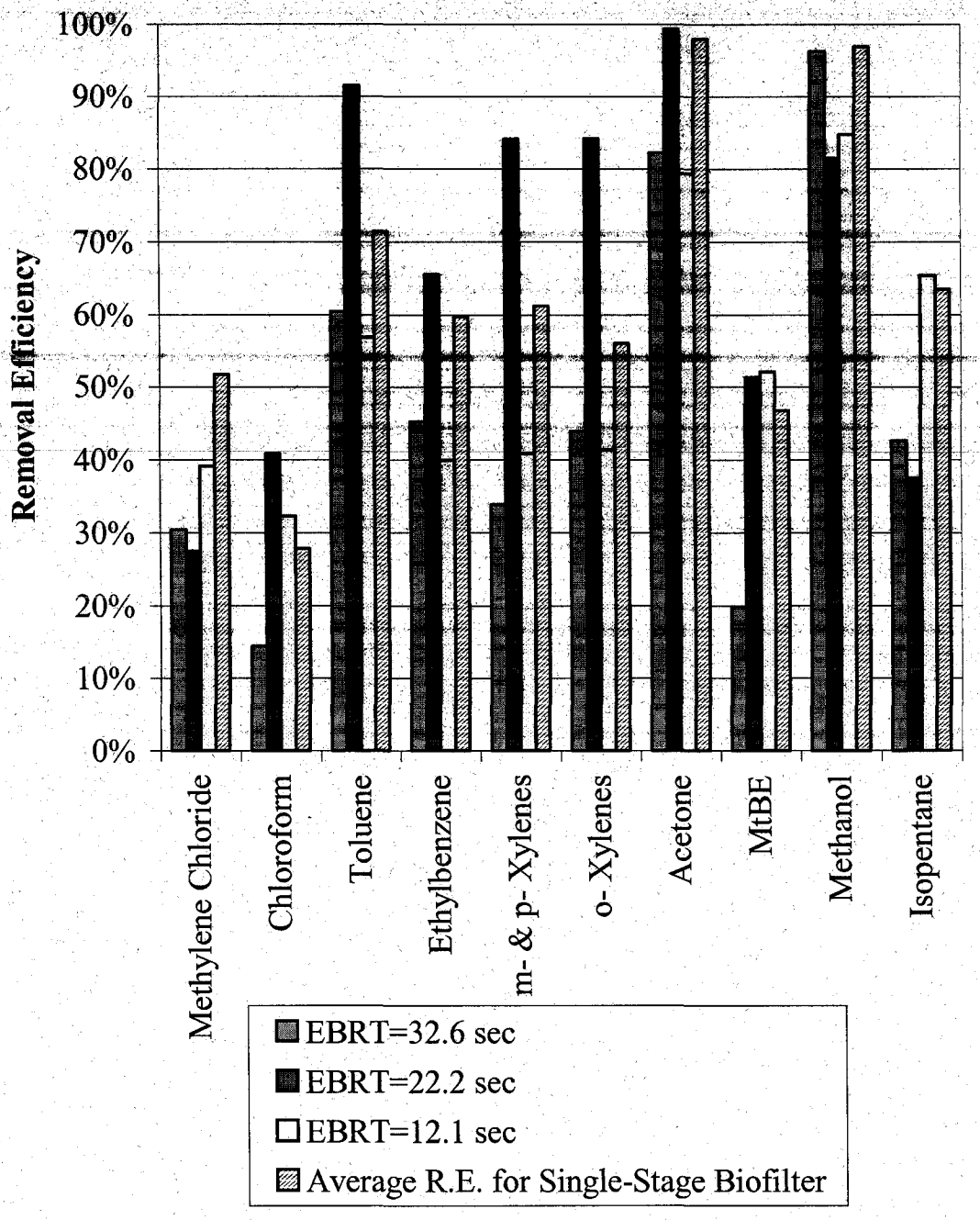


Figure 5.4 **Removal efficiency of organic contaminants in AGB during the demonstration in comparison to the average removal in the single stage biofilter.**

