Demonstration of Biotrickling Filtration for Soil Vapor Extraction of Gasoline Compounds at Edwards AFB

Final Report Prepared for
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Acknowledgments

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1. EXECUTIVE SUMMARY

Biological treatment is an emerging technology for air pollution control. Two reactor types show the most promise as alternatives to physical and chemical treatments: biofilters and biotrickling filters. Biofilters have been used successfully for odor abatement and to a lesser extent for volatile organic compound control in industry for over several decades.[1] Waste air treatment using biotrickling filters is a newer but promising technique. In biotrickling filters, polluted air is passed together with a recycled liquid through a packed bed on which a pollutant-degrading biofilm develops. Compared to biofilters, biotrickling filters usually exhibit higher pollutant elimination capacities over a broader range of pollutants. This is because of the presence of a free trickling liquid phase which allows for better control of the operating conditions. For these reasons, biotrickling filters show good promise for cost effective treatment of exhaust air generated by soil vapor extraction.

Between the months of May and December 1999, biotrickling filtration field tests were conducted at Site 17, Edwards AFB. Site 17 is a former fueling station with reported releases of gasoline and jet fuels from underground storage tanks. The objective was to assess the feasibility of using biotrickling filters to treat exhaust air from soil vapor extraction/air sparging (SVE/AS) operations. The principal investigators for the project were the Dr. Deshusses (University of California, Riverside) and Dr. Devinny (University of Southern California). They were assisted by personnel from Earth Tech, Inc (Earth Tech) who were in charge of the SVE/AS operation and also provided assistance with the biotrickling filter.

The pilot/full-scale biotrickling filter used in this project was designed and constructed in 1996 under the supervision of Dr. Deshusses (UC Riverside). A schematic of the system setup is shown in Figure 1.1. The reactor included two side-by-side tanks constructed of 304 stainless steel, each with an internal diameter of 1.6 m (5 ft) and height of 3.4 m (10 ft). Each tank had a filter bed height of 2.1 m (7 ft), and was packed with a PVC structured packing (COOLdek™ PVC Munters 12060). The system was setup to treat an airflow of about 190-200 cfm (320 $m^3 h^{-1}$). The air passed in series through the two tanks. The bed volume per tank was 4.2 m^3 which resulted in a gas empty bed contact time of 47 seconds per tank. The system was highly automated and included a wide range of monitoring and automated controls. The latter proved to cause a number of problems under the harsh conditions encountered at Site 17, Edwards AFB.

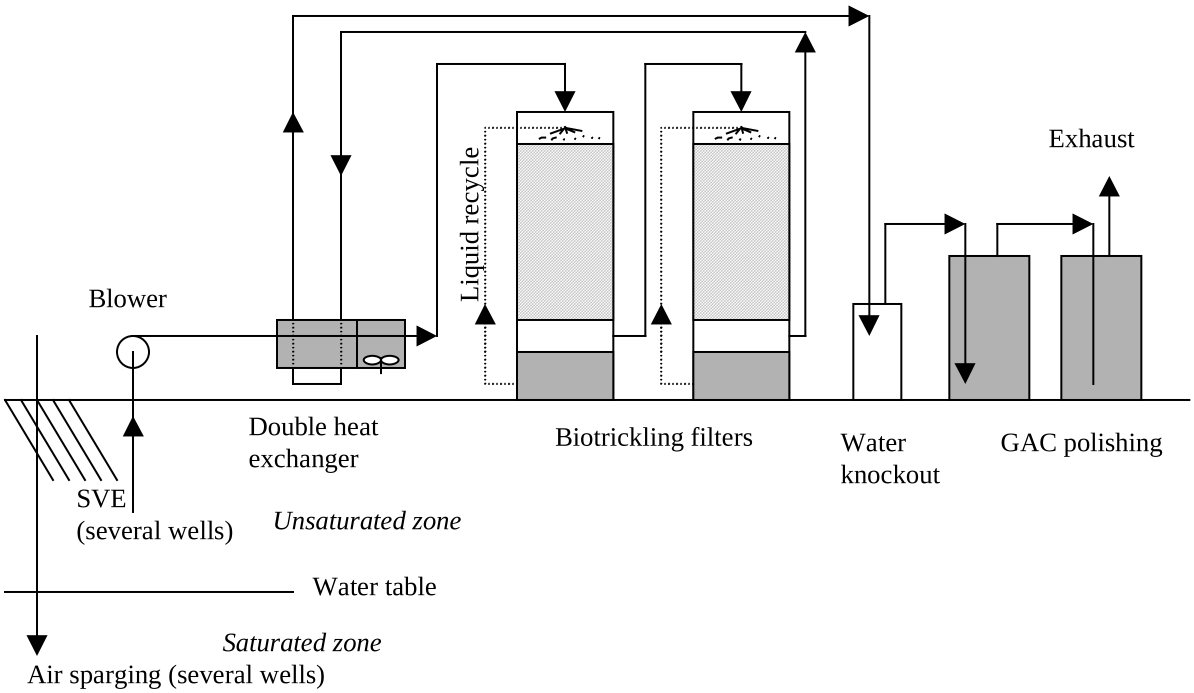


Figure 1.1 Schematic of the SVE/AS biotrickling filtration systems with GAC polishing unit installed at Site 17, Edwards AFB (not all details shown).

The operation of the biotrickling filter focused on monitoring inlet and outlet total petroleum hydrocarbon (THP) concentrations. The overall operation at Site 17 was characterized by an unusually high number of system upsets related for most part to the biotrickling filter control system. This affected the pollutant removal performance since the establishment of an effective population of hydrocarbon degraders is known to be greatly affected by periods without pollutant supply and by frequent on-off events. Hence, the full performance of the system was not reached during the project. When the biotrickling filter was operated for extended periods of time (more than 7-10 days) a gradual increase of the removal performance was observed.

Average TPH removal over the duration of the project is reported in Figure 1.2 and Table 1.1. The data show that only partial removal of the input TPH could be obtained. The data also reflect the improvement of pollutant removal over time during the project. Overall, the present study demonstrated that biotrickling filtration can degrade gasoline constituents, but that further testing will be required to determine to full extent of biotrickling filter capabilities. At concentrations of about 150-200 ppm, about 50-60 ppm could be removed at an empty bed contact time of 94 seconds, while at inlet concentrations of 40-70 ppm, about 50% of the influent contaminant could be degraded for the same contact time. At high concentrations (600-1200 ppm TPH), about 200 ppm could be removed, which corresponded to a removal of 4.0-5.4 kg (as hexane) per day, which is significant. However, as stated previously, we think that these performances are not representative of the maximum performance possible with biotrickling filters. Extensive testing was performed to find the causes of the lower than expected pollutant removal, and both mass transfer and nutrient limitations were ruled out. The most probable cause for low performance was that operation was interrupted by very frequent shutdowns and that relatively high temperatures prevailed in the trickling filter. These resulted in suboptimum conditions for the process culture and probably prevented the establishment of higher pollutant removal. Therefore, further testing would be needed to gather the necessary data to correctly size a biotrickling filter for the treatment of SVE/AS exhausts.

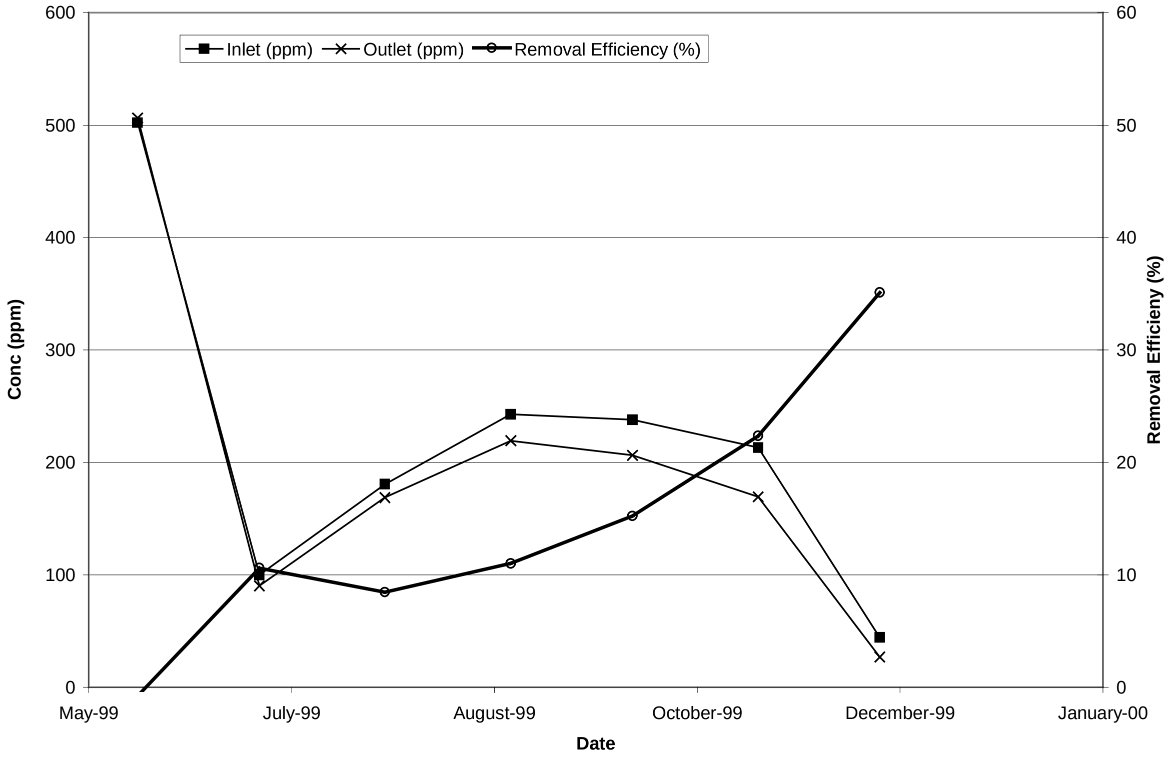


Figure 1.2 Monthly averages of the biotrickling filter performance (ppm as hexane).

Table 1.1 Monthly averages of the biotrickling filter performance (ppm as hexane).

	Number of samples	Inlet conc. (ppm)	Outlet conc. (ppm)	Removal Efficiency (%)	Daily mass removed (g/day)
Jun-99	2	502.1	506.3	0	0
Jul-99	5	99.8	89.9	10.6	266
Aug-99	8	180.4	168.7	8.4	314
Sep-99	21	242.7	219.2	11.0	632
Oct-99	24	237.8	206.1	15.2	852
Nov-99	18	213.0	169.2	22.3	1177
Dec-99	12	44.2	26.7	35.1	470

In retrospect, the pilot/full-scale biotrickling filter system included too much sophistication in the control system. When the control system started to fail, it was quite detrimental to good operation of the system. Biotrickling filters do not need to be complex. The bioreactor has subsequently been refurbished and the automated controllers have been removed. While remote control operation is no longer possible, the operation has so far been 100% reliable. Thus, future biotrickling filter designs should consider simple and reliable controls.

A cost comparison of thermal oxidizer, granular activated carbon (GAC) and biotrickling filtration was conducted for the evaluation of the treatment of SVE exhaust. It revealed that above SVE gas concentrations of about 400-500 ppm TPH, the thermal oxidizer is probably the most economical control technology. While it was not considered in details inhere, catalytic oxidation is better suited for medium to low concentrations than thermal oxidation. Thus it is possible that it will enable to extend the range of cost effective oxidation down to about 300-400 ppm. In the range of 50 to about 400-500 ppm, the biotrickling filter is the best control technology, and below 50 ppm, GAC adsorption is preferred. As stressed before, it is likely that as biotrickling filtration technology matures, treatment performance will improve and the overall treatment cost will decrease, which will enlarge the window of possible applications for biotrickling filters. In most cases, regulations will require GAC post-treatment after the biotrickling filter, but as confidence grows in the biological treatment for SVE exhaust, one can foresee that biotrickling filters alone will be permitted for SVE exhaust treatment.

In conclusion, while this study did not provide answers to all of the questions that were asked, it clearly showed that biological treatment should be further considered by the Air Force as an alternative to conventional treatment. A key question, when considering biological treatment for SVE/AS exhaust will be whether treatment for a given bioreactor at given conditions will be effective. It is probable that for the next few years, pilot or lab tests will be needed to define reactor design parameters (size and treatment performance). However, with further experiment with biological treatment, it is anticipated that this will no longer be needed.

Based on this study, the following recommendations are made to the Air Force:

1. Further experimental evaluation of biological techniques for air treatment should be conducted. In particular comparative studies of biofilters and biotrickling filters should be considered.
2. When considering biological treatment for SVE/AS exhaust treatment, conducting short term (6 months) laboratory tests to assess the treatability of the main contaminants should be considered to collect key pollutant removal data for reactor sizing.
3. Bioreactors for contaminated air treatment should be built with simple controls to minimize the possibility that component failure causes down time. In the event a sophisticated process control is installed, one should consider installing a redundant simple system to operate the system when the complex controllers fail.
4. The choice of SVE blower should consider that for effective treatment in a biological reactor, the temperature of the air discharged by the blower should not exceed about 98^{o} F.
1. If a GAC post-treatment is to be installed after the biotrickling filter, the design of the biotrickling filter should consider including effective means (demisters, water knock out) to reduce carry over of free water to the GAC and possibly heating the air prior to GAC unit to maximize the use of the GAC adsorptive capacity.
5. Further studies should be conducted to determine the optimum SVE/AS treatment train configuration and overall system operation that will minimize remediation costs.

2. BACKGROUND AND INTRODUCTION

Biological treatment of contaminated air is a new and very promising technique which utilizes mixed microbial populations to degrade gases. Gaseous pollutants or vapors are sorbed into an aqueous phase prior to biodegradation. These techniques excel in two main domains: 1) removal of odorous compounds[1-3] and 2) elimination of volatile organic chemicals, primarily solvents, from waste air.[1,3-8] Inorganic wastes may also be efficiently removed.[1,9-11] It is only recently that biological treatment of waste air was considered for the treatment of contaminated air generated by soil vapor extraction (SVE).[1,12,13] Biological treatment of waste air is environmentally friendly and does not produce secondary wastes such as nitrogen oxides or contaminated activated carbon.

Reactors for biological waste air treatment are distinguished by their operational mode, the existence of a free liquid phase, and their continuous phase reaction media (gas or liquid).

