# Biotreatment of Odors from the Zimpro Sludge Conditioning Process

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## ABSTRACT

Management of odor emissions generated during thermal sludge conditioning is a well known disadvantage of the "Zimpro" process. Traditional methods of using chemical oxidation and high temperature destruction result in the formation of secondary products, such as chlorine gas, organic halocarbons or nitrogen oxides. In this study, biotrickling filter technology was evaluated at the Villa Hills wastewater treatment plant, operated by Sanitation District No. 1 in Northern Kentucky. The objective of this pilot-scale study was to assess the performance of PRD Tech's biotrickling filter for treating the headspace air of the sludge tanks, which hold heat treated sludge before filtration and landfill disposal. Air samples were taken from the inlet and outlet of the biotrickling filter, and analyzed using an odor panel, odor meter (Sensidyne Inc., Clearwater, FL), and measurement of detection and recognition thresholds by an independent laboratory (St. Croix Sensory, Inc., Stillwater, MN). Experimental results demonstrated that PRD Tech's biotrickling filter was able to significantly reduce Zimpro process odors from the sludge holding tanks, achieving greater than 99.9% reduction in the detection and recognition thresholds. Further, the biotrickling filter's performance was manipulated by varying the inlet concentration of ammonium chloride in the nutrient mixture. Sensidyne's odor monitor readings were correlated with the odor panel's response and the detection and recognition threshold values. Preliminary economic analysis has shown that biotrickling filter is a cost-effective technology for odor abatement at wastewater treatment plants.

## INTRODUCTION

The thermal sludge conditioning process of U.S. Filter/Zimpro Corporation, Rothschild, Wisconsin (Zimpro process) is a well-known technology for sludge conditioning at municipal wastewater treatment plants. Sludge is conditioned expressly to improve its dewatering characteristics. The two methods most commonly used involve heat treatment and the addition of chemicals. Heat treatment is both a stabilization and a conditioning process that involves heating the sludge for shorter periods of time under pressure. This method is used to coagulate solids, break down the gel structure, and reduce the water affinity of sludge solids.

The Zimpro process entails a partial breakdown through oxidation and hydrolysis of complex, high molecular weight organic compounds, such as, proteins, fibres, carbohydrates, and fats.

The partial breakdown of chemical bonding results in the formation of smaller chain, volatile, lower molecular weight organic substances. These compounds are generally described in the literature on Zimpro process to be aldehydes, ketones, volatile organic acids, alcohols, esters, and some alkanes (primarily methane). A gas chromatographic analysis of the compounds present in the spent process vapors has typically identified peaks of methane, methanol, ethanol, methyl formate, acetaldehyde, acetone, etc. followed by several unidentified peaks indicating the presence of complex organic substances.

The volatile organics formed due to chemical breakdown of the sludge are the source of odors, characteristic of the Zimpro process, which have very high values for the detection and recognition thresholds (DT and RT). Detection and recognition thresholds are defined as volume ratios of carbon filtered air to air sample volume, which represent the minimum dilution level above which the odors cannot be detected (Detection threshold, DT) or recognized (Recognition threshold, RT) by a trained human odor panel. Standard ASTM method is used to measure the detection and recognition thresholds.

## ODOR CONTROL TECHNOLOGIES

Traditionally, odor control has been achieved by oxidation using chemical scrubbers and conventional biofiltration methods using compost media. The chemical scrubbing methods to treat (oxidize) the odorous organic compounds generated during the Zimpro sludge thickening process commonly use oxidizing agents such as chlorinated water, sodium hypochlorite, hydrogen peroxide, and potassium permanganate solutions. The hydrogen peroxide is a weak oxidizing agent requiring considerable reaction time (15 to 20 minutes) and effective treatment is achieved only if added upstream of the headworks. The permanganate solutions are strong oxidizing agents; however, they are difficult to handle as a dry powder and require a high dosage to be effective. The hypochlorite solutions have been used for scrubbing odorous gases, and in many cases, scrubbers have been staged to increase the overall removal efficiency. The addition of chlorinated water for chemical scrubbing operation is generally effective when treating odors containing hydrophilic compounds (high mass transfer rates to water). When the odorous compounds are hydrophobic, such as the branched chain compounds which usually exhibit low aqueous solubility, mass transfer into the liquid phase limits the odor removal efficiency. The chemical handling hazards, potential release of halocarbons into the environment as a result of the chemical reaction of chlorinated water with the odorous gases, and pumping costs are other operating considerations with a chemical oxidation treatment system.