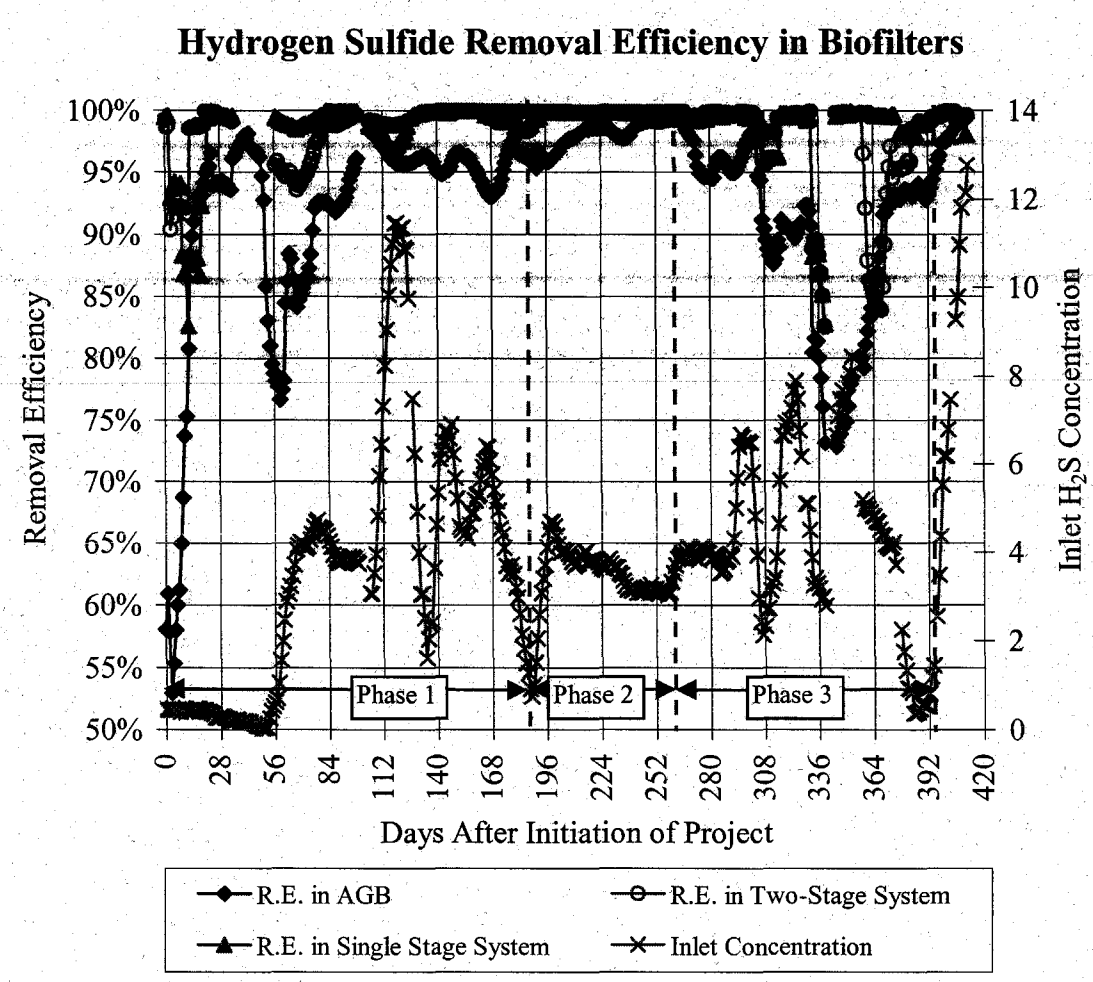


Figure 5.5 **Hydrogen sulfide removal efficiency and inlet sulfide concentration during the demonstration.**

6.0 DISCUSSION REGARDING BIOLOGICAL ACTIVITY

When a claim that biological activity is actually taking place, it must be supported by facts.

- The removal efficiencies discussed above could only be accounted for by microbial activity.

- Lava rock has a very small surface area (2.5 cm^2/g) compared with activated carbon, which has a surface area on the order of 1000 m^2/g. Adsorption onto the lava rock is expected to be negligible.

- The water volume in the biofilter is too small to account for removal of contaminants. For example the H_2S in the air would reach equilibrium with H_2S in water in 19 minutes at the operation flowrates and inlet concentrations. Abiotic degradation of H_2S is not expected, therefore efficiency would fall to zero in a matter of minutes if microbes were not continuously degrading the contaminants.

- Decrease in pH of leachate as a function of time (hydrogen sulfide oxidized to sulfuric acid) and increase in weight of AGB Tank 1 until pH reached approximately 4 (Figure 6.1). At this low pH level, the weight stayed essentially constant.

- Lava Rock samples obtained at various depths indicate that the volume of water on the medium stayed essentially the same during the study (Figure 6.2), however, the volume of biomass increased over time (Figure 6.3).

- Scanning Electron Microscope (SEM) images demonstrate a thick biofilm developed on the lava rock medium (Figure 6.4 and 6.5) even at low pH encountered on the rock. Active microbes were abundant on the rock (Figure 6.6).

- The effectiveness of biological activity in biofilters has been generally accepted by the scientific community for many years (Appendix A – References).