- Biofilters are reactors in which a humid polluted air stream is passed through a porous packed bed, usually of compost, on which pollutant-degrading microbial cultures are naturally immobilized. Biofilters present a tremendous potential for air treatment; they have been implemented at full-scale and have proven to be cost effective.[1,3,14,15] They are not appropriate for the treatment of acid-producing pollutants such as chlorinated solvents. Biofilters also require a large footprint.
- Bioscrubbers are reactors where a pollutant-containing waste air stream is in contact with a scrubbing solution. The most promising setup is a ***biotrickling filter*** where absorption and biodegradation of the pollutants is achieved in a single packed bed column reactor. Biotrickling filters offer promise for the elimination of various pollutants such as BTEX, chlorinated VOC's including dichloromethane, possibly trichloroethylene (TCE) and perchloroethylene (PCE), or inorganics such as H_2S.[16-19] At this time, biotrickling filters have yet to be implemented for industrial usage. The main drawbacks of biotrickling filters are their higher capital costs and clogging of the packed bed reactor by growing biomass.[20-23] Even so, biotrickling filters have proven largely superior to biofilters in many instances. The reason is that in biotrickling filters, environmental conditions can be much better controlled than in biofilters. The full potential of biotrickling filters has not yet been explored.

To this date, only a few full-scale biotrickling filters have been constructed. In particular, no biotrickling filter was ever used for the treatment of contaminated air from soil vapor extraction/air-sparging (SVE/AS) operations. This is particularly regrettable since these reactors have shown remarkable performance at the bench scale, in particular when highly contaminated air streams were treated.[21,24] Thus, biotrickling filters could possibly be cost effectively used for treating SVE/AS exhaust air when the concentration of contaminants is too low to be cost effectively incinerated (about 1000 ppm and below). It should also be noted that US-EPA has recently expressed concerns about the formation of dioxins from the incineration of SVE/AS exhaust. Under these circumstances, regulatory agencies may not be willing to continue to permit incineration or catalytic oxidation where other treatment techniques are available.

Recently, a highly sophisticated pilot/full-scale biotrickling filter was constructed by the University of California, Riverside and was available for demonstration projects.[25-26] For the present project, the objective was to evaluate of the feasibility of biotrickling filtration for the treatment of SVE/AS exhaust. Additional objectives were:

- To optimize the elimination of gasoline/jet fuel contaminants by the biotrickling filter
- To determine the best strategy for combining SVE/AS and biotrickling filtration
- To calculate treatment costs for various operating conditions
- To provide the Air Force with an opportunity to test and evaluate a high-tech full-scale biotrickling filter and collect sufficient and significant data to enable to evaluate the usefulness of biotrickling filtration for the treatment of SVE/AS exhaust.

3. MATERIALS AND METHODS

Reactor equipment

The pilot-scale reactor design was based on three successful years of operation of a bench-scale biotrickling filter at the Swiss Federal Institute of Technology.[24] The prototype system, designed and constructed by the University of California at Riverside and Environmental Biosystems (formerly located in Long Beach, CA), included two side-by-side tanks constructed of 304 stainless steel, each with an internal diameter of 1.6 m and height of 3.4 m (Figures 3.1-3.3). Each tank had a filter bed height of 2.1 m (7 ft), consisting of 7 layers of a COOLdek™ PVC Munters 12060 structured packing with a specific surface area of 230 $m^2\ m^{-3}$ (68 $ft\ ft^{-2}$). The bed volume per tank was 4.2 m^3.

Standard Operation

The biotrickling filter reactor was setup at Site 17, Edwards AFB as schematically shown in Figure 3.1. A positive displacement blower served for soil-vapor extraction. Initially, the air stream was set at approximately 500 $m^3\ h^{-1}$ (300 cfm) which resulted in excessive pressure drop through some sections of 3" diameter pipe on the biotrickling filter. Adjustment of the blower reduced the air flow to about 320 $m^3\ h^{-1}$ (190 cfm) for the remainder of the project. This gave an empty bed contact time of 47 seconds per tank. The blower exhaust was cooled from 180-210°F to about 90-130°F in a heat exchanger prior to treatment in the biotrickling filter. After the biotrickling filter, the air was heated by the heat exchanger to reduce its relative humidity and improve the life of the granular activated carbon (GAC) polishing units. Towards the end of the project, it was noticed that some water was being carried over from the biotrickling filter and a water knock out drum was installed between the biotrickling filter and the GAC polishing units. It consisted of a simple 55 gallon drum.

The biotrickling filter included one 5 HP water pump used to recycle the scrubbing solution over the packed beds (see Figures 3.2 and 3.3). The pump sprayed recycled liquid in parallel to the two tanks through Schedule 40 and 80 PVC piping (diameters of 1 to 3 inches) at flowrates up to 24 $m^3\ h^{-1}$ (105 gpm). A portion (~6 $m^3\ h^{-1}$) of the total recirculating water was directed to the base of each tank to provide adequate mixing in the tank bottom. A volume of 0.8 m^3 of recycled liquid was maintained in the base of each tank. This served as a water reservoir to control pH and other water parameters. A water level observation tube was connected with vinyl tubing to two separate locations outside each reactor tank. One of the connections was to the base of the tank (below the water line), while the other was connected above the water line. Float level sensors inside the tube detected changes in the tank water level. The reactor also contained a water strainer basket to remove large particulates from the recirculated water and a knockout pod to remove air phase particulates and water from the effluent air.

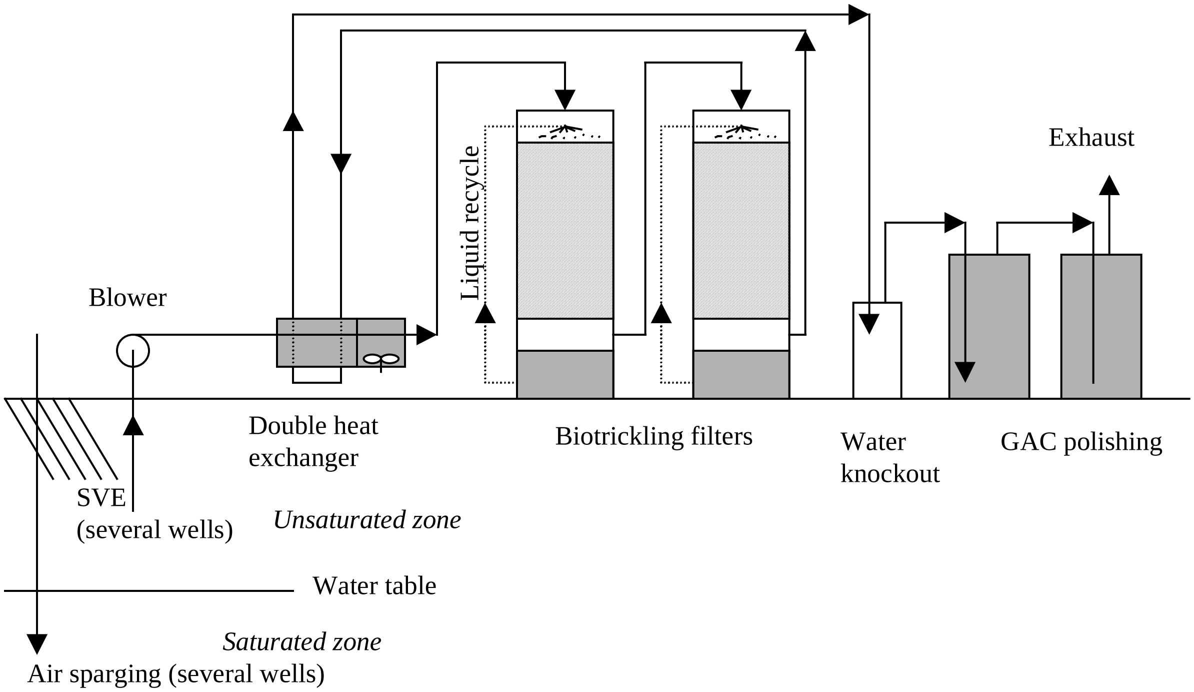


Figure 3.1 Schematic of the SVE/AS biotrickling filtration systems with GAC polishing units installed at Site 17, Edwards AFB (not all details shown).

Figure 3.2 Picture of the pilot biotrickling filter. The air flows in series through the two tanks.

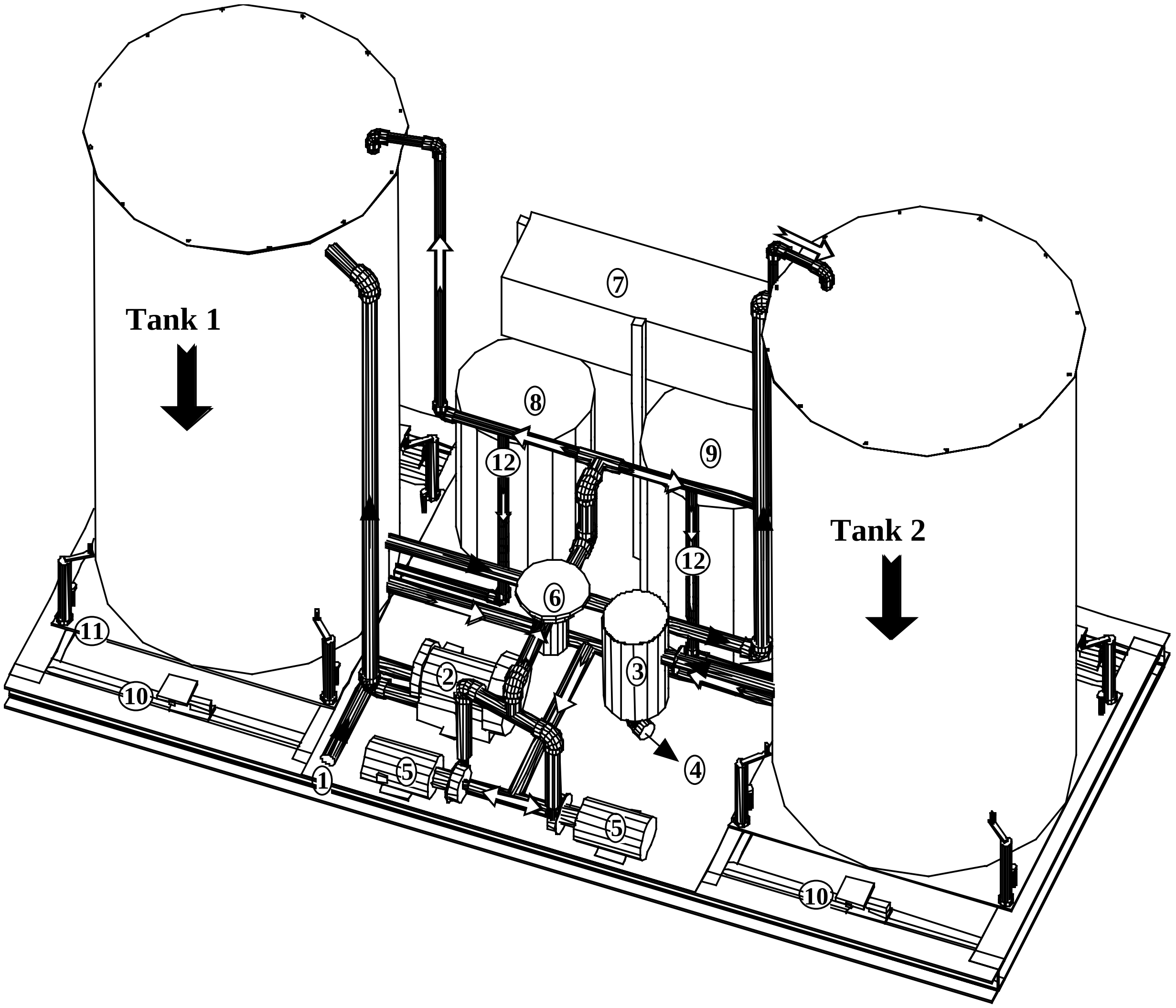


Figure 3.3 CAD drawing of the constructed biotrickling filter. Full arrows indicate air flow, open arrows indicate water flow;. 1) contaminated air inlet; 2) blower; 3) knock-out pod; 4) outlet purified air; 5) water pumps; 6) strainer basket; 7) control box; 8) nutrient tank; 9) caustic tank; 10) sliding load cells (outside position); 11) jacks; 12) water return to tank bottoms (for mixing).

The nutrient and caustic were stored in 0.8 m^3 tanks and supplied periodically through 1.3 cm ports on the pressure side of the water piping. Using two diaphragm nutrient feed pumps, a GrowMore hydroponic premixed fertilizer (Gardena, CA) containing 12/9/11 mass percentage of N/P/K and the trace elements iron, magnesium, calcium, zinc, copper, manganese, and sulfur, was added to the recirculation water at a feed concentration of 0.7/0.5/0.6 g l^{-1} of N/P/K. Two diaphragm feed pumps metered a caustic solution of 5% NaOH into the recirculation water to maintain the pH between 6 and 8.

A programmable logic controller (PLC) unit, programmed using Labview Software (National Instruments, Austin, TX), was implemented to monitor and control important parameters such as inlet and outlet concentrations, air and water flowrate, nutrient and caustic addition, water addition and removal, pressure drop, temperature, pH, and conductivity. The PLC used feedback control logic to maintain the operating parameters of the reactor within specified input limits. Specific methods used to measure many of the parameters are listed in Table 3.1.

Table 3.1 Biotrickling filter operational and performance parameters measured using a programmable logic controller computer with feedback control capabilities.

Parameter to be measured	Type of instrument	Notes
Air flowrate	Orifice plate (differential pressure)	Differential pressure used to calculate flowrates. Located downstream of blower before tank 1.
Air phase concentration	Flame ionization detector (FID)	Air measured at inlet, between, and outlet of two tanks. Also, set up to measure concentration along the length of each tank.
Air pressure	Pressure gauges (electronic)	Measured across both tanks, the blower, and the entire system.
Air temperature	Thermocouples	Air measured at inlet, between, and outlet of two tanks. Also, set up to measure concentration along the length of each tank.
Tank weights	Load cells	Three load cells per tank.
Water conductivity	Conductivity probe	Measured after water pumps.
Water flowrate	Paddlewheel flow sensors	Measured at the inlet of both tanks.
Water level indicators	Water float sensors	Measured outside of each tank in a water level observation acrylic tube.
Water pH	pH probes	Measured directly in each tank.
Water pressure	Pressure gauge (electronic and analog)	Measured in-line on pressure side of pumps.
Water temperature	Thermocouples	Measured at the outlet of both tanks.

The system was inoculated on several occasions with 10 to 30 L of activated sludge from Edwards AFB wastewater treatment plant. The inoculum was added to the recirculating water along with a nutrient solution to promote growth. Water and nutrient additions depended on the mode of operation (manual or automatic) during the experiments. The continuous mode of operation involved the hourly removal of 10 liters of recirculation water and the replacement with 10 liters of a fresh nutrient solution.