Other treatment methods, such as, thermal incineration, or catalytic oxidation have even greater disadvantages when compared to chemical oxidation which includes:

- High investment and operating costs (natural gas consumption)
- Generation of nitrogen oxides from the nitrogen present in odorous compounds and air
- Increased generation of carbon dioxide, a greenhouse gas
- Thermal pollution due to higher operating temperatures

Biofiltration is gaining wide recognition as a viable alternative that offers potential cost advantages when compared to other control technologies currently used at wastewater treatment plants. The major potential cost advantages are operational, specifically no supplemental fuel requirements or catalyst replacement (associated with plugging and/or fouling of catalytic oxidizers). An additional advantage of biofiltration over thermal or catalytic oxidation is that it does not produce nitrogen oxides or excess carbon dioxide (greenhouse gas).

## BASICS OF BIOFILTRATION

Biofiltration involves biological destruction of the odorous compounds by active microbial populations present in or on a support media. The support media can be broadly classified into two main types[1]: (1) Naturally bioactive media, such as soil, peat, compost, etc.; and (2) Synthetic media. In naturally bioactive support media, the active microorganisms are immobilized inside the porous support matrix, while in the synthetic media, the active microbes are usually supported on the media surface in the form of biofilms.

Soil biofilters are relatively large compared to filters using other media since soil pores are smaller and compounds have low permeability in soil. Soil biofilters also have limited depths due to problems associated with maintaining humidity and minimizing pressure drop. Further, limited soil sorption capacity for organics results in poor performance and large biofilter sizes.

Compost biofilters exhibit higher removal rates for hydrophobic compounds than biofilters which use activated sludge organisms. However, compost biofilters suffer from low degradation capacity, gas channeling and require elaborate control of water content[2] to prevent drying of the compost media. Both of these effects adversely impact biofilter performance. Further, the nitrogen content of the compost media gets depleted and eventually require replacement of the compost media. The products of biomass decay cannot be washed out of the filters and the replacement interval has not been well established as a function of VOC loadings. Low degradation rates result in large biofilters which are expensive and cumbersome to install. Shallow beds with very large footprints are required to minimize evaporation losses, which result in drying of the compost media. Hence, while compost organisms have advantages for biodegradation of hydrophobic compounds, there are significant disadvantages in using compost biofilters, especially when the odorous gases contain significant quantities of biodegradable organic material. Further, gradual acidification of the compost beds results in inhibition of biological activity, which eventually decreases compost bed efficiency. Therefore, compost biofilters handling acidic compounds require periodic replacement of the media, resulting in significant operation and maintenance costs associated with landfilling of the compost bed material.

Biotrickling filters using synthetic pelletized and structured media are gaining recognition, as an excellent alternative for treatment of air streams with higher organic loadings. Synthetic media biofilters, as compared to natural media biofilters, also allow effective control of biomass build-up. Extensive research has been conducted at the Department of Chemical Engineering, University of Cincinnati for more than a decade, through funding by USEPA, Cincinnati, on the development of synthetic media biotrickling filters for odor/VOC control applications[3,4]. These biofilters are able to handle higher concentrations of VOCs without the eventual build-up of biomass. PRD Tech, Inc., a small business company established in Florence, Kentucky is involved in marketing these biofilters for commercial applications.

## DESIGN OF PILOT-SCALE BIOTRICKLING FILTER

A skid-mounted pilot scale biofilter system on wheels was designed and assembled for performing the study at the Sanitation District facility. This system was designed to handle air flows of 50-100 standard cubic feet per minute (scfm). A flexible 2” hose was lowered into the underground sludge tanks through holes drilled in the tank lids, to enable withdrawing odorous gases from the headspace. A schematic of the single stage biotrickling filter system used to perform the study at the Sanitation District facility is shown in Figure 1. The incoming odorous gas, estimated at temperatures up to 180$^{o}$F, was first cooled in the Cooling Tower to achieve a desired inlet temperature of 75$^{o}$F to 90$^{o}$F entering the biofilter bed. The cooling tower contained a 20% glass filled polypropylene packing material. Fresh tap water was sprayed continuously from the top using a ½” NPT, 105 degree spray heads, to produce uniform jet of water flowing at 0-5 gallons per minute (gpm) countercurrent to odorous gases entering the cooling tower at the bottom. The water leaving the cooling tower was allowed to drain into the underground sludge tanks using a gravity flow pump operating on a level sensor mechanism, installed approximately 6” from the bottom. The cooled odorous gases exited the cooling tower at the top and passed through the biofilter tank containing the proprietary packing material, which had the active biofilm established on its large surface area. The packed media height was five feet in both tanks and they were each two feet in diameter and seven feet tall. The odorous gases were passed co-current from top to bottom in the biofilter bed, with a small flow of nutrients trickling down through ½” NPT, 105$^{o}$ angle spray heads, producing uniform flow at approximately 1.0 gpm. Minimal cell decay products were generated during this study and were returned to the sludge tank.