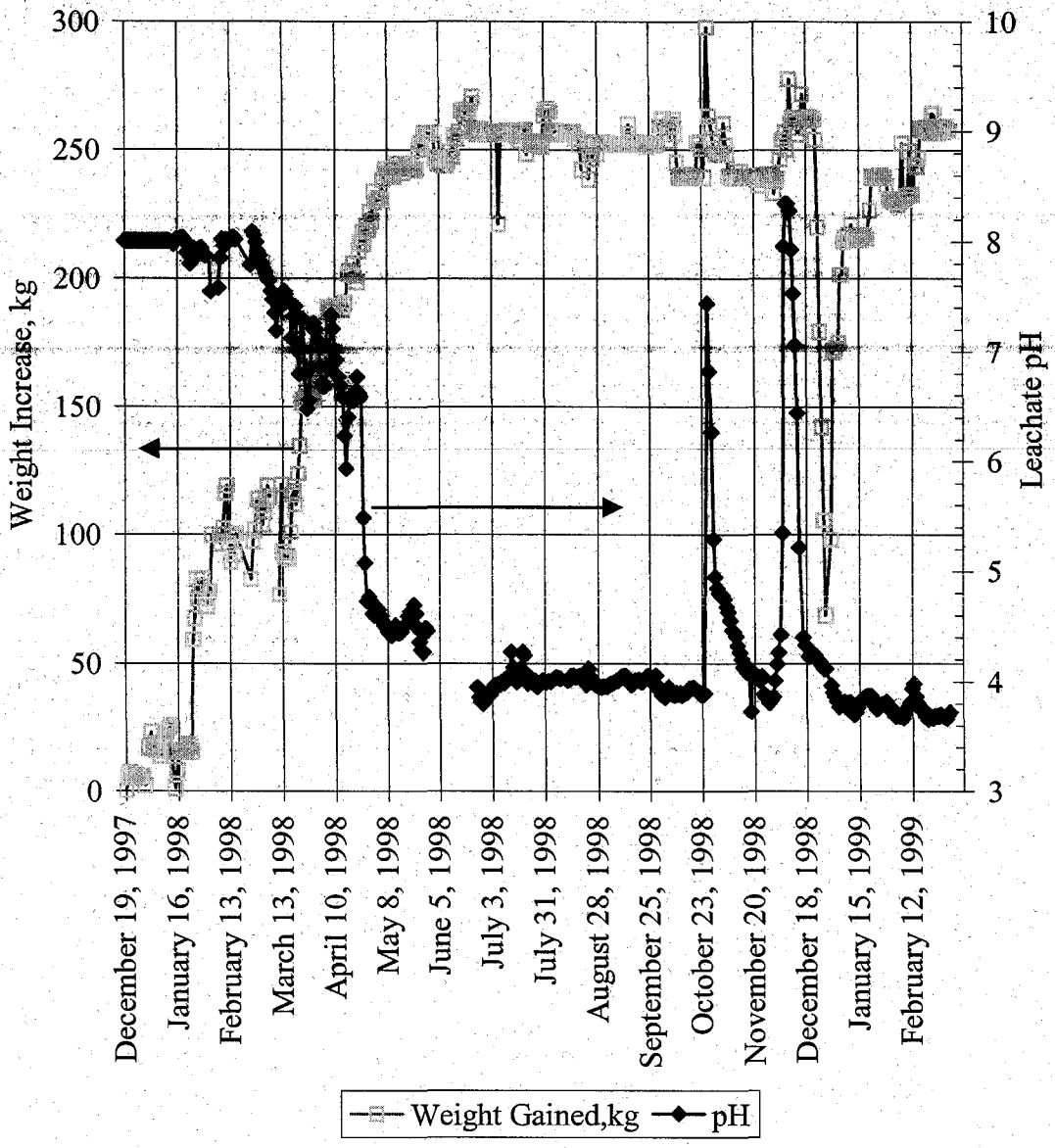


Figure 6.1 **Weight gained and leachate pH as a function of time. Low pH suppressed production of biofilm, therefore weight stayed constant when the pH was less than 4.**