Operating conditions at Site 17, Edwards AFB were quite severe. The outside temperature often exceeded 115^{o}F in the summer, which resulted in electrical component failures. Hence a small air conditioning unit was installed on the control box to maintain the temperature of key components at lower temperatures (70-80^{o}F).

The focus of the experiment was to evaluate the feasibility of SVE/AS vapor treatment using the biotrickling filter and evaluate the applicability of biotrickling filters for SVE/AS exhaust treatment in general. Over a 6-month period, several measures were taken to optimize pollutant biodegradation. Unfortunately various operational problems were experienced that affected pollutant removal. In Chapter 4, project milestones and key activities are summarized, detailed experimental results are presented and discussed in Chapter 5. Treatment cost comparisons for various technologies are presented in Chapter 6, while Chapters 7 and 8 place the general work in perspective and contains general recommendations.

4. SUMMARY OF ACTIVITIES

A short summary of the activities is presented in Table 4.1. Detailed down time periods are listed in Table 5.8, and are discussed together with the analysis of the system upsets (Section 5.4).

Table 4.1 Summary of the activities.

Date (all in 1999)	Activity
3/17	The biotrickling filter is moved from UCR to Site 17, Edwards AFB.
3/23-4/19	Piping work is conducted by Earth Tech contractor; electrical connections are finalized by Earth Tech on 4/19.
4/19	Piping connection from/to the heat exchanger to/from the biotrickling filter is completed; sensors are calibrated. Biotrickling filter final preparation.
4/26	Earth Tech drills new wells at Site 17. New wells are connected 5/17.
4/29	Biotrickling filter is ready to attempt startup. Problems with the control software occur rapidly, repeated shutdowns are experienced because of problems with the control software.
5/4	Biotrickling filter operation commences, air flow is high (300-330 cfm) and high pressure drops are experienced which causes SVE blower to shut down, usually after 30 minutes of operation. Several leaks in the biotrickling filter have to be fixed.
5/31-6/8	Biotrickling filter inlet temperatures are high (>120 ^oF) due to low cooling by the heat exchanger and intermittent operation.
6/11	SVE/Biotrickling filter operation is discontinuous because of the high air flow and frequent blower shutdowns due to excessive pressure drop (30-60" of water column). Inlet concentration is ~900 ppm as hexane, but these are transient conditions (concentration rebound) due to the high downtime of the SVE.
6/26	The SVE blower is modified to supply a lower flowrate (190-210 cfm). Under these conditions pressure drop is acceptable and the SVE/biotrickling filter system can operate continuously. Inlet air biotrickling filter temperatures are high (122 ^oF), but continuous treatment with the biotrickling filter commences.
7/16	Biotrickling filter computer is upgraded in an attempt to reduce the frequency of computer crashes and possibly enhance the modem connection. FID detector needs repair (probably damaged by water carried over in the sampling line).
7/27-7/29	Computer problems. New computer is installed.
August, Sept.	Relatively stable operation. Performance increases. Various tests are performed.
9/28	Biotrickling filter inlet-outlet sampling for GC-MS analysis (by Earth Tech)
10/12	Biotrickling filter inlet-outlet sampling for GC-MS analysis (by UCR/USC)
10/23-10-24	Study the effect of liquid recycle rate and peat humic substance addition to the biotrickling filter. Various experiments and attempts to optimize performance are conducted.
10/31	A problem with a solenoid valve caused flooding of the control box. Equipment is severely damaged. Computer needs to be replaced.
11/6	Computer is replaced.
11/6-11/8	Restart at high concentration (600-1200 ppm)
11/10-11/16	System is down for replacement of GAC.
11/23	Night temperatures at Edwards AFB get cooler (20-30 ^oF).
12/1	SVE blower starts having problems (overload) possibly because of freezing in either the biotrickling filter water knock out or in other parts of the system.
12/12	SVE blower belt breaks down. Blower is repaired and restarted on the 13.
12/14	Operation of the biotrickling filter at Site 17 is stopped.
12/15-17	Decommissioning of the site.
12/22	Biotrickling filter is moved back to UCR.

5. RESULTS

5.1 Treatment Performance

As will be discussed further in Section 5.3, the operation of the biotrickling filter was characterized by an unusually high number of system upsets related for the most part to the biotrickling filter control system. This undoubtedly affected the pollutant removal performance. Hence, it is our opinion that the full performance of the system was unfortunately not reached during the project. When the biotrickling filter was operated for extended periods of time (more than 7-10 days), a gradual increase of the removal performance was observed.

The daily average total petroleum hydrocarbon (TPH) concentrations at the inlet and at the outlet of the biotrickling filter are reported in Figure 5.1. The inlet concentration data show a high degree of variability over time, which is not unusual for an SVE/AS system. It also reflects the fact that the SVE/AS was often shutdown (Section 5.3) and that concentrations rebounded after such shutdowns. Also, the operation of the SVE/AS system was often modified by Earth Tech personnel to adjust the concentration (40-500 ppm) based on UCR/USC personnel recommendation. Detailed examination of Figure 5.1 reveals that biotrickling filter outlet concentrations follow closely those of the inlet, suggesting very little removal of the contaminants, except at low concentrations (150 ppm and below). The various attempts that were made to improve the performance are discussed in Section 5.3.

Monthly averaging of inlet and outlet concentrations was performed to eliminate short term variations, and is reported in Figure 5.2 together with the TPH removal percentage. The same data are listed in Table 5.1. Figure 5.2 and Table 5.1 highlight that the removal during most of the project was low (10-15%). There was improvement of the removal over time, especially towards the end of the project. It should however be noted that this improvement occurred as the inlet concentration was decreased to about 40 to 60 ppm, which is a typical behavior for a bioreactor. Hence, this did not correspond to an increase in the hourly mass removed. Even so, the trend was towards further improvement of the performance. Towards the end of the project, some of the hourly removal averages reached values up to 47%. It was scheduled to retest high concentrations, but on December 12, the SVE blower had a belt problem which required a day to repair. Operation of the biotrickling filter was stopped one day later.

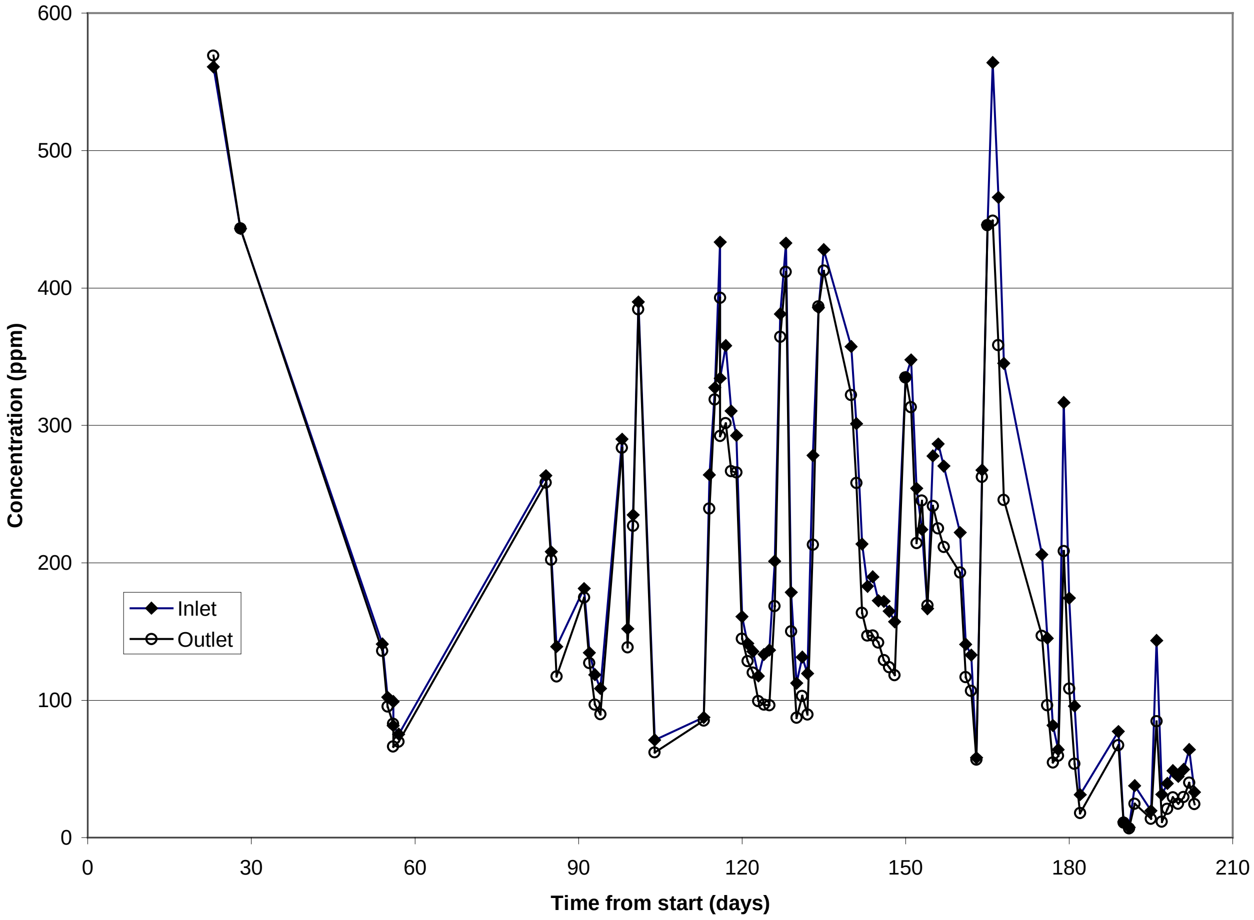


Figure 5.1 Daily values of the biotrickling filter inlet and outlet TPH concentration (ppm as hexane).

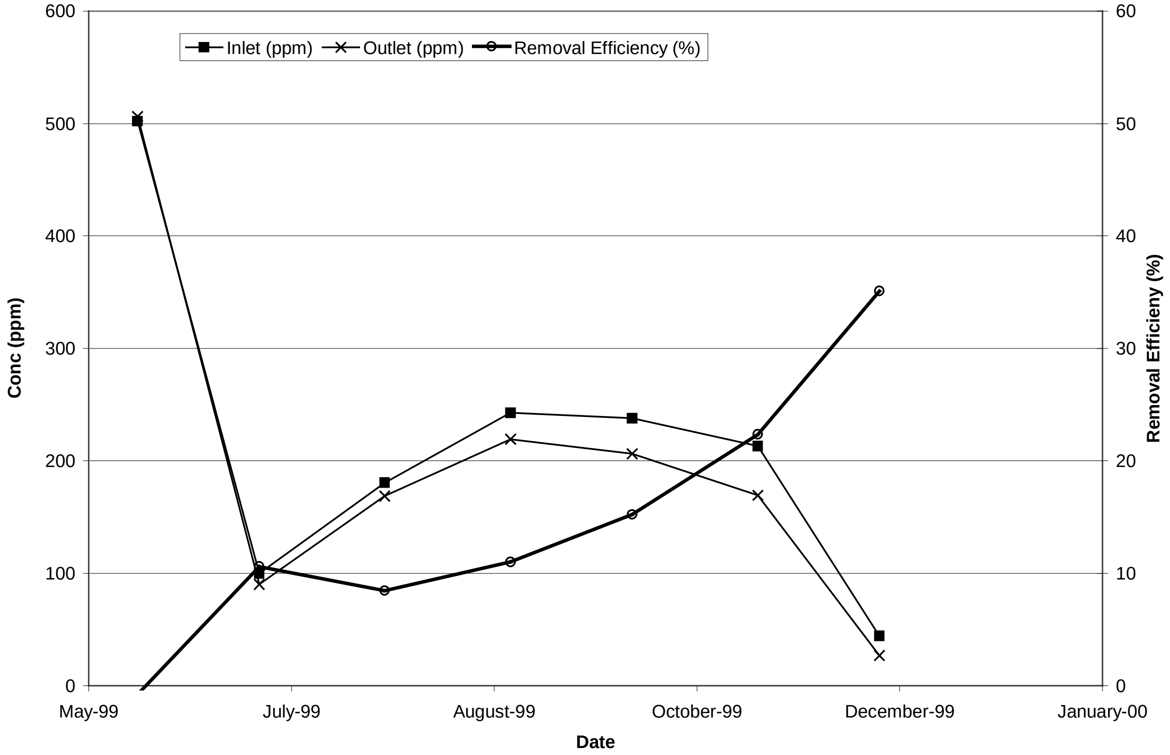


Figure 5.2 Monthly averages of the biotrickling filter operation (ppm is as hexane).

Table 5.1 Monthly averages of the biotrickling filter inlet and outlet TPH concentrations (ppm as hexane).

	Number of samples	Inlet conc. (ppm)	Outlet conc. (ppm)	Removal Efficiency (%)	Daily mass removed (g/day)
Jun-99	2	502.1	506.3	0	0
Jul-99	5	99.8	89.9	10.6	266
Aug-99	8	180.4	168.7	8.4	314
Sep-99	21	242.7	219.2	11.0	632
Oct-99	24	237.8	206.1	15.2	852
Nov-99	18	213.0	169.2	22.3	1177
Dec-99	12	44.2	26.7	35.1	470

Selected operating parameters or performance data are reported in the following pages to illustrate daily biotrickling filter operation. Figure 5.3 shows that reactor temperatures were high, which can be detrimental to effective biodegradation. The pressure drop through the reactor was high (30-35” water column), mostly because of some short sections of small piping, because of check valves in the air conduits and of the water knock out. Note that this has now been modified, and that the airflow has been doubled (~400 cfm) while the pressure drop is less than one inch of water column.

In Figure 5.4, the inlet and outlet concentration and the concentration between the two tanks is reported for two consecutive days. The data illustrate that biotrickling filters do not have a large

VOC sorption capacity. Hence, when changes in the inlet air concentration air occurred, the outlet concentration followed the trend, with only a minimal delay.