## SAMPLING PROCEDURE

Air samples were collected from each sampling location in 10-liter tedlar bags for analysis by the odor panel. The sample ports were ¼” diameter openings. The inlet sampling location was at the 2” ID air inlet line at the bottom of the cooling tower. The exit was a similar opening in the biofilter tank, just above the 2” air exit line.

A Supelco sampling apparatus equipped with a small sampling pump and a rotameter was used to collect the air samples. A flexible ¼” tubing was connected from the sample port through the ¼” fitting in the Supelco apparatus, to a tedlar bag. The apparatus was closed tight with the tedlar bag in place, and the sampling pump was turned on to create a vacuum in the headspace. The negative headspace pressure allowed the tedlar bag to inflate, withdrawing air from the sample ports at an adjustable rate of 0-5 liters per minute (lpm). The sampling pump was automatically turned off by a level strip circuit breaker switch located at the top of the apparatus, when the bag was fully inflated. The tedlar bag valve was closed immediately, labeled, and removed from the apparatus.

Air samples were collected from the inlet and exit of the biofilter system. Each sample was labeled using a unique identification method that indicated the sampling date and location (inlet, exit, or other).

## ODOR PANEL ANALYSIS AND CALIBRATION

A local odor panel, consisting of at least 7 people, were used to evaluate the relative concentration of odors in each sample. Each odor panel member inhaled the sample by manually pressing the tedlar bag, and recorded the relative strength of the odors on a 1 (no odor detected) to 10 (maximum odor concentration) scale[5]. Some samples were analyzed both by the odor panel and also sent to St. Croix Sensory Laboratory for measurement of detection and recognition thresholds. The objective of conducting both analyses was to develop a correlation between the local odor panel response and the detection and recognition thresholds, as determined by a trained odor panel at the St. Croix Laboratory. It was not possible to send all the samples to St. Croix, due to high cost of analyzing each sample by the trained odor panel.

Samples were also collected directly from the sludge tank headspace (inlet of the biotrickling filter) and new samples were synthesized at various dilution levels (5% raw sample with 95% carbon filtered air, 10%, 15%, 20%, 50%, 60% and 70%) for calibrating the local odor panel.

The average odor panel responses for each synthesized odor sample were calculated and plotted versus the odor removal efficiency, defined as follows:

% Removal Efficiency = (100 - % Concentration of Zimpro Odors in the Sample) (1)

Figure 2 shows the % Removal Efficiency plotted versus the average local odor panel response. Carbon filtered air sample, containing 0% Zimpro odors, and corresponding to 100% removal efficiency, resulted in local odor panel responses between 0 and 3. Higher percentages of Zimpro odors, corresponding to lower % removal efficiencies, produced higher average odor panel responses. Earlier studies have shown that the odorous compounds in Zimpro odors are biodegradable.

A membership function was generated, which best represented the actual calibration data, and the values assigned to the membership function for different values of % removal efficiency are shown in Figure 2. The membership function was assigned a 100% removal efficiency when the average odor panel response was less than or equal to 3.0. The limiting value of 3.0 was selected since odor panel evaluation of carbon filtered air showed that responses generally varied between 1-3, although the samples contained no odors. The variability in the responses is mainly due to the subjective nature of human odor detection measurements.

The selected membership function provided a useful correlation to derive the % removal efficiency from the average odor panel response. It should be noted that the membership function closely agrees with the calibration data, except when the odor panel response is 7.0 or greater. The calibration data decreases linearly when the odor panel responses are greater than 7.0, while the membership function is assigned a value of 0. This provided a more conservative estimate of % removal efficiency, especially for low removals, since in the case of Zimpro odors, low removal efficiency essentially means that the treated air smells just as bad as the untreated air.