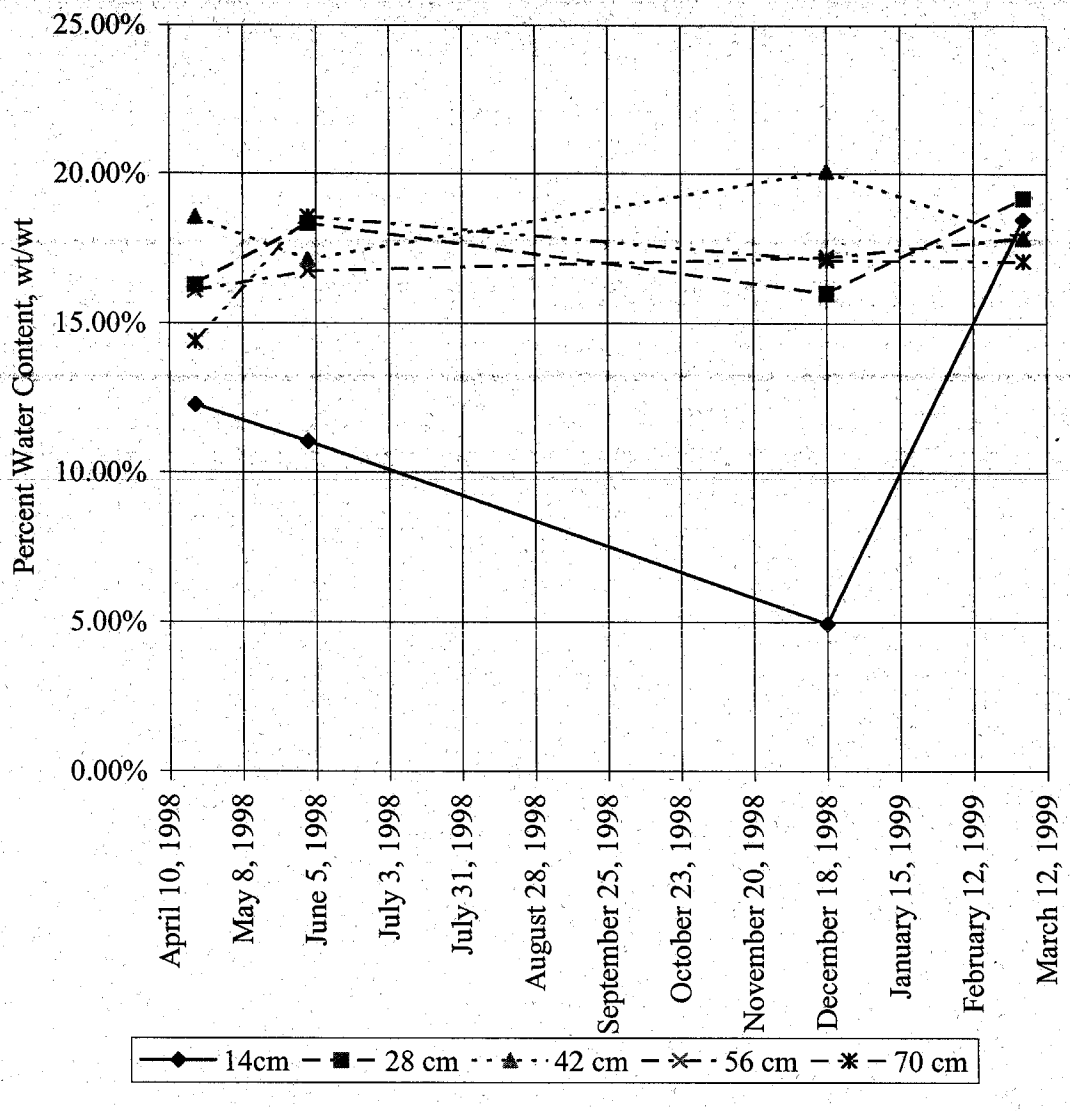


Figure 6.2 **Water content on lava rock medium at various depths in AGB. The water content essential was constant at most depths. Fluctuation in the top part of medium occurred because of inadequate humidification of the inlet air.**

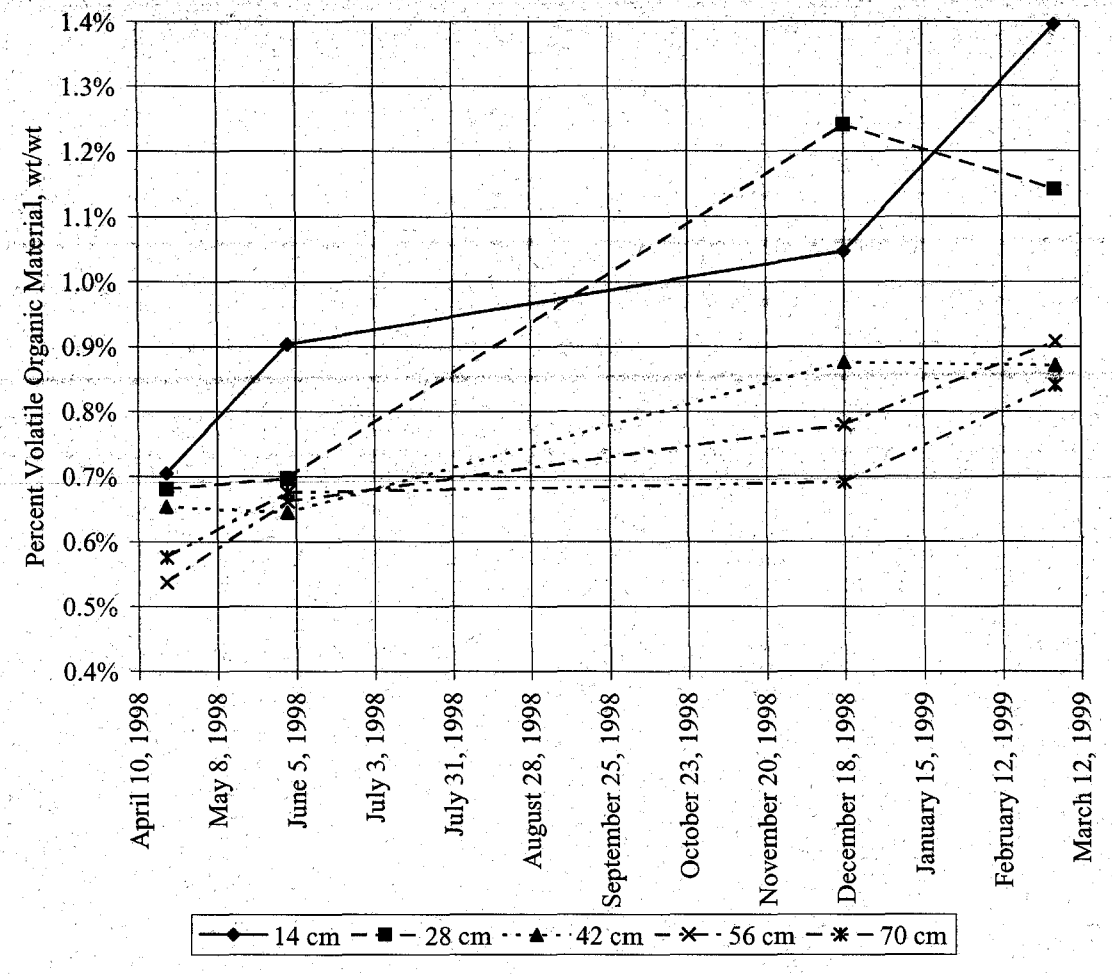


Figure 6.3 **Volatile organic content on lava rock medium at various depths in AGB. Predominant amount of organic material was at the top of the medium near the inlet.**