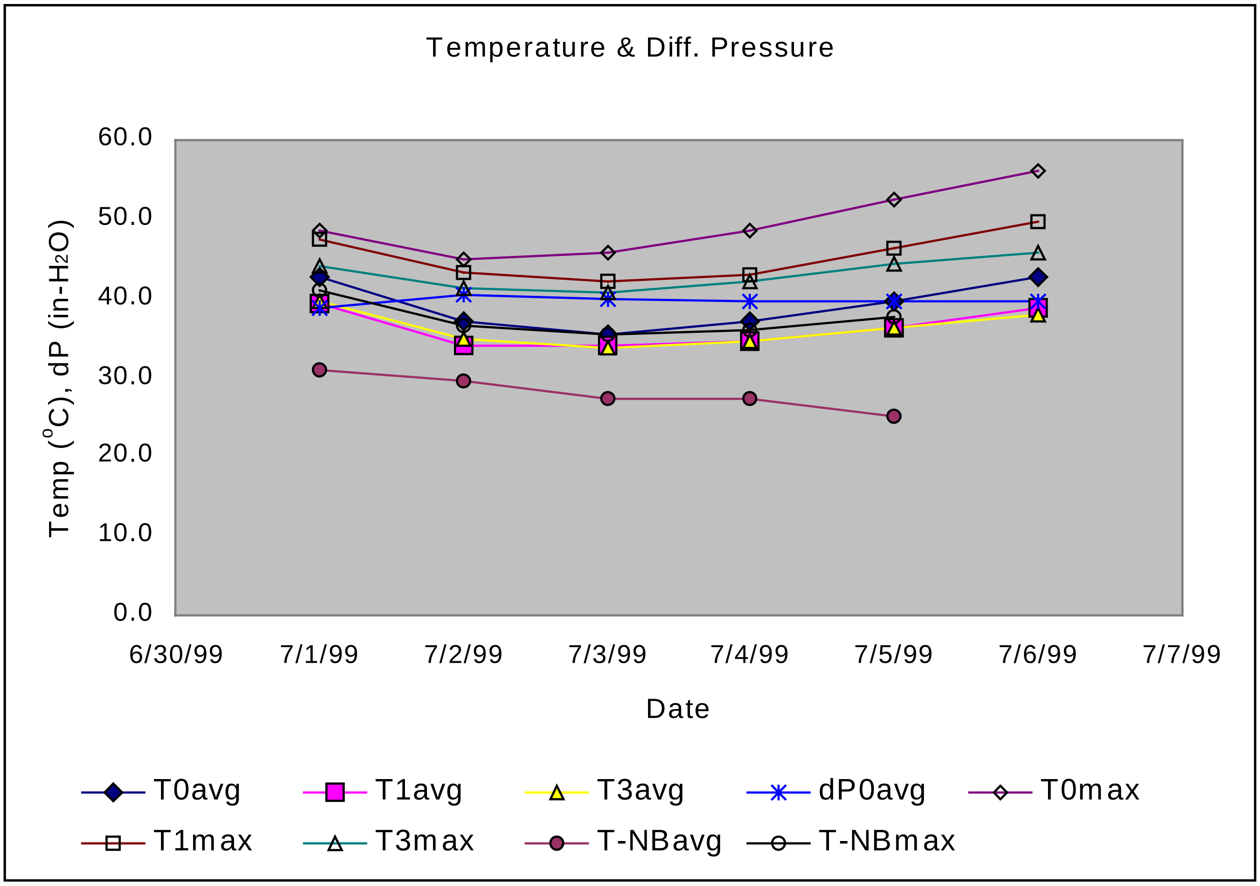


Figure 5.3 Average values of selected parameters T0: Temperature in control box (°C); T1: Air inlet temperature (°C); T3: Air outlet temperature (°C); T-NB: Ambient air temperature monitored in North Base (°C); dP0: differential pressure in air inlet (inch-H_2O). Airflow: 190-200 cfm.

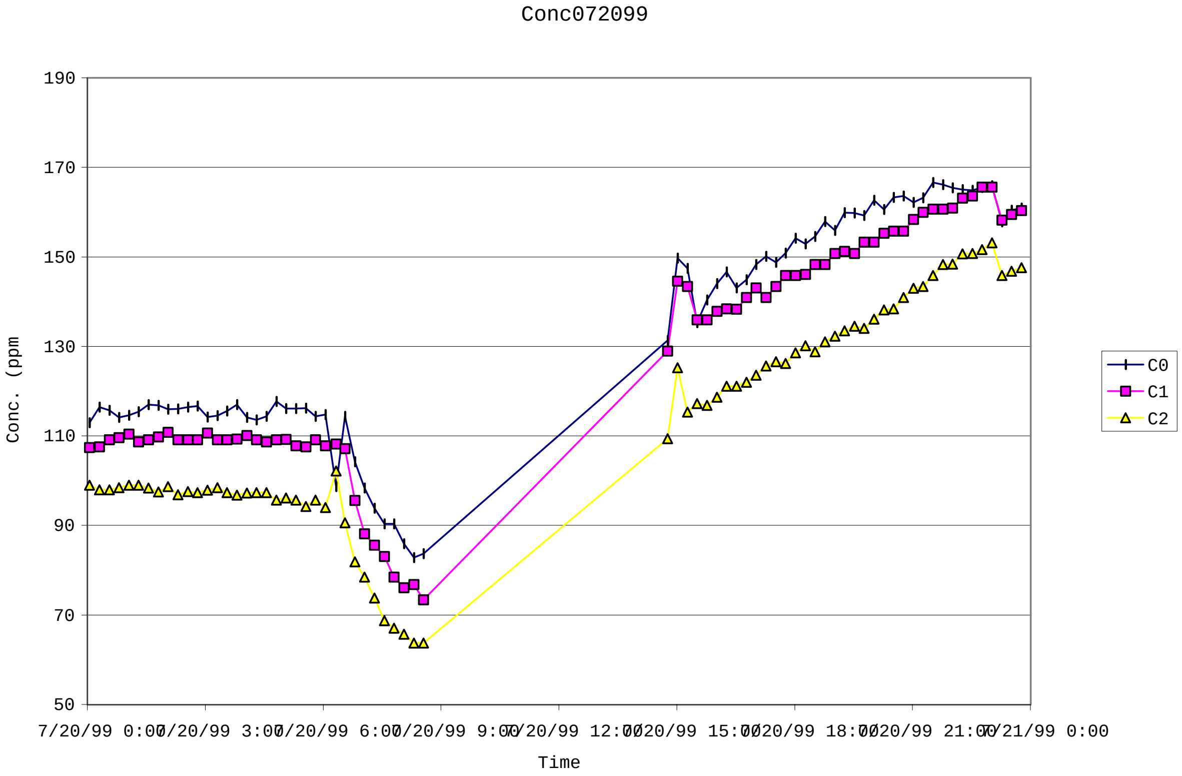


Figure 5.4 Concentration (TPH as hexane) in the inlet air, between the tanks and in the outlet air for 2 consecutive days.

In several instances throughout the project, the biotrickling filter performance increased substantially. This was usually after a few days without any system shutdown as illustrated in Figure 5.5 and in Table 5.2. Examination of Figure 5.5 reveals that a) inlet concentration decreased over time and b) after a 4 day shutdown, removal upon restart was marginal, but slowly increased. This is most probably due to the acclimation and growth of the process culture. In previous research (Deshusses, unpublished), we found that shutdowns for more than 2 days were detrimental to the performance of the biotrickling filter. A similar acclimation effect is reported in Table 5.2. Over time, after re-acclimation, for concentration ranging from 200-300 ppm, about 100 ppm could be degraded. We speculate that if the reactor operation could have been maintained for longer time, further improvement of the performance would have been observed.

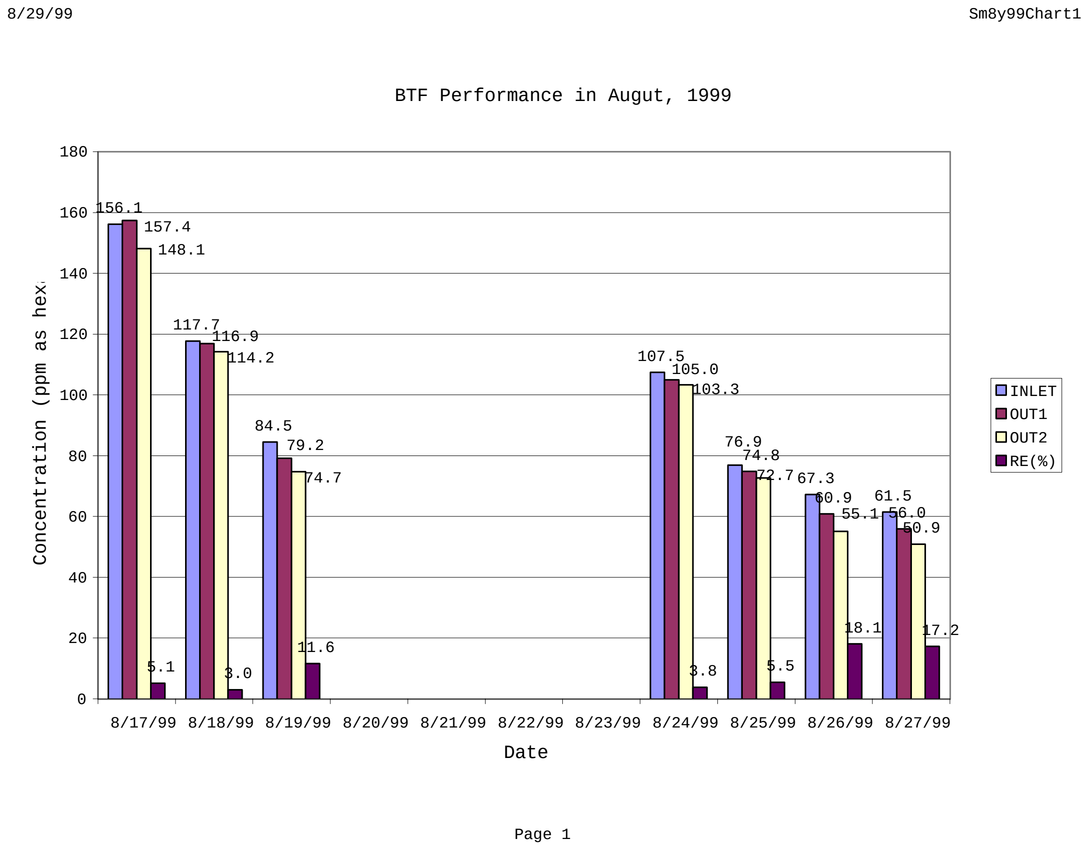


Figure 5.5 Daily average biotrickling filter inlet, between the tanks (OUT1) and outlet (OUT2) concentrations, and percentage removal (RE%) after restart from a 4 day (8/20-8/24) period of down time.

Table 5.2 Average daily concentration for 6 consecutive days.

Date	Inlet concentration (ppm)	Between tanks (ppm)	Outlet concentration (ppm)	Removal (%)
9/21/99	491	437	360	26.7
9/22/99	270	211	197	27.1
9/23/99	237	186	174	26.6
9/24/99	228	175	164	28.2
9/25/99	199	146	136	31.4
9/26/99	227	143	134	41.0

A short term experiment was performed at relatively high inlet concentration (800-1200 ppm). The results are reported in Figure 5.6. As for the experiment at low concentration (Figure 5.4), the outlet concentration follows closely the variations of the inlet concentration. Here, it is interesting to note that on average about 150-200 ppm of TPH was removed by the biotrickling filter. This corresponds to a removal of 4.0-5.4 kg (as hexane) per day, which is significant.

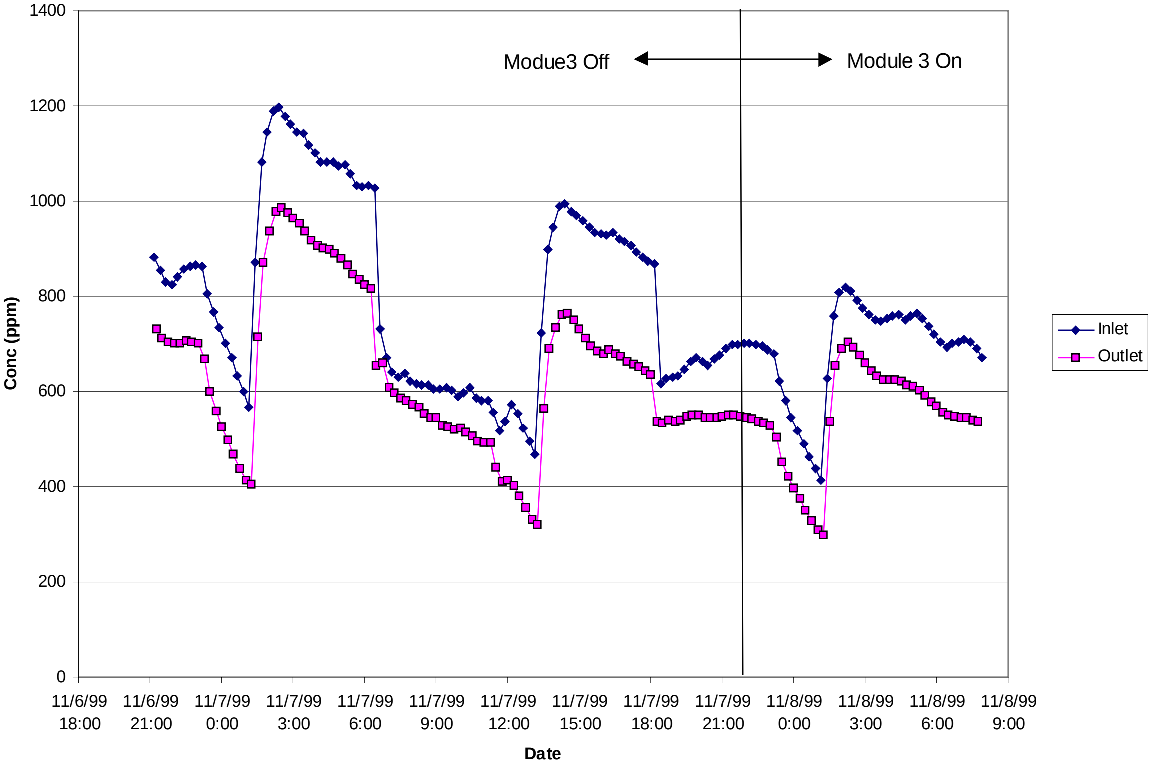


Figure 5.6 Concentration (TPH as hexane) in the inlet and outlet air of the biotrickling filter for 2 consecutive days at high inlet concentrations (module 3 on/off refers to some of the air sparging operation).

5.2 Identification of the Compounds Removed by the Biotrickling Filter

On September 28, 1999, Earth Tech sampled the biotrickling filter inlet and outlet air stream and Quanterra Laboratories analyzed the samples for volatile organic compounds using EPA method TO-14. CO_2, oxygen, methane and nitrogen were analyzed by method ASTM D1946, and TPH (as gasoline) by EPA method TO-3. On the latter analysis, it should be noted that Quanterra Laboratories indicated that a sample chromatographic pattern revealed that their gasoline standard was different from our sample, so that quantification may not be accurate. The results are summarized in Table 5.3.