## RESULTS AN DISCUSSION

### Biotrickling Filter Removal Efficiency

Using the membership function, shown in Figure 2, the average local odor panel responses were converted to biotrickling filter % removal efficiencies. Figure 3 shows the average percent biotrickling filter removal efficiency versus sampling date. Replicate data points, generated from duplicate sample, are indicated by a vertical line in the figure. The biotrickling filter performed at an average percent removal efficiency exceeding 80% for 64% of its operating time. The large variability between duplicate samples is typical of human odor panels, demonstrating that odor perception is very subjective. Further, Zimpro odors adsorb strongly to clothing, skin, hair, etc. and hence it was very difficult to prevent the desorption of odors during the odor panel testing, resulting in high odor panel responses even when the sample was relatively odor free.

## Effect of Ammonium Concentration in the Nutrients

Experiments were conducted with three levels of ammonium ion concentrations in the nutrients used in the biotrickling filter. The mineral nutrients mainly consists of phosphates and ammonium compounds, which provide the nitrogen and phosphorus needed for microbial growth. As the concentration of the ammonium ion was increased, the performance of the biotrickling filter also improved (detection and recognition thresholds for the treated gas decreased), although the increase in performance was marginal beyond an ammonium ion concentration of 25 mg/L. Figure 4 shows the impact of ammonium ion concentration in the mineral nutrients on the exit gas detection and recognition thresholds. The ammonium ion concentration decreased with time, and an exponential equation was found to fit the ammonium concentration data:

$$C_{NH4} = 25 \exp(-0.038t) \qquad (2)$$

Where $C_{NH4}$ is the ammonium ion concentration in the mineral nutrients (mg/L), and t is the time (hours) elapsed after addition of fresh nutrients. Volatilization of ammonia was found to be negligible. The above equation shows that the ammonium ion concentration decreased from an initial value of 25 mg/L to a final value of 1 mg/L after 84 hours of operation.

The effect of ammonium ion concentration shows that the performance of the biotrickling filter can be manipulated by varying the concentration of the ammonium ion in the mineral nutrients. This allows the biotrickling filter performance to be manipulated automatically, based on the odor concentration in the biofilter treated gas.

## Detection and Recognition Thresholds

Table 1 summarizes the results of detection and recognition thresholds (DT and RT), as measured by St. Croix Sensory Laboratory for the samples that were shipped from the inlet and outlet of the biotrickling filter. The results show that the detection threshold (DT) varied in the range of 4,100 to 28,000 and the recognition threshold (RT) varied from 1,800 to 16,000. This was mainly due to variations in the treated sludge concentrations in the sludge tanks. When both Zimpro units were operating, the concentrations of the odor compounds in the sludge tank headspace was expected to be higher than when only one Zimpro unit was running. Further, the liquid level in the sludge tanks varied, and this also impacted the odor levels in the tank headspace.

It should be noted that the odor descriptors, given in Table 1, are typical of Zimpro odors. Since chlorine addition was on-going during the duration of the biotrickling filter test, chlorine gas was present in the tank headspace, as described by the trained odor panel as “chlorinous”. The presence of chlorine gas at the inlet of the biotrickling filter also caused upsets in biofilter operation, since chlorine is a known anti-bacterial agent.

The detection and recognition thresholds for the gas samples taken from the exit of the biotrickling filter were substantially reduced, as compared to the inlet values. Table 1 summarizes the percent reduction in detection and recognition thresholds due to biodegradation of the odorous compounds in the biotrickling filter. Clearly the odorous Zimpro compounds are biodegradable, and hence undergo biotransformation and/or biomineralization in the biotrickling filter.

The detection and recognition thresholds were also correlated with the average odor panel responses. A linear correlation was derived between the DT and RT values and the average odor panel responses, and this allowed DT and RT values to be estimated for gas samples that were not sent to St. Croix Sensory Laboratory for analysis. The linear correlations that were found were as follows:

$$\text{Log (DT)} = 1.2 + 0.416 \times r \qquad R^2 = 0.82 \qquad (3)$$

$$\text{Log (RT)} = 0.72 + 0.44 \times r \qquad R^2 = 0.74 \qquad (4)$$

where DT is the detection threshold, RT is the recognition threshold, and r is the average odor panel response. It should be noted that according to these correlations when the average odor panel response is 3.0, the detection threshold is 281 and recognition threshold is 110, which represent the maximum values for 100% removal efficiency of the biotrickling filter.

Figure 5 shows a plot of calculated DT values, derived using the linear correlation, for the inlet and outlet gas samples from the biotrickling filter. There were wide fluctuations in the inlet DT values; however, the biotrickling filter was able to maintain substantial reduction in DT values, as shown in Figure 5. Similar performance was achieved for the RT values.