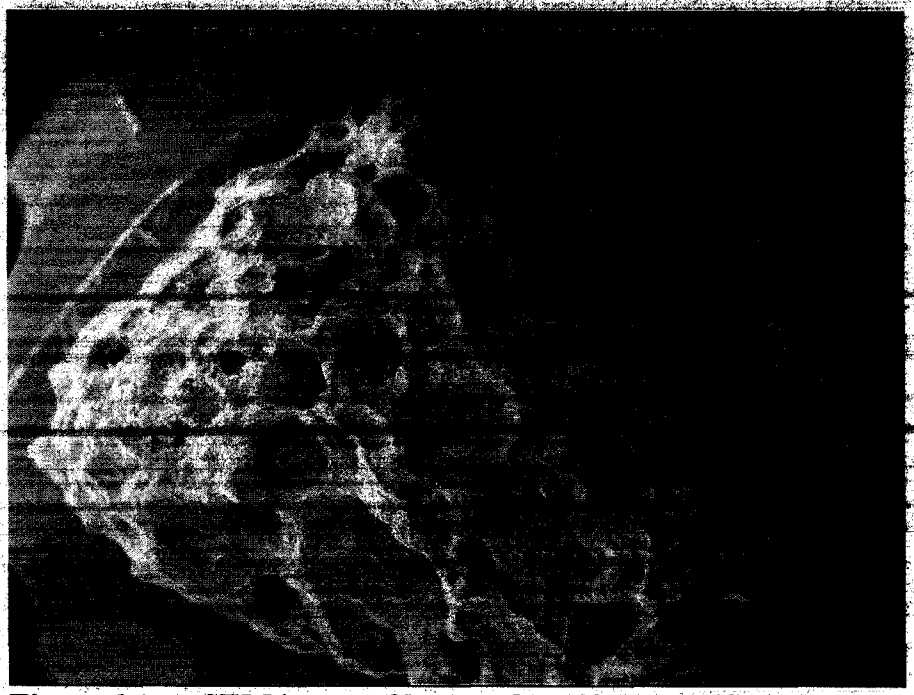


Figure 6.4 **SEM image of lava rock at 12.4 magnification. Rock was covered with a white biofilm. Approximate size of rock is 10 mm (0.4 inches) across.**

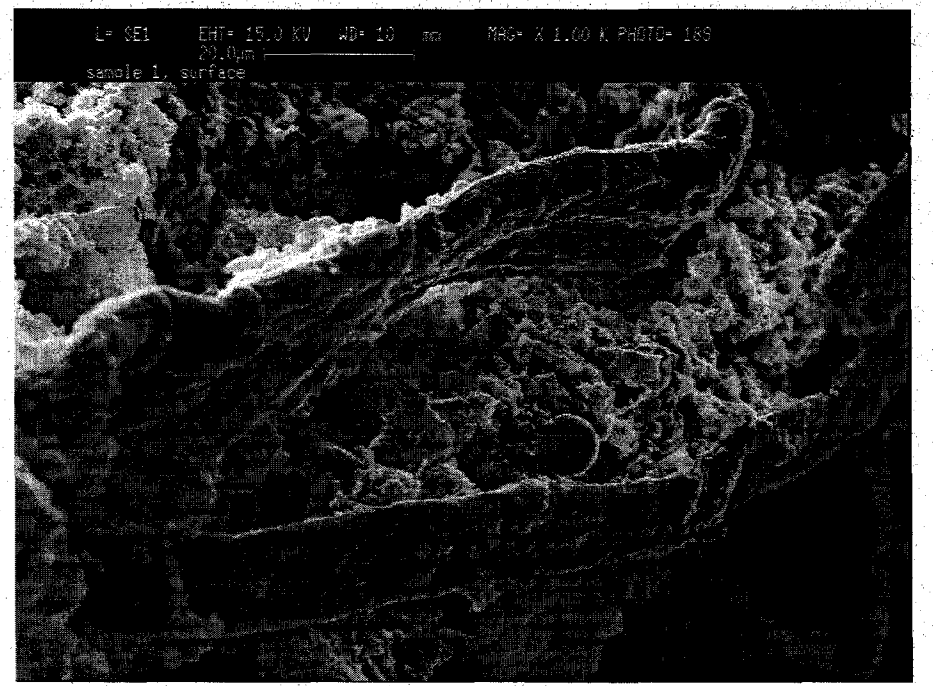


Figure 6.5 **SEM image of the edge of the lava rock at 1000 magnification. White material is biomass (most of it is not living) with some cocci microbes.**