Examination of Table 5.3 reveals that inlet concentrations of the reported individual contaminants were, in general, very low (1-100 ppb range). Even so, a number of compounds of environmental concern were very well degraded by the biotrickling filter. For example, 75% of 77 ppb benzene were removed, 96% of 150 ppb xylenes were removed, while toluene removal was a little lower (56%). Methylated benzenes were also well removed by the biotrickling filter and surprisingly some chlorinated compounds such as trichloroethene or tetrachloroethane were degraded (see Table 5.3). These compounds are usually degraded faster or exclusively under anaerobic conditions. Partial degradation of these compounds in biofilters had already been reported by Devinny et al. in 1995,[27] who speculated that biodegradation occurred in thick biofilms subject to oxygen limitation. This may have occurred as well in our biotrickling filter. Another possible mechanism for the biodegradation of these compounds could be via cometabolism with the biodegradation of aromatic or aliphatic hydrocarbons.

TPH removal reported in Table 5.3 was only about 18% on that day, which contrasts with the high numbers for the removal of each individual compounds. A further discrepancy exists in the concentrations reported as TPH (170 ppm in the inlet and 140 ppm in the outlet) and the summation of the concentration of all the individual compounds (596 ppb and 111 ppb in the inlet and outlet, respectively). It is unclear what compounds were not picked up by method TO-14 and were included in the TPH measurement]. Methane was present but only at about 24 ppm; both in the inlet and in the outlet. Because of the source of the contamination, one would expect various aliphatic hydrocarbons to be present. This motivated a further GC-MS analysis in USC laboratories.

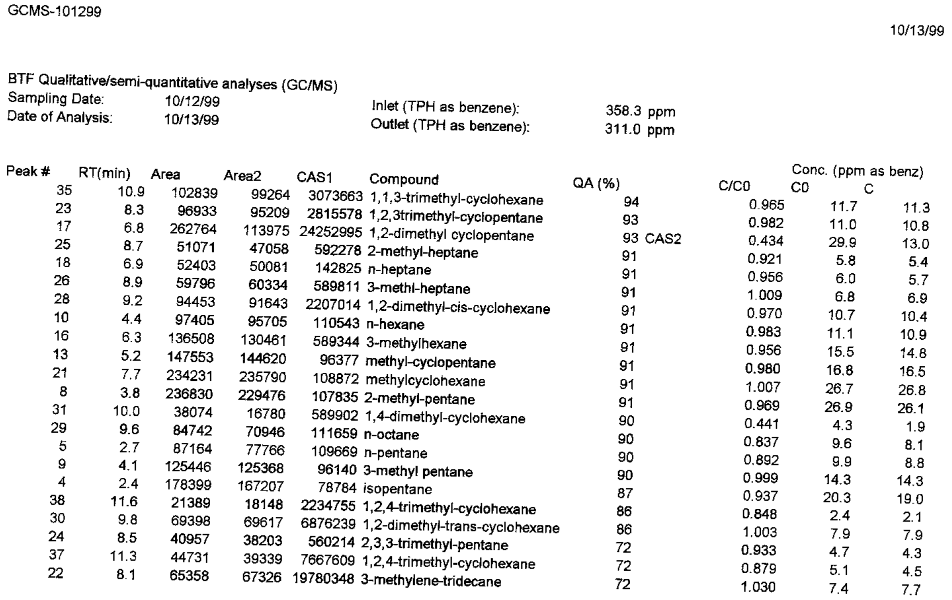
Unfortunately, the in-house GC-MS measurements could only be performed on 12/12/99, i.e., about 2 weeks after the sampling event analyzed by Quanterra. Thus, concentrations can not be directly compared, but the identification of the contaminants remains valid because it is improbable that the compositions of the exhaust changed significantly over this short time. The results of the in-house GC-MS analyses are presented in Table 5.4. The summation of all the peaks gives an approximate inlet concentration of 356 ppm (as benzene) while the outlet was about 311 ppm, i.e., about 13% removal. The aliphatic alkanes that were identified in the ppm range were also consistent with the usual gasoline composition. The removal of these compounds was marginal (less than 10%), except for a few compounds such as 1-4 dimethyl cyclohexane or 1-2 dimethyl cyclopentane. The comparison of the in-house analysis and the results by TO-14 reveals striking discrepancies. As a follow up, the total ion chromatograph of the 9/28 samples were obtained from Quanterra. The spectra do indeed show 3-5 unidentified peaks, which are comparable is size to the compounds reported. But, the unreported peaks remain a minority. Their estimated amount is certainly very far from the 140-170 ppm missing from the TPH measurement. The only suitable explanation, is that there was of problem with either the analysis or the sampling for the 9/28 samples.

Table 5.3 Biotrickling filter inlet (duplicate) and outlet concentrations of volatile compounds, and permanent gases analysis. For the volatile compounds, no value is reported if the result was non detect.

Compound	Unit	MDL	Inlet conc. 1st sample	Inlet conc. 2nd sample	Avg. inlet conc.	Outlet	% removed
1,1,2-Trichloro-1,2,2-trifluorethane	ppb	2.5	19	18	18.5	17	8.1
2-Butanone	ppb	10	37	38	37.5	31	17.3
Benzene	ppb	4	78	76	77	19	75.3
Trichloroethene	ppb	2.5	5	4.5	4.75	3.7	22.1
Toluene	ppb	2.5	11	11	11	4.8	56.4
Tetrachloroethane	ppb	2.5	10	5.5	7.75	4.6	40.6
Ethylbenzene	ppb	2.5	30	33	31.5	2.5	92.1
Xylenes (total)	ppb	4	140	160	150	6	96.0
4-Ethyltoluene	ppb	2.5	33	36	34.5	3	91.3
1,3,5-Trimethylbenzene	ppb	4	96	110	103	17	83.5
1,2,4-Trimethylbenzene	ppb	2.5	87	99	93	2.8	97.0
Sum of the above	ppb				569	111	80.4
Carbon Dioxide	%	0.001	0.84	0.86	0.85	0.83	2.4
Oxygen	%	0.01	21	21	21	21	0
Nitrogen	%	0.04	78	78	78	78	0
Methane	%	2.0e-5	0.0024	0.0024	0.0024	0.0024	0
TPH (as gasoline)	ppm	1.5	170	170	170	140	17.6

Note: all ppb, ppm, or % are by volume.

Table 5.4 Biotrickling filter inlet (C_o) and outlet (C) concentrations of volatile compounds measured by GC-MS. C/C0 represent the non-removed fraction, QA(%) is the degree of confidence in the identification of the compound.



GCMS-101299

10/13/99

BTF Qualitative/semi-quantitative analyses (GC/MS)

Sampling Date: 10/12/99

Date of Analysis: 10/13/99

Inlet (TPH as benzene): 358.3 ppm

Outlet (TPH as benzene): 311.0 ppm

Peak #	RT(min)	Area	Area2	CAS1	Compound	QA (%)		C/C0	Conc. (ppm as benz)	
									C0	C
35	10.9	102839	99264	3073663	1,1,3-trimethyl-cyclohexane	94		0.965	11.7	11.3
23	8.3	96933	95209	2815578	1,2,3trimethyl-cyclopentane	93		0.982	11.0	10.8
17	6.8	262764	113975	24252995	1,2-dimethyl cyclopentane	93	CAS2	0.434	29.9	13.0
25	8.7	51071	47058	592278	2-methyl-heptane	91		0.921	5.8	5.4
18	6.9	52403	50081	142825	n-heptane	91		0.956	6.0	5.7
26	8.9	59796	60334	589811	3-methl-heptane	91		1.009	6.8	6.9
28	9.2	94453	91643	2207014	1,2-dimethyl-cis-cyclohexane	91		0.970	10.7	10.4
10	4.4	97405	95705	110543	n-hexane	91		0.983	11.1	10.9
16	6.3	136508	130461	589344	3-methylhexane	91		0.956	15.5	14.8
13	5.2	147553	144620	96377	methyl-cyclopentane	91		0.980	16.8	16.5
21	7.7	234231	235790	108872	methylcyclohexane	91		1.007	26.7	26.8
8	3.8	236830	229476	107835	2-methyl-pentane	91		0.969	26.9	26.1
31	10.0	38074	16780	589902	1,4-dimethyl-cyclohexane	90		0.441	4.3	1.9
29	9.6	84742	70946	111659	n-octane	90		0.837	9.6	8.1
5	2.7	87164	77766	109669	n-pentane	90		0.892	9.9	8.8
9	4.1	125446	125368	96140	3-methyl pentane	90		0.999	14.3	14.3
4	2.4	178399	167207	78784	isopentane	87		0.937	20.3	19.0
38	11.6	21389	18148	2234755	1,2,4-trimethyl-cyclohexane	86		0.848	2.4	2.1
30	9.8	69398	69617	6876239	1,2-dimethyl-trans-cyclohexane	86		1.003	7.9	7.9
24	8.5	40957	38203	560214	2,3,3-trimethyl-pentane	72		0.933	4.7	4.3
37	11.3	44731	39339	7667609	1,2,4-trimethyl-cyclohexane	72		0.879	5.1	4.5
22	8.1	65358	67326	19780348	3-methylene-tridecane	72		1.030	7.4	7.7

5.3 Determination of the Rate Limiting Step and Performance Troubleshooting

The low removal performance of the biotrickling filter was unexpected and several attempts were made to a) increase the pollutant removal performance, and b) find the reason(s) for the low removal performance. These are discussed below.

Biotrickling filter inoculation

In previous projects with difficult-to-degrade compounds, we found that it was important to perform vigorous inoculation of the reactor.[26] Hence, several times throughout the project, return activated sludge (usually 5 – 10 gallons) from the Edwards AFB sewage treatment plant was added to the reactor. In particular, inoculation was always performed if the biotrickling filter had undergone a shutdown of more than 2-3 days. The long term effect of inoculation is difficult to evaluate in the absence of controls. Even so, one can reasonably speculate that the sludge additions enhanced the biodiversity of the process culture, while also serving as a sporadic supply of nutrients. In any case, except for the initial startup, no major effect was observed immediately after inoculation or within the next few days. In several instances, an extract of peat humic substances which was known to enhance the growth of microorganisms was added to the reactors, but again no effect could be detected. Overall, the results proved that repeated inoculations were not detrimental, but whether they were really needed is unclear. In general, unless there is a major upset that would kill the process culture, it is believed that re-inoculation is not necessary. However, the fact that re-inoculation did not have a significant effect does not rule out the possibility of biological limitation. In particular, it is quite possible that the right density of organisms was achieved in the reactors, but that the stress caused by frequent shutdown and relatively high temperatures may have partially inhibited the biodegradation of the contaminants.

Test for a mass transfer limitation

In biotrickling filters, the pollutants have to be transferred from the bulk gas phase to the biofilm in order to be biodegraded. The pollutant transfer mechanisms are complex[22] and quantification of mass transfer rates is difficult. In particular, a good set of methods to test for specific transfer or biological limitations have yet to be developed. During this project, a simple method was developed to test whether the transfer from the bulk gas to the bulk liquid was limiting the rate of pollutant biodegradation. Gas samples were taken at the exit of the biotrickling filter in a 5 L tedlar bag. At the same location, a sample of the recycle liquid was taken. The liquid sample was analyzed by GC-FID for dissolved volatile compounds in UCR labs. It was compared to a chromatogram of a drop of liquid introduced in the tedlar bag filled with the gas sample which was allowed to equilibrate for 30 minutes. It was hypothesized that since most contaminants present had a high Henry's law coefficient, the introduction of less than 1 mL water in the tedlar bag would not change the gaseous concentration of the contaminants. Further, if the same chromatogram were obtained, one could conclude that bulk gas to bulk liquid mass transfer (A to B on Figure 5.7) was not limiting. Indeed, the chromatograms were identical and such a mass transfer limitation could be ruled out. As stated before, other mass transfer limitations are difficult to test. Other investigations were performed which considered possible nutrient limitations or presence of inhibitors in the recycle liquid (see below).

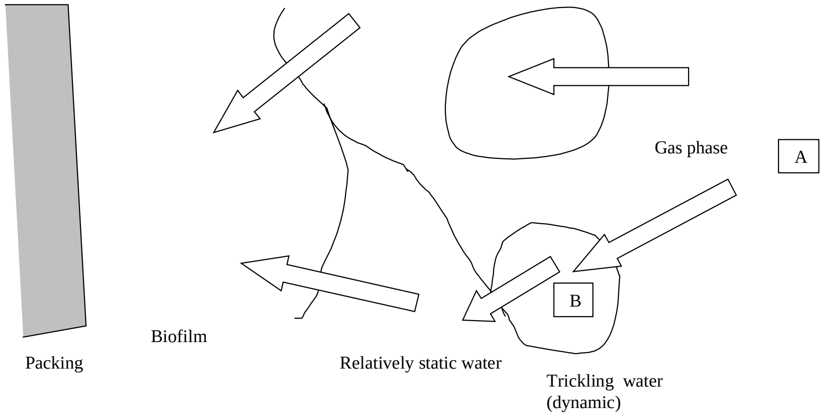


Figure 5.7 Schematic representation of the possible mass transfer paths for a contaminant in a biotrickling filter. While gas to liquid to biofilm is usually the only route considered, direct gas to biofilm mass transfer exists. The possible mass transfer limitation tested here was from point A to point B. It was found to be not limiting.

Investigations on the recycle liquid

The recycle liquid composition may affect the performance of biotrickling filters. Inhibition of the process culture may result from:

1. Nutrient limitation
2. Large excess of nutrient
3. Presence of a growth inhibitor (e.g., pollutant, a metabolite, or toxic chemical in the recycle liquid)

Whether any of the above situations occurred was tested as follows. Recycle liquid from the biotrickling filter was brought back to UCR labs and centrifuged to remove suspended matter and suspended organisms. 50 ml of the liquid with or without different amendments were then used as a medium for growing an ethanol-degrading consortium. Controls and other liquid media were investigated in parallel. All experiments were performed in 250 mL serum flasks capped with Teflon-lined silicon septa. The growth characteristics, in particular the biomass yield (expressed as the final optical density), were monitored to determine whether adverse conditions existed in the recycle liquid of the Edwards AFB biotrickling filter. The rationale for the choice of the various conditions are presented in Table 5.5, while the results are presented in Figure 5.8 and Table 5.6.

Table 5.5 Composition of the different flasks to test the adequacy of the recycle liquid.