## Odor Monitor Measurements

The performance of the odor monitor (Sensidyne Inc., Clearwater, FL) was tested in this study with the objective of using the monitor for on-line control of the biotrickling filter. Since it is not possible to control odor control processes based on odor panel responses, an automatic control system could be developed which operates the nutrient flow rate valve based on the odor monitor readings of the treated air, exiting the biotrickling filter. It has been shown earlier that increasing the concentration of the ammonium ions can improve the performance of the biotrickling filter.

The calibration samples were analyzed by the odor monitor and Figure 6 shows the plot of log(meter reading) versus the log (percent concentration of raw Zimpro odors). When the Zimpro raw odor concentration exceeded 15%, the meter reading had almost attained full-scale reading of 2000 odor units and required more than 20 minutes to attain a stable reading. The meter response was fitted to the concentration of Zimpro odors and a satisfactory linear correlation was achieved on a log-log plot, as shown in Figure 6. This correlation can be used to control the biotrickling filter process, by using the meter reading to infer the % concentration of Zimpro odors in the exit treated gas, and hence obtain the percent treatment efficiency of the biotrickling filter.

The meter reading was also correlated with the average odor panel responses as shown in Figure 7. The correlation showed that below an average odor panel response of 2.6, the meter reading was very close to zero, which agreed with the earlier finding that when the average odor panel response was 3 or less, the % removal efficiency of the biotrickling filter was 100% or there were no detectable odors in the exit treated gas. Hence, it can be concluded that the odor monitor readings were consistent with the average odor panel responses, and that the meter readings could be used to automatically control the biotrickling filter. The only limitation of the meter was that a gas sample would have to be diluted sufficiently to maintain the raw Zimpro odor concentration less than 15% or less to prevent the meter from saturation or attaining full-scale value.

## ESTIMATED COSTS FOR BIOTRICKLING FILTER

Preliminary capital and operating costs were estimated for the biotrickling filter, and the following assumptions were made in this analysis: (1) operating labor requirements are 0.5 hours per shift; (2) maintenance labor requirements are 0.5 hours per shift; (3) maintenance materials are 2% of the total capital cost; (4) electricity requirements to operate the blower system are 0.306 kWh per 1,000 $m^3$ of gas; (5) equipment operates 8,000 hours per year; and (6) capital is borrowed at 10% interest rate and the site preparation costs are fixed at $7,500. Tables 2 and 3 summarize the cost parameters used in the cost estimations. Figure 8 shows the Total Capital Cost as a function of gas flow rate (scfm), and the total capital cost includes the cost of PRD Tech’s proprietary support media, installation and instrumentation. Figure 9 shows the Annual Operating Cost as a function of gas flow rate (scfm), and operating cost includes electricity costs, operation and maintenance costs for the biotrickling filter. It should be noted that the cost estimations are ± 30% and more detailed engineering analysis, for a specific site application, are required to provide a more accurate assessment of biofilter treatment costs.

## CONCLUSIONS

The pilot-scale study described in this paper demonstrated that biotrickling filters are capable of treating Zimpro odors, resulting in significant reduction of odor emissions. Currently, emissions of odors is a major disadvantage of the Zimpro sludge conditioning process, which otherwise is capable of producing a fairly dry sludge cake. The pilot-scale biotrickling filter used PRD Tech’s proprietary support media and was operated at the Sanitation District’s waste water treatment plant for a period of 4 months. A local odor panel (consisting of at least 7 members), in addition to measurements of detection and recognition thresholds and odor monitor measurements were used to assess the performance of the biotrickling filter system. A membership function, generated from calibration data, was used to convert average odor panel responses to a biofilter removal efficiency. Linear correlations were generated between the detection and recognition thresholds, the odor monitor readings, and the average odor panel responses. The pilot-scale biotrickling filter showed significant reductions in detection and recognition thresholds (> 99.9%), and it was shown that the concentration of ammonium ions in the liquid nutrients had a major impact on biofilter performance. It was also concluded that the odor monitor (Sensidyne Inc., Clearwater, FL) was capable of quantifying the odor concentrations and could be used for automatic control of the biotrickling filter system by manipulating the liquid nutrient flow rate. Preliminary cost estimates has shown that the biotrickling filter is a cost-effective treatment technology for treating odors at waste water treatment plants, especially Zimpro odors.