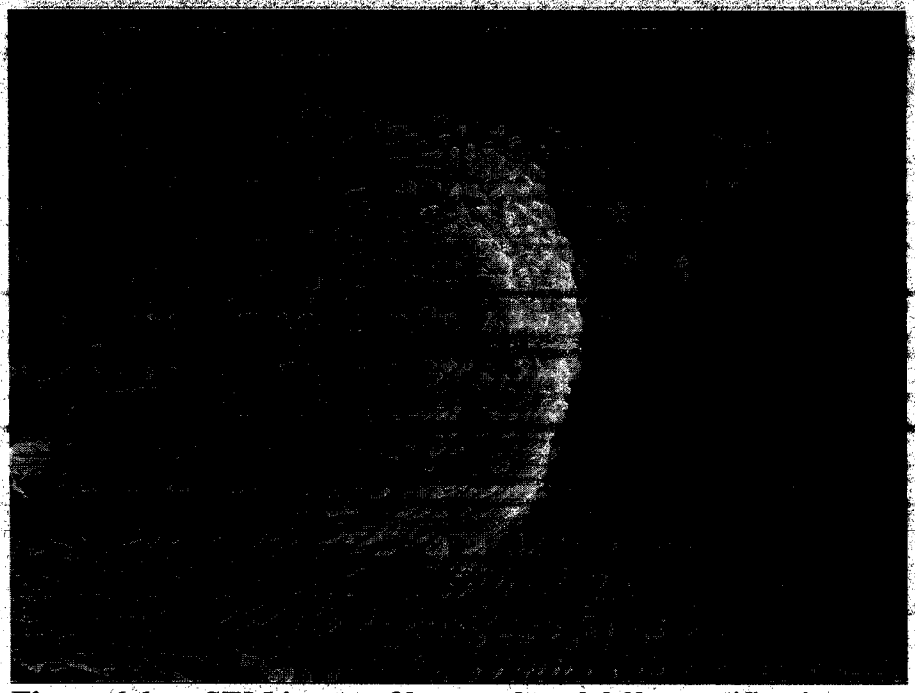


Figure 6.6 **SEM image of lava rock at 2,260 magnification. Rod shaped microbes were abundant on the lava rock as can be seen in this image. The pH of the biofilm on this rock was approximately 4.**

7.0 ENVIRONMENTAL IMPACT ASSESSMENT

Biological treatment of air pollutants is appealing because biofilters are a benign and environmentally friendly technology. The primary barrier to adoption of biofilter technology at POTW's and other applications is the lack of operating experience. Plant managers are understandably reluctant to adopt new systems without a successful track record. Even the California Air Resources Board (CARB) was initially hesitant to support a non-mechanical or non-chemical system of treating air pollutants.

Emissions of foul smelling hydrogen sulfide gas (H_2S), mercaptans, and other compounds have generated complaints from nearby residents. These complaints grow more serious as increasing development puts more homes near treatment plants. Recently, there has been talk at the United States Environmental Protection Agency that H_2S may be regulated.

The market for biofilters at POTW's is potentially huge and is a small fraction (10%) of the overall market for biofilters. Conventional treatment of odors using chlorine scrubbers is a hazardous process that is chemical intensive. A biofilter can immediately replace a chlorine scrubber system. If a POTW plant operator is afraid to rely entirely upon a biofilter, the chlorine scrubber system (already a sunk cost) can be started and used to treat the odors as a back up system.

Volatile organic compounds (VOCs) such as benzene and trichloroethylene are found in wastewater flows as a result of illegal dumping. Venting of air spaces, and particularly aerobic biological treatment release these compounds into the atmosphere. While concentrations are generally not high, the large amounts of water handled by POTW's means that total emissions can be significant.

The environmental benefits of the biofilter for POTW discharges includes reducing odors, neighborhood exposure to toxic chemicals, and generation of smog precursors.

The potential benefits of adoption of a dual stage biofilter at publicly owned treatment works are as follows:

(a) Economic Benefits: Economic benefits will accrue first to sanitary districts in California, which will have an inexpensive means of meeting their regulatory responsibilities. Industry will benefit as more installations are made, providing employment for engineers, contractors, and operators. Cost savings will accrue to the taxpayers of the State of California due to lower costs for treating foul vapors in the form of lower municipal bond costs. Based on work market research performed by The Reynolds Group, saving per installation could amount to nearly $500,000 per installation at a POTW when compared to operating a chlorine based scrubbing system. For every biofilter that is constructed, two new jobs to California each year including design, permitting, construction, and operating aspects of the systems. Already, at least three new jobs have been created as a

result of this project. As California's cumulative experience in biofilters for POTW's accumulates, the opportunities for California based experts to export their knowledge to other states and countries around the world will grow. Already, The Reynolds Group has received tremendous technical interest from Mexico, specifically Baja California.

(b) Technical Benefits: Biofilters are a superior alternative to conventional methods of treatment such as burning (oxidation) where fuel costs are high, absorption where contaminants are simply transferred from the air to another medium (such as carbon), and chemical processes that consume large amounts of chemicals and generate another disposal problem.

(c) Environmental Benefits: Biofilters are benign air pollution control devices that use biological means to treat contaminated air streams. The filter medium is generally very inexpensive and available. When the biofilter has run through its useful life, it can be disposed without any special considerations. Biofilters for POTW's are clean, "green" and socially/politically acceptable.

Emissions from wastewater treatment plants are identified as significant air pollution sources. The POTW cannot relocate, and has only partial control over the composition of wastewater it receives. The amounts of air to be treated are substantial. Regulation and control of this pollution source will succeed when a technically feasible, economically viable technology like the dual stage biofilter that succeeded in this project is commercially.

8.0 TECHNOLOGY TRANSFER

In order to accelerate the expansion of biofiltration to end users, The Reynolds Group has continued to underwrite, fund and manage several efforts aimed at technology transfer.

The Reynolds Group has invested in the construction and implementation of an internet web site that contains a section for biofiltration and will soon contain links to other biofiltration web sites. The web site contains a very simple inquiry system so that potential customers may contact The Reynolds Group directly when the have a potential application. When biofiltration is searched on the World Wide Web, The Reynolds Group's biofiltration capabilities are often found. Currently, approximately six new leads per month are being generated through the web site.