#	Liquid source	Amendment	Rationale, test for:	Final conc. (g/L)	Innoculated	Ethanol conc.
1	Edwards	None	Reference flask	N/A	Yes	1 g/L
2	Edwards	None	Duplicate #1	N/A	Yes	1 g/L
3	Edwards	KNO_3	N limitation	1.0	Yes	1 g/L
4	Edwards	NH_4NO_3	N limitation	1.0	Yes	1 g/L
5	Edwards	K_2HPO_4 + KH_2PO_4	pH problem, P limitation	1.0	Yes	1 g/L
6	Edwards	Trace elements	Trace elements limitation	0.2	Yes	1 g/L
7	Edwards	Trace elements + NH_4NO_3 + $MgSO_4$	Trace and N and Mg (almost full mineral medium), test for inhibitors	0.1 mL trace elements + 1 NH_4NO_3 + 0.2 $MgSO_4$	Yes	1 g/L
8	UCR	None	Compare reference to a btf at UCR	N/A	Yes	1 g/L
9	UCR	None	Duplicate #8	N/A	Yes	1 g/L
10	UCR	Cell free recycle liquid from UCR btf (centrifuged)	Test dilution.	50 mL added	Yes	1 g/L
11	Edwards	added 10 g GAC[a]	Adsorb possible inhibitors	N/A	No (which was a mistake)	1 g/L
12	Edwards	GAC[a]	Duplicate #11	N/A	No (which was a mistake)	1 g/L
13	Edwards	GAC[a] + trace elements + NH_4NO_3	Remove possible inhibitors and add N uninoculated	0.1mL trace elements + 1 NH_4NO_3	No (which was a mistake) mistakes made results of #11, 12, 13 useless	1 g/L
14	Edwards	None	no ethanol control, test for easily degradable dissolved compounds	N/A	Yes	0 g/L
15	Edwards	None	Duplicate #14	N/A	Yes	0 g/L

[a] GAC was added to the liquid, the solution was stirred and GAC was allowed to settle and filtered/centrifuged, the clear liquid was used for further tests.

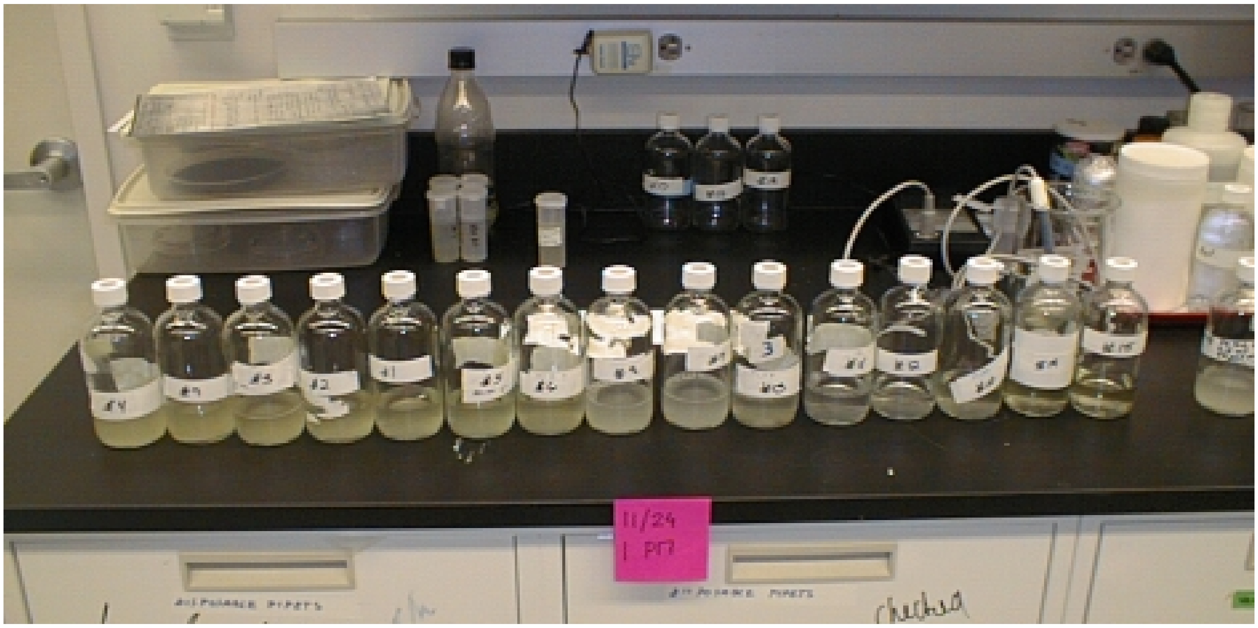


Figure 5.8 Visual ranking of relative turbidity.

Table 5.6 Optical density (OD 600 nm) of the culture in the different flasks at the end of the growth phase. A high OD indicates that the liquid was able to sustain significant growth.

Flask #	OD 600 nm	Conclusion, observation
4	0.544	Only samples with N exhibited more growth than the reference with the Edwards AFB biotrickling filter recycle liquid "as is". Thus adding N can sustain better growth (1.5 to 2 fold).
7	0.532	
9	0.368	
5	0.332	
3	0.328	
1 **Btf recycle liquid as is**	**0.240**	**Less growth than with N added, but growth was sufficient to rule out severe N limitation**
2 **Btf recycle liquid as is**	**0.180**	**Less growth than with N added, but growth was sufficient to rule out severe N limitation**
6	0.105	Trace are not limiting
13	0.086	A mistake was made, no bacteria was added, which understandably resulted in no growth
12	0.073	Uninoculated control did not grow, which was expected.
10	0.068	Experiment failed.
11	0.056	A mistake was made, no bacteria was added, which understandably resulted in no growth
14	0.019	There is no significant source of carbon source for growth dissolved in the recycle liquid
15	0.017	There is no significant source of carbon source for growth dissolved in the recycle liquid

Although visual ranking of the turbidity was subjective, it did provide a semi-quantitative measure of the growth in each serum bottle, i.e., the adequacy of the medium to support fast bacterial growth (Figure 5.8). The bottles were ranked: 4,7,3,2,1,5,6,9,13,8,10,11,12,14,15. Further quantification of the optical density was performed (Table 5.6) and revealed that the most optimum conditions were those flasks amended with a nitrogen source. This indicated that some degree of nitrogen limitation may have existed in the biotrickling filter. Even so, decent growth was obtained in sample #1 and #2 which indicates sufficient residual nitrogen. Comparison with the other samples suggests that the recycle medium was appropriate, and that there was no inhibitor present in the recycle liquid at the time of sampling. Thus the reason for the low removal was not related to the composition of the liquid medium.

Conclusions

For effective biodegradation in biotrickling filters, a high density of active pollutant-degrading organisms is required. Usually, the mass of wet biomass in the system is a relatively good criterion to find out whether sufficient biomass is present. This is why the biotrickling filter was originally equipped with load cells allowing the determination of the increase of reactor weight over time. Unfortunately, the load cells did not function properly and prevented monitoring of the weight increase. The only measure of biomass was by visual observation through the sampling ports along the column height which revealed that there was probably enough biomass attached to the packing. The exact amount could not be determined. In general, one estimates that a biofilm thickness of only 200-300 μm is sufficient. If the biofilm is too thick, parts of it become anaerobic, and no longer participate in the treatment. Visual inspection did not allow for determination of the extent of packing coverage with biofilm, nor did it allow for determination of wetting of the biofilm. These are important parameters which may have not been optimum, and may have affected the performance.

On the other hand, we know from other tests that the system can work well and that the packing is well suited for biotrickling filtration operation. For example, the biotrickling filter is presently being used at a wastewater treatment plant for the treatment of hydrogen sulfide. Initial tests have shown that more than 90% of 10-20 ppm of hydrogen sulfide are degraded in less than 20 seconds contact time (only one of the two column in series is used for this project). This represents good performance, indicating that the packing and the whole system are adequate for biotrickling filtration, and was not the cause of performance problems experienced at Edwards AFB.

In conclusion, the exact cause of the poor removal performance could not be firmly identified. It is likely that it was a combination of the following:

1. Repeated shutdowns that prevented the establishment of an optimum process culture. Such a behavior has been described before for the biodegradation of compounds requiring a long acclimation phase.[12]
2. Excessive temperatures in the reactor (most of the time the reactor temperature exceeded 40°C) which may have inhibited some of the pollutant-degrading organisms and may have slowed down the mass transfer of slightly soluble contaminants.

If timing had allowed, we would have set up bench-scale biotrickling filters in the laboratory, and optimized pollutant removal performance using a synthetic airstream generated with the 5-

10 major components detected in the Site 17 exhaust. Such studies would have been best conducted with 2-4 biotrickling filters in parallel, so that in the influence of several parameters could have been studied. It would have required another 6 months and about $60,000 of funding.

5.4 Analysis of System Upsets

As stated earlier, the biotrickling filter system experienced an unusually high number of equipment failures. The reasons are probably related to the harsh conditions encountered at Edwards AFB and aging of some electrical components. It was not unusual to have temperatures exceeding 120^{o}F at the site, which weakened electrical components. it was necessary to mount an air conditioning unit on the control box to keep the control equipment cool. Before this, temperature in the control box sometimes exceeded 150^{o}F. At the end of the project, there was a problem with the SVE blower, which kept the biotrickling filter system down a day. Usually, this is not too detrimental to the process culture, but this was at a time when the temperature would go below the freezing point which caused more damage to the process culture. GAC exchanges also resulted in long down time. Such long periods of pollutant starvation are detrimental to the biotrickling filter process culture, and should be minimized if biological reactors are to be further used for SVE exhaust treatment. Specific system upsets are described and analyzed below.

The biotrickling filter system initially failed due to the high rate of airflow (300 cfm). High airflow caused excessive back pressure and air and water to leak from the system. It took over a month to repair the seal on the system and to adjust the blower to a lower flow rate (~200 cfm). At the same time, the heat exchanger was modified to elevate the high-temperature shutdown point so that the system would operate without frequent shutdowns.

Table 5.7 summarizes the biotrickling filter system shutdowns between June 1, 1999 and December 14, 1999. The causes of system shutdown include power surges, biotrickling filter system failures, biotrickling filter system warming, interruptions for system maintenance, and special events. Power surges occurred frequently at the site, but most did not affect system operation. However, three of the power surges caused computer breakdowns and biotrickling filter system failure. Most biotrickling filter system failures were caused by the computer, the Labview control software configuration, the water level controllers, and load cell errors. Biotrickling filter maintenance included instrument calibrations and modifications. The SVE/AS system failures included blower shutdown due to high temperatures after the heat exchanger at the early stage of system operations, and at the end of operational stage by water condensation due to cold weather. Another cause of SVE blower down time was replacement of parts. The special events were manual system shutdowns for major sampling events, GAC replacement, and AFB special occasions.

Biotrickling filter system failures and air blower shutdown are the major causes of system shutdown, and represented 71% of the occurrences and 74% of the total downtime duration. Biotrickling filter maintenance was a minor factor in system down time (1%), although it was 12 % of the total number of system shutdowns (Figures 5.9 and 5.10). This is because biotrickling filter maintenance is mainly performed while the system is running, and because maintenance requires only short down time.

Table 5.7 Summary of the biotrickling filter system shutdown.

	Occurrences	Duration (days)			
Category		Total	Mean	Min	Max
Power surge	3	6.39	2.13	0.54	3.42
Biotrickling filter system failure	10	16.40	1.64	0.14	4.83
Biotrickling filter system warning	2	3.88	1.94	0.19	3.69
Biotrickling filter maintenance	5	0.37	0.07	0.05	0.09
Air blower	19	37.16	1.96	0.13	11.08
Special events	2	7.65	3.82	1.66	5.99

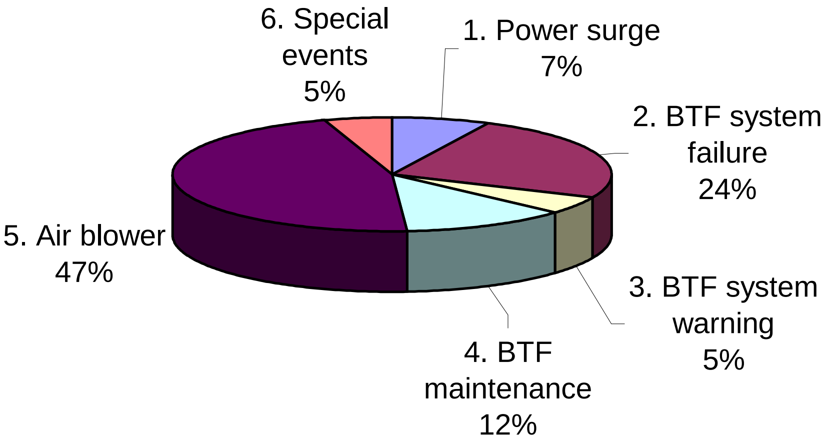


Figure 5.9 Distribution of the causes of system shutdown by number of occurrences.

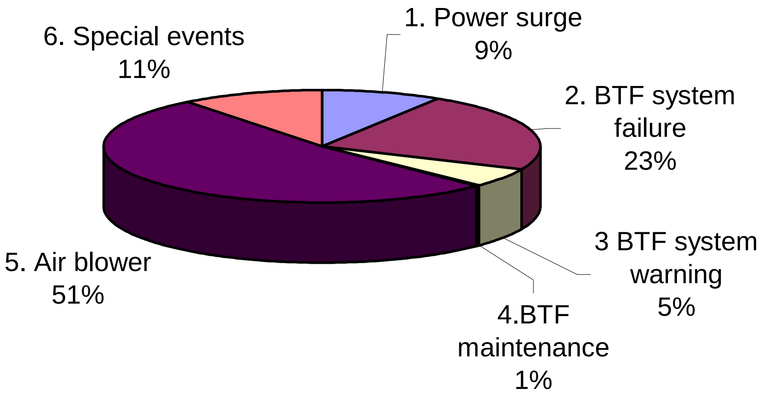


Figure 5.10 Distribution of the categorized causes of system down time by total duration.

Table 5.8 Detailed description of system shutdowns.