## ACKNOWLEDGMENTS

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**Table 1.** Values of Detection (DT) and Recognition (RT) thresholds for the Inlet and Outlet gases.

| **Sample Location** | **Detection Threshold (DT)** | **Recognition Threshold (RT)** | **Odor Descriptors** | **% Reduction in Detection Threshold** | **% Reduction in Recognition Threshold** |
|---|---|---|---|---|---|
| Inlet(12/9/97) | 4,100 | 1,800 | Foul, Burnt, Sewer, Chlorinous, Chemical | | |
| Exit (12/9/97) | 1,700 | 660 | | 58.5% | 63.3% |
| Exit (12/9/97) (Duplicate) | 1,100 | 440 | | 73.2% | 75.6% |
| Inlet (12/18/97) | 5,200 | 2,100 | Foul, Chemical, Pungent, Chlorinous, Bleach | | |
| Exit (12/18/97) | 200 | 70 | | 96.2% | 96.7% |
| Inlet (1/7/98) | 13,000 | 5,000 | Foul, Rotten, Pungent, Sour | | |
| Exit (1/7/98) | 30 | 14 | | 99.8% | 99.7% |

**Table 2.** Cost Parameters for Estimating Total Capital Cost of the Biotrickling Filter.

| Cost Item | Factor |
|---|---|
| **Direct Costs** | |
| Taxes | 0.03 x Capital Cost |
| Freight | 0.05 x Capital Cost |
| TOTAL INSTALLED DIRECT COST (TIDC) | Capital Cost + Taxes + Freight |
| Site Preparation Cost | Assumed to be fixed at $7,500 |
| TOTAL DIRECT COST (TDC) | TIDC + Site Preparation Cost |
| **Indirect Costs** | |
| Engineering and Supervision (E&S) | (1.08/1.404) x TIDC |
| Construction and Field Expenses (C&FE) | 0.15 x (1.08/1.404) x TIDC |
| Startup and Performance Test (S&PT) | 0.03 x (1.08/1.404) x TIDC |
| Contingency (CON) | 0.03 x (1.08/1.404) x TIDC |
| TOTAL INDIRECT COST (TIC) | (E&S +C&FE+S&PT+CON) |
| **TOTAL CAPITAL COST** | TDC + TIC |

**Table 3.** Cost Parameters for Estimating Annual Operating Cost of the Biotrickling Filter.

| Cost Element | Unit Cost Factor |
|---|---|
| **Direct Annual Cost** | |
| Electricity | $0.0596/kWh |
| Operating Labor | $12.96/hr |
| Maintenance Labor | $14.26/hr |
| Supervisory Labor | 15% of operating Labor |
| Maintenance Materials | 2% of Total Capital Cost |
| **Indirect Annual Costs** | |
| Overhead | 0.6 x Maintenance |
| Property Tax | 1% of Total Capital Cost |
| Insurance | 1% of Total Capital Cost |
| Administrative | 2% of Total Capital Cost |
| Capital Recovery | 0.1628 x Total Capital Cost<br>(Assuming 10 year life and 10% interest rate) |