As a result of the heightened interest in The Reynolds Group's biofilter capabilities, The Reynolds Group has employed a full time business development representative to respond to and address potential customers' specific biofiltration needs. Because of the broad range of biofilter applications for industry, a particular client requires special attention be directed at the specific effluent application. As a result, there is a growing demand on the business development representative's time to explain and describe the biofilter application.

The Reynolds Group has proposed several pilot scale demonstrations of biofilter applications. The California Air Resources Board was instrumental in introducing the firm to the Louisiana Pulp and Paper Company in Humboldt County, California. As a result of that meeting, The Reynolds Group has advanced its understanding of the H_2S problems at pulp and paper mills so that in the coming year there is a very good chance that additional biofilter pilot units might be demonstrated in the industry. Other pilot scale studies are in the negotiation phases.

During the ICAT contract-operating period, The Reynolds Group has invited numerous interested parties to visit and see the biofilter technology on site at the Ojai Valley Waste Water District. The grand opening of the wastewater plant expansion project was attended by more than 200 regulators, politicians, and environmental interest groups. Since then, many interested parties from other POTW's have visited the site to view for themselves the technology. Most recently, a team of POTW experts from Ensenada, Baja California, Mexico have visited the site to see for themselves if the biofilter technology that has been created here in California can be applied to control the severe odor problems in the state.

Every other year, The Reynolds Group in conjunction with the University of Southern California sponsors a Conference on Biofiltration. Every other year the leading researchers, vendors, and users of biofilters gather in Los Angeles to discuss the latest issues regarding biofilters. As a result of the last conference there was a move afoot to start a Society of Biofiltration and a committee was formed to establish the society.

In addition to the above efforts at technology transfer, the following papers have been presented at various technical conferences:

- Derek Chitwood and Joe Devinny have been invited to present a paper entitled "Two Stage Biofiltration of Sulfides and VOCs from Wastewater Treatment Plants" at the IAWQ International Specialty Conference of the Chemical Industry Group, Waste Minimization and End of Pipe Treatment in Chemical and Petrochemical Industries, Merida, Yucatan, Mexico.

- Derek Chitwood and Joe Devinny have submitted a technical paper entitled Co-Treatment of VOCs in Low-pH Sulfide Biofilters for presentation at the Air & Waste Management Association 92nd Annual Meeting & Exhibition, June 20-24, 1999 in St. Louis, Missouri

- Derek Chitwood, Joe Devinny, and Ed Reynolds presented a technical paper entitled Two Stage Biofiltration for Wastewater Treatment of Off-Gases for presentation at the Air & Waste Management Association 92nd Annual Meeting & Exhibition, June 14-18, 1999 in San Diego, California

- Derek Chitwood and Joe Devinny presented a technical paper entitled "Flow Heterogneity in Low Head Loss Biofilter Media" to the October, 1998 Conference on Biofiltration that was held Los Angeles, California and that was sponsored by The Reynolds Group and the University of Southern California.

One of the major contributors to the transfer of this technology will be the support and credence lent to the project by the CARB. The Reynolds Group will work with the CARB to promote and accelerate this technology into the market place.

9.0 CONCLUSIONS AND RECOMMENDATIONS

This report has summarized the year long full scale demonstration of the two-stage biofilter at the Ojai Valley Sanitary District's newly modernized POTW. Topics presented in this report included a description of the demonstration, the sampling methods, and the results. The conclusions of this project are that:

h) a lava rock pre-stage biofilter can be a very effective means of removing H_2S and VOCs from the waste air flow stream at a POTW or other facility where H_2S is a component of the effluent,

i) the low pH biofilter can effectively treat H_2S emissions at contact times as low as 12 seconds, which means that the pre-treatment unit can be sized very small and that current compost based biofilters may be over designed,

j) lowering the pH in the first stage of the biofilter neutralized the pH in the second stage of the biofilter resulting in longer life of the second bed,

k) lava rock provides an excellent medium for a low pH biofilter,

l) VOCs can be removed in the low pH biofilter,

m) internet based instrumentation and software that can monitor and control the performance of the biofilter from remote locations have serious implications for the business model that will successfully compete in the industry, and

n) traditional problems associated with biofilters including acidification, flow heterogeneity, and measurement can be resolved with proper design and sufficient operating experience.

The Reynolds Group recommends that biofilter technology for treatment of air streams at POTW's be certified by the Office of Environmental Technology of the State of California Air Resources Board.

APPENDIX A

REFERENCES

REFERENCES

Choi, D. S., T. S. Webster, et al. (1996). Quantitative structure-activity relationships for biofiltration of volatile organic compounds,. Proceedings of the 1996 Conference on Biofiltration (an Air Pollution Control Technology), The Reynolds Group, Tustin, CA.

Ergas, S. J., E. D. Schroeder, et al. (1995). "Control of Volatile Organic-Compound Emissions Using a Compost Biofilter." Water Environment Research **67**(5): 816-821.

Hach (1992). Hach Water Analysis Handbook 2nd Edition.

Harrison, J., A.P. (1984). "The Acidophilic Thiobacilli and Other Acidophilic Bacteria that Share Their Habitat." Annual Review of Microbiology **38**: 265-292.