From	To	Duration (days)	Description
6/7/99 0:00	6/10/99 10:10	3.42	Power off- computer crash
6/15/99 15:05	6/17/99 8:50	1.74	Blower down
6/17/99 14:20	6/22/99 8:30	4.76	Blower down
6/30/99 10:00	7/1/99 12:30	1.10	Blower down
7/10/99 0:00	7/12/99 10:15	2.43	Power off
7/15/99 10:00	7/18/99 9:40	2.99	Computer repair
7/21/99 6:30	7/21/99 11:30	0.21	Biotrickling filter bypass-modem error
7/24/99 9:44	7/25/99 6:40	0.87	Biotrickling filter bypass-Labview error
7/27/99 10:30	7/28/99 11:47	1.05	Biotrickling filter repair-computer
7/30/99 13:40	8/10/99 15:30	11.08	Blower down
8/15/99 0:00	8/17/99 14:40	2.61	Computer repair
8/19/99 18:30	8/24/99 14:20	4.83	Computer down-system repair
8/27/99 18:30	8/31/99 11:00	3.69	Biotrickling filter bypass-high water press.
9/13/99 18:05	9/15/99 9:52	1.66	Main sampling event
9/8/99 16:40	9/8/99 17:45	0.05	Biotrickling filter maintenance-pH calibration
9/15/99 16:00	9/16/99 5:00	0.54	Power off
9/18/99 11:00	9/18/99 13:00	0.08	Biotrickling filter maintenance-sampling mod
9/22/99 21:00	9/23/99 0:10	0.13	Air compressor off
9/29/99 20:30	9/30/99 1:00	0.19	Biotrickling filter bypass- High air flow
9/30/99 21:00	10/1/99 2:12	0.22	Blower down
10/1/99 10:20	10/1/99 13:40	0.14	Level controller
10/5/99 19:47	10/6/99 12:10	0.68	Biotrickling filter bypass- High air flow
10/7/99 17:00	10/11/99 11:48	3.78	Biotrickling filter bypass- High air flow
10/11/99 11:48	10/12/99 9:30	0.90	Inlet line disconnection
10/15/99 10:30	10/15/99 12:30	0.08	Unknown
10/30/99 19:30	11/1/99 13:40	1.76	System failure-flooding
11/3/99 17:00	11/4/99 18:00	1.04	Computer down
11/5/99 16:25	11/5/99 18:10	0.07	Biotrickling filter maintenance-Level control
11/6/99 11:10	11/6/99 13:15	0.09	Biotrickling filter maintenance-computer replacement
11/10/99 10:36	11/16/99 10:20	5.99	GAC replacement
11/22/99 10:23	11/22/99 22:34	0.51	Blower overload
11/23/99 0:12	11/23/99 7:08	0.29	Blower overload
11/23/99 14:35	11/30/99 9:20	6.78	Blower overload
12/1/99 19:30	12/2/99 8:40	0.55	Blower overload
12/3/99 20:40	12/6/99 9:45	2.55	Blower overload
12/7/99 5:30	12/7/99 10:20	0.20	Blower overload
12/9/99 1:00	12/9/99 8:00	0.29	Blower overload
12/9/99 22:40	12/10/99 10:00	0.47	Blower overload
12/12/99 0:55	12/13/99 9:55	1.38	Blower overload
12/14/99 0:55	12/14/99 9:40	0.36	Blower overload

In retrospect, the biotrickling filter system probably included too much sophistication. This is useful to be able to remotely monitor the biotrickling filter, and is extremely convenient when all the components are functioning properly, but was quite detrimental to the performance when several components started to fail. In a previous project, the biotrickling filter proved reliable and had an up time of more than 99%.[26] This was no longer the case at Edwards AFB.

Biotrickling filters do not need to be complex. After the tests at Site 17, the biotrickling filter was stripped of all its controllers and electronic compounds, and simple switches and controls were installed. These include a low liquid level on-off switch for the liquid recycle pump, and a stand-alone pH controller. The liquid level, fresh water and nutrient supply are now via a series of pumps and timers. This proved to be extremely reliable. The reactor has been operating for 4 weeks now and has not experienced a single shutdown. Future biotrickling filter design should consider simple and reliable controls, especially when the reactor will be installed in a remote or harsh climate area.

5.5 Comparison of Biotrickling Filter Performance with Previously Published Work

While application of biotrickling filters to soil vapor air stripping is very new, there have been a few studies of biofiltration for this purpose. While this approach differs in that it doe not involve a moving water phase, there are some similarities, and examination of the results is helpful. However, one should keep in mind that the maximum performance of the biotrickling filter was probably not reached during this project.

A detailed study by Wright et al. (1997)[12] gives a good description of the possibilities and limits of biofilters for SVE exhaust treatment. They operated 4 small compost biofilters at a gas station performing SVE and treated the exhaust in compost biofilters followed by GAC polishing. Concentrations were high at start (1000 ppm TPH as hexane) and removals were negligible because of biofilter malfunctions. After 20 days acclimation, the biofilters operating at empty bed contact times of 2.7 minutes were able to degrade about 60-70% of an inlet TPH of about 300-400 ppm. The authors estimated that each 1.2 m^3 biofilter enabled saving about 2000 kg GAC over a period of 2.8 years. The cost savings were significant.

Douglass et al.[28] studied the application of biofiltration to the treatment of contaminated streams typically found in air stripper off gas. The initial phase of his study evaluated the properties and effectiveness of eight readily available and inexpensive packing materials for application to a simple, portable bioreactor. The second phase focused on bioreactor performance when using soil, peat, and fiberglass wool packings, which were identified as the better media. These materials were found to have removal rates of toluene and benzene of 69%-99%. Gasoline removal ranged from 21% to 61%. Maximum degradation rates were found to be 53 to 78 mg/min-m^3 (3.2 to 4.7 g/m^3/hr), respectively.

Devinny, et al.[29] operated a biofilter at a soil vapor extraction site. In the early months of the project, 25-50% of the gasoline was removed. Later, removal rates reached 40-75%. The detention time in the biofilter was 2 minutes, and inlet concentrations ranged from 99 to 1253 mg/m^3, averaging 796 mg/m^3. The elimination capacity was 13.7 g/m^3/hr. The average removal efficiency was 61%. It was concluded that biofilters were an economic choice in areas where discharge limits are less strict, or in combination with carbon post-treatment in areas where discharge criteria are more strict.

Acclimation

As previously described, it was hypothesized that the reason for the low treatment efficiency of the biotrickling filter was the frequent interruptions that prevented effective acclimation of the microbial ecosystem. This hypothesis is supported by the work of Medina and Devinny[30] (1992) on developing biofilters based on granular activated carbon (GAC). Detention time was 6.4 m in their bench-scale biofilters. Initially, high removal efficiencies (>90%) were achieved, primarily because of adsorption. However, the adsorption capacity of the GAC was exhausted within a month of operation. At this point, removal percentage fell to about 20%. After a period of four months of operation, the removal efficiency increased to 80 or 90% as biomass and biological activity increased. Because the biotrickling filter in this project was never allowed to acclimate for this period of time, this could be the explanation for the lower removal efficiencies.

Effects of Load

In general, it is expected that higher loads on biological treatment devices will increase elimination capacity, but reduce removal efficiency. The higher load produces higher concentrations that increase biological treatment rates, but more material also escapes (particularly if the load is increased by increasing flow rate rather than concentration).

Hodge et al.[31] (1991) tested bench-scale biofilters packed with GAC or diatomite on JP-5 jet fuel and diesel fuel. While results were variable, both fuels could be removed with efficiencies up to 90%. The maximum biodegradation rate for JP-5 was 5.3 g/m^3/hr, while that for diesel fuel was 1.3 g/m^3/hr. Devinny et al. (1993) reported elimination capacities for gasoline up to 100 g/m^3/hr for a biofilter in a heavily loaded system (up to 250 g/m^3/hr), but removal efficiencies were modest.

Devinny and Hodge[32] evaluated the use of biofilters for treatment of gasoline vapors. Five filter media were tested: granular activated carbon (GAC), compost, gromulch, calcinated anthracite, and GAC mixed with gromulch. Leaded gasoline severely inhibited the microorganisms, essentially preventing biodegradation of gasoline vapors. Gromulch was the most effective medium, supporting degradation of 10 g/m^3/hr. Three others, compost, GAC, and GAC/gromulch, supported degradation rates between 3 and 6 g/m^3/h. Gas chromatography was used to separate the gasoline vapors into five peaks. Compounds in the high-molecular-weight (slow-eluting) peaks were removed from the gas stream most efficiently. This may be because their lower vapor pressure kept concentrations high in the solids/water phase, promoting biodegradation.

Devinny et al.[33] carried out bench experiments to evaluate the effectiveness of biofilters for gasoline, jet fuel, and diesel fuel vapors. The lighter fuels degraded more rapidly than heavy fuels. More adsorptive media were more effective. Rates for biodegradation of gasoline were as high as 132 g/m^3/hr. Rates for diesel fuel reached 95 g/m^3/hr.

Variability with Compound

Gasoline is, of course, a mixture of many compounds. These differ in their tendency to pass into the water phase (measured by the Henry's constant) and in their intrinsic biodegradability. Treatment of some compounds may be quite successful while treatment of others is marginal, making it difficult to reach high removal efficiencies. The success of treatment will also vary with the composition of the vapors, and this can change during a soil vapor extraction project. As noted previously, Devinny, et al.,[29] operating a biofilter at a soil vapor extraction site, saw removal efficiencies rise from 25-50% to 40-75% as the project progressed. It was postulated that the improvement occurred both because the biofilter microbial ecosystem became acclimated, and because the composition of the gasoline vapors changed as the project progressed. The lightest, least soluble compounds were evaporated from the soil first, and were correspondingly just those that were most difficult to treat.

Apel, et al.[34] developed a biofilter for gasoline vapors. They found that biological removal can occur over a 22 to 40°C temperature range with removal being completely inhibited at 54°C. This may support the contention that extreme temperature conditions at the Edwards site contributed to problems in biotrickling filter performance. The addition of fertilizer to the bed medium did not increase rates of gasoline removal in short term experiments in the relatively fresh bed medium used. At lower gasoline concentrations, the absolute vapor removal rates were considerably lower than those at higher gasoline concentrations. This implied that system design facilitating gasoline transport to the microorganisms could substantially increase gasoline removal rates at lower gasoline vapor concentrations. Total BTEX removal was 50-55%. Removal of benzene was approximately 10-15% while removal of the other members of the BTEX group was much higher, typically, greater than 80%.

Medina et al.[35] performed a series of experiments to evaluate the effectiveness of biofilters for treating air contaminated with gasoline and diesel fuel vapors. Experiments were done using granular activated carbon or soil as the microorganism support medium. In each case, it was concluded that degradation was first order. Diesel degraded more rapidly than gasoline, presumably because it was more readily transferred to the water phase.

Hodge et al.,[36] in their bench-scale tests, found that jet fuel could be more rapidly degraded than diesel fuel. Presumably this reflects the degradability of their constituent compounds at high concentrations, where transfer to the water is not limiting. Devinny and Hodge[37] showed that there was a relation between the elution time on a GC for a compound and its treatability. Presumably compounds that are eluted later on the GC are also retained longer on the biofilter, and so are better treated. Devinny et al.,[38] in a study of quantitative structure-activity relationships for biofiltration determined that the octanol-water coefficient was an important descriptor of biofilter success for a specific pollutant. It was presumed that this represented the tendency of the contaminant to partition into the water phase. This suggests that the contaminants with high vapor pressures and low solubilities, such as the light fractions of gasoline, will be difficult to treat.

Devinny et al.[33] showed that under heavily loaded conditions, the elimination capacity for gasoline can be higher than that for diesel fuel. Douglass et al.[28] examined biofiltration of gasoline vapor and noted that removal of aromatics was more efficient than removal of gasoline as a whole.

6. TREATMENT COST DETERMINATION

In the present section, the specific costs for the exhaust air treatment at Site 17 are discussed. Since biotrickling filtration remains an experimental technique, some of the costs will decrease in the future as the technique matures. Hence projected treatment costs are also included.

Capital costs for the biotrickling filter

The prototype biotrickling filter used at Edwards AFB was valued at about $180,000, which included about $90,000 in materials and labor, and about $90,000 in engineering costs.[25] It should be stressed that this reactor included a lot of extra features such as controls and analytical instruments which are useful for research projects but not necessary for the proper functioning of the biotrickling filter. Also, the biotrickling filter was constructed in 304 stainless steel and included a trailer, and because it was the first of its kind, engineering costs were unusually high. Hence, a capital cost of $120,000 was used in Deshusses and Webster's calculations.[25] On the other hand, it is possible to construct biofilters or biotrickling filters at low cost with cheap materials such as polyethylene tanks. For such reactors, a cost of $50,000-80,000 for 10-20 m^3 reactors is more realistic.

In a more recent contribution which focused on the costs of large biotrickling filters, Deshusses and Cox[23] estimated that the capital costs of biotrickling filters could be described (± 20%) by Equation 6.1, where the reactor volume is in m^3:

$$\text{Total Reactor Investment Cost (\$)} = 13{,}000 \times \text{Reactor Volume}^{0.757} \qquad (6.1)$$

Although the relationship was initially developed for reactors with bed volumes ranging from 50 to 1000 m^3, it produces reasonable values for reactors of smaller size which are of interest for SVE/AS exhaust treatment (Table 6.1).

Table 6.1 Estimated costs, footprint and treatment capacity of biotrickling filter for SVE exhaust treatment.

Bed volume (m^3)	Investment costs (Equation 6.1) ($)	Approximate footprint[a] (m^2)	Approximate air flow that can be treated[b] ($m^3\ h^{-1}$) and (cfm)	
5	$44k	11	100 - 900 $m^3\ h^{-1}$	60 - 530 cfm
10	**$74k**	**13**	**200 - 1800**	**120 - 1060**
15	$100k	15	300 - 2700	180 - 1590
20	$125k	18	400 - 3600	235 - 2120
30	$170k	23	600 - 5400	350 - 3180

[a] Estimated using a 2 m bed height plus 8 m^2 for controls and auxiliary equipment; to convert to an approximate square footage, multiply by 10. [b] Calculated using EBRT of 20 s to 3 minutes.

Because of the uncertainties in the cost of the reactor, a reactor value of $100,000 was used, which is an average of the previously estimated value of $120k and the value returned by equation 6.1. Based on a 20-year reactor life and 7% interest, the yearly capital costs will be about $9300, or $775 per month. It should be noted here that as the biotrickling filtration technology matures, it is probable that very simple and very reliable biotrickling filters will become available. These bioreactors will probably have a minimum of controls and monitoring and therefore their cost could be much lower (20-40%) than that shown in Table 6.1.

Operating costs for the biotrickling filter

For the evaluation of the total operating expenses, the following costs were included.

1. Nutrients, chemicals and water
2. Electricity for the recycle pump and miscellaneous
3. Maintenance
4. Capital costs (amortization)

After the biotrickling filter is installed and the system started, maintenance is minimal, i.e., about 2-3 hours per week. Regular maintenance consists of cleaning the level controllers, checking their proper functioning, calibrating sensors and analytical devices, preparing the stock nutrient solution, checking spray nozzles, and general system inspection. Note that during the UCR/USC tests at Site 17, the biotrickling filter system required extensive troubleshooting, and that maintenance effort significantly exceeded the above mentioned 2-3 hours per week.

Table 6.2 Variable costs used for the calculation of the operating costs.