**Figure 1.** Schematic of the Pilot-Scale Biotrickling Filter Used in this Study.

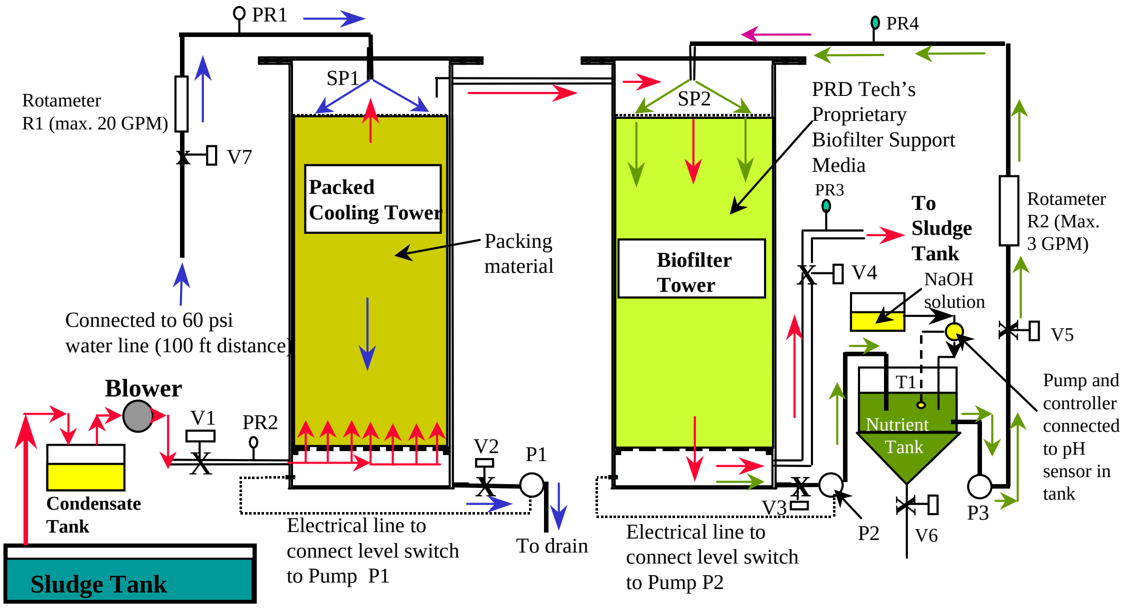

**Figure 2.** Plot of Calibration Data for Odor Panel and Membership Function.

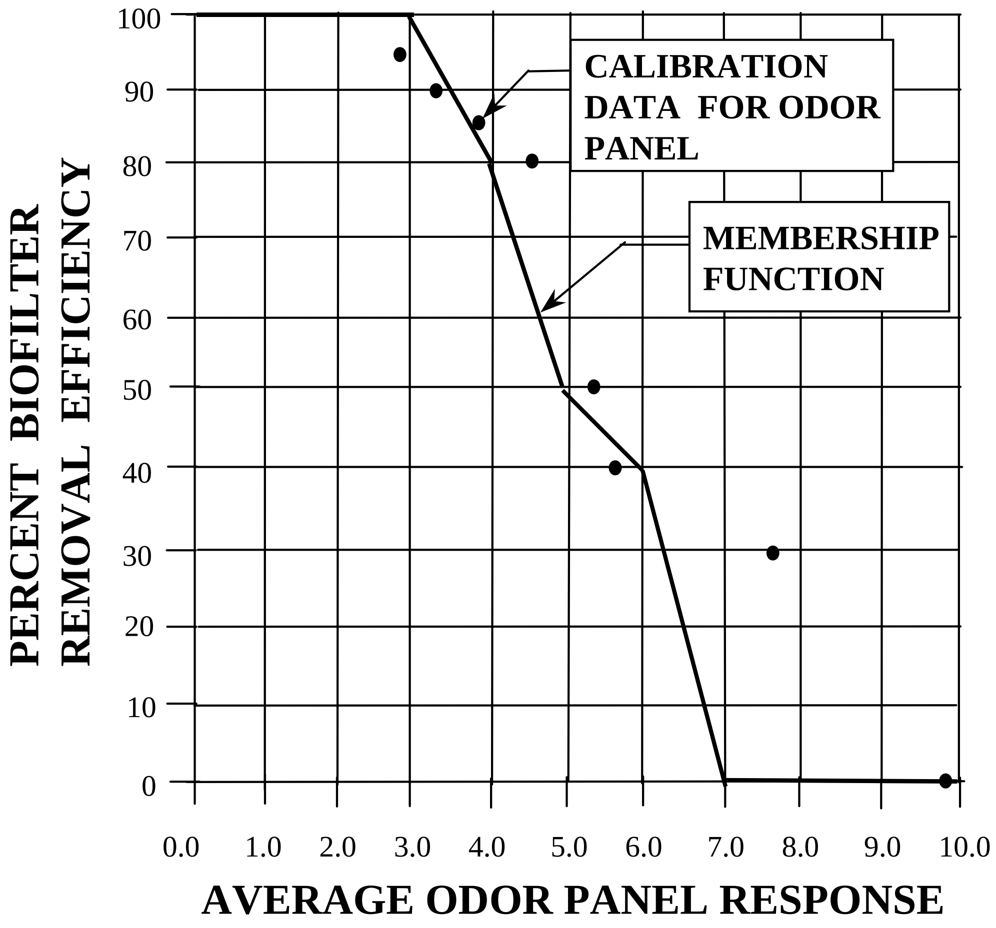

**Figure 3.** Average Percent Removal Efficiency of the Biotrickling Filter during the Pilot-Scale Test. (Replicate Data are connected by a vertical line).