Hodge, D. S. (1993). Biofiltration: Application of Treatment of Ethanol Vapors. Environmental Engineering Program. Los Angeles, CA, University of Southern California: 1993.

Hodge, D. S. and J. S. Devinny (1995). "Modeling Removal of Air Contaminants By Biofiltration." Journal of Environmental Engineering-Asce **121**(1): 21-32.

Montgomery, J. H. (1996). Groundwater Chemical Desk Reference, 2nd Edition. Chelsea, Michigan, Lewis Publishers, Inc.

Morton, R. L. and R. C. Caballero (1997). Removing Hydrogen Sulfide from Wastewater Treatment Facilities' Air Process Streams with a Biotrickling Filter. Proceedings of the 90th Annual Meeting & Exhibition of the Air & Waste Management Association,, Toronto, Ontario, Canada.

Reyes, C. (1998). Personal Communication: Carlos Reyes, Associate Engineer, Rancho Las Virgenes Municipal Water District, CA.

Standard Methods (1995). Standard Methods for the Examination of Water and Wastewater, 19th Edition.

Stevenson, R. (1999). Personal Communication: Roger Stevenson, Principle Engineer, Montgomery-Watson, Pasadena, CA.

Webster, T. S. (1996). Control of Air Emissions from Publicly Owned Treatment Works Using Biological Filtration. Environmental Engineering Program. Los Angeles, California, University of Southern California.

Yang, Y. H. and E. R. Allen (1994). "Biofiltration Control of Hydrogen-Sulfide .1. Design and Operational Parameters." Journal of the Air & Waste Management Association **44**(7): 863-868.

APPENDIX B

RAW DATA

Table 1 Concentration values in parts per billion by volume from analytical company for Phase 1 of demonstration.

Phase 1

	06/02/98					06/25/98				07/16/98				
	AGB Inlet	Tank 1 Out	AGB Out	Second Out	Single Out	AGB Inlet	AGB Out	Second Out	Single Out	AGB Inlet	AGB Inlet (2)	AGB Out	Second Out	Single Out
Methylene Chloride	966	945	1050	1091	430	726	648	302	634	1749	1921	864	319	49.5
Chloroform	6.08	6.98	5	5	5	8.11	6.72	5	10.1	164	162	138	142	117.8
Toluene	894	410	934	638	358	122	72.7	15.6	18.2	687	642	182	112	303
Ethylbenzene	38.9	31.6	61.4	33.9	21	24.7	10.9	5	5	191	176	92.6	68.8	85.3
m- & p- Xylenes	121	138	298	119	68.6	72.1	62.5	5	30.46	828	759	452	372	405
o- Xylenes	43.6	28.3	47	33.4	21.5	41.1	22.1	5	7.75	303	282	161	129	149
Acetone	1066	107	761	60.9	33.5	160	241	45.5	42.4	1561	1438	136	98	68
MtBE	253	241	337	315	131	107	121	10	127	1366	1258	979	1010	1019
Methanol	5310	200	940	200	200	ND	ND	ND	ND	ND	ND	ND	ND	ND
Isopentane	390	200	300	200	200	253	422	33.4	381	513	493	35.6	5	5

Table 2 Concentration values in parts per billion by volume from analytical company for Phase 2 of demonstration.

Phase 2												
	08/29/98				09/04/98				09/29/98			
	AGB Inlet	AGB Out	Second Out	Single Out	AGB Inlet	AGB Out	Second Out	Single Out	AGB Inlet	AGB Out	Second Out	Single Out
Methylene Chloride	196	130	174	156	61	62	58	63	817	587	556	447
Chloroform	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	186	110	120	96
Toluene	379	23	23	28	337	45	45	27.5	941	73	63	135
Ethylbenzene	132	47	0.5	0.5	101	47	10	31	217	61	0.5	32
m- & p- Xylenes	113	17	12	16	89	18	23	23	420	64	11	86
o- Xylenes	113	23	16	15	113	22	16	15	210	24	24	34
Acetone	464	5	5	5	312	5	5	5	1424	5	5	5
MtBE	974	449	760	538	504	235	273	354	1384	707	536	515
Methanol	20	5	5	5	36	5	5	5	25	5	5	5
Isopentane	430	310	330	330	300	160	150	200	900	550	480	330

Table 3 **Concentration values in parts per billion by volume from analytical company for Phase 3 of demonstration.**

Phase 3										
	11/02/98				11/18/98				02/11/99	
	AGB Inlet	AGB Out	Second Out	Single Out	AGB Inlet	AGB Out	Second Out	Single Out	AGB Inlet	AGB Out
Methylene Chloride	1100	615	596	588	1816	1144	676	960	984	615
Chloroform	176	96	90	81	270.1	207	127	161	11	6.6
Toluene	943	267	197	196	728	467	486	457	1462	617
Ethylbenzene	148	53	63	53.6	378	276	173	214	208	112
m- & p- Xylenes	326	72	83	85	639	514	446	401	929	535
o- Xylenes	166	52	47	44	431	317	270	264	193	94
Acetone	1357	5	5	5	838	66	5	5	1569	705
MtBE	1268	643	655	684	1883	773	771	557	855	501
Methanol	1561	12	10	10	418	19	10	10	2973	723
Isopentane	650	360	420	380	3150	700	400	500	1000	600

APPENDIX C

TECHNICAL PAPERS