Item	Cost	Usage
Tap water (\$ m^{-3})	1.32[a]	30 -300 L day^{-1}
Mineral salts (\$ kg^{-1})	1.7[c]	10 - 100 kg month^{-1}
Sodium hydroxide (\$ kg^{-1})	1.32	2 kg month^{-1}
Electricity (\$ kWh^{-1})	0.05	4.2 kW
Personnel (\$ h^{-1})	40	10 h month^{-1}

[a]Combined water and sewage cost (estimated cost, source reference #25). [b]Premix fertilizers.

Table 6.3 Actual monthly operating costs for the biotrickling filter at Site 17.

Category	Costs (\$ per month)
Tap water	4
Mineral salts	20
Sodium hydroxide (pH control)	3
Electricity (5 HP water pump + 10% for miscellaneous)	150
Total chemicals and electricity	**\$177**
Personnel[a]	400
Total operating costs (personnel, chemicals + electricity)	**\$577**
Capital costs[b]	775
Total monthly treatment costs (sum all)	**\$1352**

[a]10 h per month at \$40/h. [b]Capital yearly costs are based on \$100,000 reactor, 20 year reactor life and 7% interest.

Examination of the numbers reported in Table 6.3 reveals that chemical costs to operate the biotrickling filter are very low. The electrical consumption for the liquid recycle pump was significant because the pump was overdesigned (5 HP). In fact, this pump has now been replaced by a 1.5 HP that provides very similar performance for a fraction of the cost of the previous pump. It is even conceivable that a smaller pump (0.5 – 1 HP) would be sufficient for a non-R&D application. Capital costs and reactor maintenance costs turned out to be the most significant expense. This shows the importance of careful design and material selection in order to minimize capital expenditures and avoid expensive repairs. This suggests that over-dimensioning biotrickling filters to allow for near complete removal of the pollutants undergoing treatment should be carefully evaluated. At some point, it will become cheaper to change the GAC in the polishing unit downstream of the biotrickling filter more frequently.

Maintenance of the biotrickling filter can probably be included in the daily or weekly routine of the SVE/AS maintenance schedule. The cost is significant. Overall the total costs for the treatment amount to about \$1752 per month, or \$7 per 1000 m^3 of air treated. This is relatively high compared to other biofiltration or biotrickling filtration work (these usually range from \$0.5-2 per 1000 m^3 treated). However, one should remember that the small scale of the biotrickling filter considered here increases unit costs. Also, in many instances, capital costs, maintenance and/or reactor repairs are not included in cost evaluation. The numbers of Table 6.3 reveal that they should be included to get the full picture of the costs, since they represent a major fraction of the total costs.

To place these costs of biotrickling filtration in perspective, the costs associated with the operation of the SVE/AS or with the catalytic oxidizer are listed in Table 6.4.

Table 6.4 Various monthly treatment costs at Site 17.

Category	Costs ($ per month)
Costs associated with any chosen treatment technique at Site 17	
Electricity for SVE blower (15 HP = 11 kW)	$396
Electricity for AS compressor (15 HP)	$396 if used 100% of the time $198 if used 50% of the time
Personnel, monitoring (10 hours at $40/hour)	$400
Costs associated with treatment using Earth Tech oxidizer alone: thermal model	
Electricity for combustion blower (1.5 HP)	$40
Natural gas usage (160,000 cf at $0.00597/cf) [a]	$955
Costs associated with treatment using Earth Tech oxidizer alone: catalytic model	
Electricity for combustion blower (1.5 HP)	$40
Natural gas usage (52,400 cf at $0.00597/cf) [b]	$313
Costs associated with treatment using GAC adsorption alone	
Cost for replacing the 3600 lbs. load of GAC	$3000
Costs associated with treatment using the biotrickling filter	
Chemicals and electricity for the biotrickling filter	$177

[a]Data from reference #39, second quarter 1998, inlet VOC concentration averaged 166 ppm. [b]Data from the 4th quartely report, average flow 326 cfm, mass removed, 559 lbs in 3 months, average concentration is 0.31 g m^{-3} or 55 ppm.

Natural gas usage is expected to vary with the inlet pollutant concentration and with the mode of the oxidizer (thermal or catalytic). In the following paragraphs, the change in the natural gas consumption was estimated as a function of the inlet VOC concentration. Only the case of the thermal oxidation is considered.

Data from the quarterly report[39] on remediation activities at Site 17, Edwards AFB by Earth Tech, collected over a 3 month period (second quarter 1998 data), show that the average air flow was 374 cfm (635 m^3 h^{-1}), and the TPH mass removed was estimated at 1,871 lbs. (849 kg over three months, or 624 lbs. $month^{-1}$). Thus the average VOC concentration in the air was about 0.62 g m^{-3}, or about 166 ppm_v as toluene. It is reasonable to assume that as the concentration of VOCs in the SVE air decreases, one will have to compensate it with an equal calorific value of natural gas. Thus, one can calculate the amount of natural gas needed as follows:

The monthly calorific value of TPH, on a toluene basis (17,600 BTU lb^{-1}) will be 1.1 10^7 BTU

If this had to be entirely compensated by natural gas (1,000 cubic feet (Mcf) of gas = ten therms = 10^6 BTU), one would need 11,000 cubic feet of natural gas in addition to the 160,000 cf used for when the TPH concentration is 166 ppm. Hence, as VOC concentration decreases, the estimated monthly costs for natural gas will be as in Table 6.5. Below a concentration of about 200-500 ppm, the change in natural gas usage over time is minor.

Table 6.5 Estimated monthly natural gas costs for treatment of Site 17 air in the oxidizer as TPH concentration in SVE/AS air decreases.

TPH (as toluene) concentration in the SVE/AS air (ppm)	Natural gas monthly usage (cubic feet)	Natural gas costs ($ per month)
2000	38468	230
1000	104734	625
500	137867	823
166	**160,000**	**955**
100	164,373	982
60	167,024	997
40	168,349	1005
20	169,675	1013
10	170,337	1017
5	170,669	1019

The costs for medium to low concentrations are relatively high but they are consistent with our previous comparisons with thermal oxidizers[25] where fuel costs of about $1 to $5 per 1000 cubic meter of air treated were estimated. This would amount to $450 to $2300 per month in the present case.

One should also compare the biological and thermal treatment costs with those of adsorption onto granular activated carbon (GAC). Site 17 was equipped with 2 vessels, each having 1800 lbs. of GAC. Earth Tech estimated that the TPH adsorption capacity of the carbon would be approximately 16% by mass, i.e., about 600 lbs. of volatile organics. The replacement cost for the GAC was about $3000, hence the following operation and cost for GAC treatment alone can be estimated (Table 6.6)

Table 6.6 Estimated treatment for GAC only at Site 17 (air flow used 374 cfm).

TPH (as toluene) concentration in the SVE/AS air (ppm)	Pounds of TPH removed per day (lbs/day)	Time between GAC change (days)	GAC costs ($ per month)
2000	251	2.4	37,622
1000	125	4.8	18,811
500	63	9.6	9,405
300	38	16	5,643
166	**21**	**29**	**3,123**
100	13	48	1,881
60	7.5	80	1,129
40	5.0	120	752
20	2.5	239	376
10	1.3	478	188
5	0.6	957	94

Other costs associated with GAC treatment are expected to be low since GAC adsorption units have no moving parts. Basic maintenance and monitoring will still be required to determine the time for the change in GAC, but these costs will be similar to those of monitoring biotrickling filters or thermal/catalytic oxidizers. Still, comparison of thermal/catalytic oxidizer and GAC treatment costs shows that when the TPH concentrations in the SVE/AS exhaust get below about 60 ppm, it is probably cheaper to switch to GAC adsorption, while at high concentrations GAC treatment is both impractical and not economically viable.

In many cases, biotrickling filters will have to be equipped with a GAC polishing unit, as was the case at Site 17. This may be required by the regulatory agency or simply because the safety of a backup treatment is desired. In any case, the biotrickling filter should probably be designed so that the biotrickling filter exhaust TPH concentration is below 20-40 ppm and the GAC costs are kept low. There is presumably an optimum in the biotrickling filter size that will minimize the overall treatment costs. The optimum design will depend (amongst other things) on the pollutant biodegradation kinetics in the biotrickling filter, and the size of the site and the type of pollutant treated (which will determine the rate of cleanup).

A summary of the general cost evaluation is presented in Table 6.7. Unfortunately, it is difficult to obtain a good level of confidence for the TPH removal in the biotrickling filter. Therefore, two cases were considered: the first, which is a low estimate, assumes TPH removal of 80 ppm and is independent of concentration, and the second, which is based on present lab data, assumes 200 ppm removal. It should be noted that the second case is not an exaggeration of current performance. Based on our current knowledge it should be possible to sustain a degradation of at least 200 ppm with 90% or more removal in the field. Examination of Table 6.7 reveals that above 400-500 ppm, the thermal oxidizer is most economical. In the range of 50 to about 400-500 ppm, the biotrickling filter is the best control technology, and below 50 ppm, GAC adsorption is preferred. As stressed before, it is likely that as biotrickling filtration matures, performance will improve and cost will decrease, which will enlarge the window of possible applications for biotrickling filters.

Table 6.7 Summary of the overall estimated treatment costs for the different techniques.

	Thermal oxidizer	**GAC**	**Biotrickling filter[c]**	**Biotrickling filter[d]**
Monthly costs ($)				
Capital costs[a]	1008	388	775 (+388 if GAC is needed)	775 (+388 if GAC is needed)
Monitoring	400	400	400	400
Chemicals,[b] inlet TPH is 500 ppm	823	9405	8078	5820
Chemicals,[b] inlet TPH is 166 ppm	955	3123	1795	177
Chemicals,[b] inlet TPH is 100 ppm	982	1881	553	177
Chemicals,[b] inlet TPH is 50 ppm	1005	752	177	177
Chemicals,[b] inlet TPH is 10 ppm	1017	188	177	177
TOTAL monthly costs ($)				
Inlet TPH is 500 ppm	2231	10193	9641[e]	7383[e]
Inlet TPH is 166 ppm	2363	3911	3358[e]	1352
Inlet TPH is 100 ppm	2390	2669	2116	1352
Inlet TPH is 50 ppm	2413	1540	1352	1352
Inlet TPH is 10 ppm	2425	976	1352	1352

[a] Over 20 years, 7% interest; capital costs were estimated for the thermal oxidizer and for GAC at 1.3 and 0.5 times the capital costs of biotrickling filtration, respectively. [b] nutrients, water and electricity for biotrickling filter, GAC only for GAC, or natural gas only for the thermal oxidizer. [c] Low biodegradation is assumed (80 ppm) and GAC polishing, if necessary; [d] High biodegradation is assumed (200 ppm) and GAC polishing, if necessary. [e] Probably wiser to install a larger biotrickling filter to obtain better removal of TPH in the biotrickling filter.

7. CONCLUSIONS AND SIGNIFICANCE OF THE RESULTS FOR THE AIR FORCE

Biological treatment of contaminated air is an emerging technology which will play an increasingly important role in the future. This is because other technologies such as incineration are being severely scrutinized and their application restricted due to the possible release of other toxics such as dioxins and nitrogen oxides. As the technology matures, a greater confidence will exist in installing biological systems for SVE exhaust air treatment. The Air Force has a large number of sites contaminated with volatile organics and petroleum hydrocarbons (jet fuel or gasoline). Many of these sites will undergo remediation in the next 20 years. Clearly, biological treatment in a biofilter or a biotrickling filter should be considered as an alternative to conventional treatment. In most cases, the bioreactor will be followed by another treatment technique, probably adsorption, which will remove the compounds that are difficult to biodegrade or are recalcitrant (for example, highly chlorinated compounds). A key question when evaluating biological treatment for SVE/AS exhaust treatment will be that of the efficacy of treatment for a given reactor at given conditions. It is probable that for the next few years, pilot tests may be needed to answer that question, to properly design the bioreactor. This will be the case until documentation of a sufficient number of cases will allow to extrapolate directly from past applications.

The results of the present study suggest that biotrickling filter design should be simple and rugged. Sophisticated monitoring devices can be included if desired, but the number of feedback controls should be limited to the strict minimum so that reactor operation is kept independent of complex electronics. During operation at Site 17, most of the biotrickling filter down time was due to aging of the electrical connections, faulty sensors, or computer problems. Presently, the reactor is working with only one mechanical switch, and it has not experienced any down time between April 5 (date of start) and to this time (June 14). Thus, in the process of designing and building reactors, simplicity and reliability should be emphasized. Building simpler reactors will drive the equipment cost down, it will simplify maintenance, and it will increase the competitiveness of biotrickling filtration against other technologies.

In terms of treatment performance, the present study demonstrated that biotrickling filtration can degrade gasoline constituents. At high concentrations (600-1200 ppm TPH) and at an empty bed contact time of 94 seconds, about 200 ppm could be removed. At concentrations of about 150-200 ppm, about 50-60 ppm could be removed, while at inlet concentrations of 40-70 ppm, about 50% of the inlet concentration could be degraded for the same contact time. This is relatively modest performance, most probably because the operation was characterized by very frequent shutdowns and difficult conditions which prevented the maximum performance from being attained. Unfortunately, further testing would be needed to gather the necessary data to correctly size a biotrickling filter for the treatment of SVE/AS exhausts. However, from our tests, it is reasonable to conclude that higher performance can be obtained if the reactor down time can be minimized, and if the operating temperature can be maintained below about 98^{o}F.

In terms of treatment costs, the present study demonstrated that biological treatment is probably the least expensive technique if the range of concentration is between about 40 ppm and 400-500 ppm. One can reasonably speculate that as the technology further matures, the range of applicability of biotrickling filtration will further extend to both lower and higher concentrations.

8. RECOMMENDATIONS

The following is recommended to the Air Force:

1. Further experimental evaluation of biological techniques for air treatment should be conducted. In particular, comparative studies of biofilters and biotrickling filters should be conducted.

2. When considering biological treatment for SVE/AS exhaust treatment, conducting short term (6 months) laboratory tests to assess the treatability of the main contaminants should be considered to collect key pollutant removal data for reactor sizing.

3. Bioreactors for contaminated air treatment should be built with simple controls to minimize the possibility that component failure causes down time. In the event a sophisticated process control is installed, one should consider installing a redundant simple system to operate the system when the complex controllers fail.

4. The choice of SVE blower should consider that for effective treatment in a biological reactor, the temperature of the air discharged by the blower should not exceed about 98°F.

5. If a GAC post-treatment is to be installed after the biotrickling filter, the design of the biotrickling filter should consider including effective means (demisters, water knock out) to reduce carry over of free water to the GAC and possibly heating the air prior to GAC unit to maximize the use of the GAC adsorptive capacity.

6. Further studies should be conducted to determine the optimum SVE/AS/treatment train configuration and overall system operation that will minimize remediation costs.

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