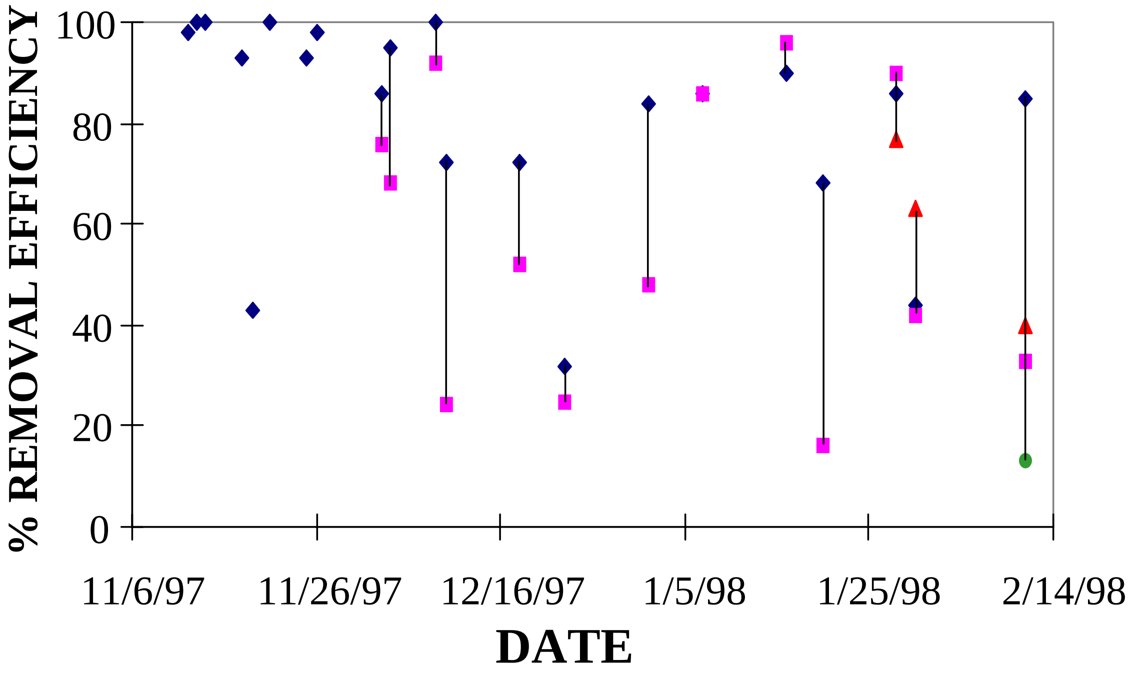

**Figure 4.** Impact of Ammonium Ion Concentration in the Mineral Nutrients on the Detection and Recognition Thresholds (DT and RT) for the Treated Gas.

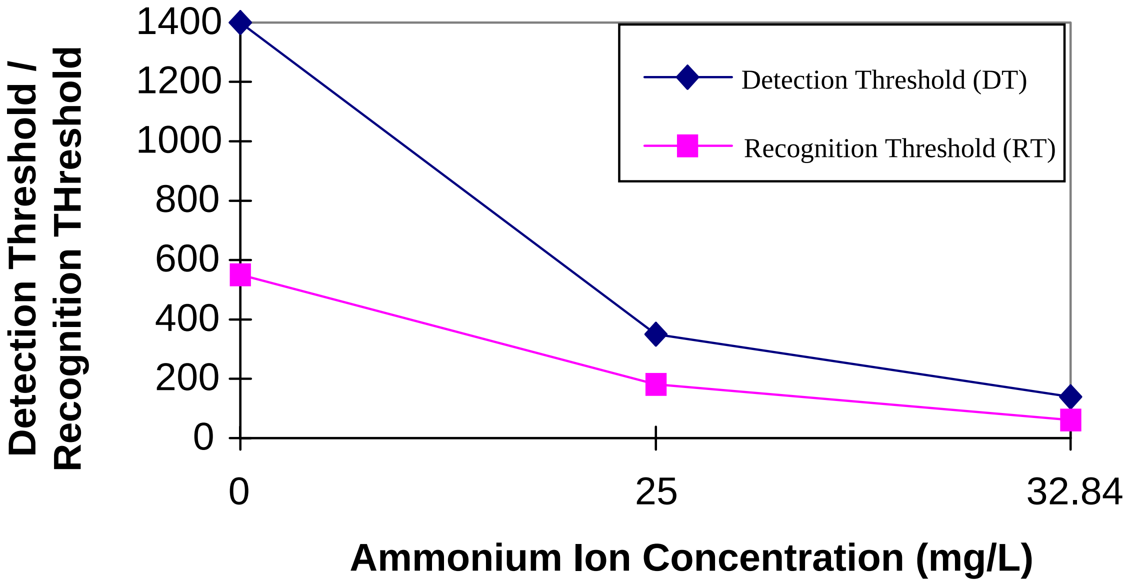

**Figure 5.** Plot of Calculated Detection Threholds (DT) Values for the Inlet and Treated Gases.

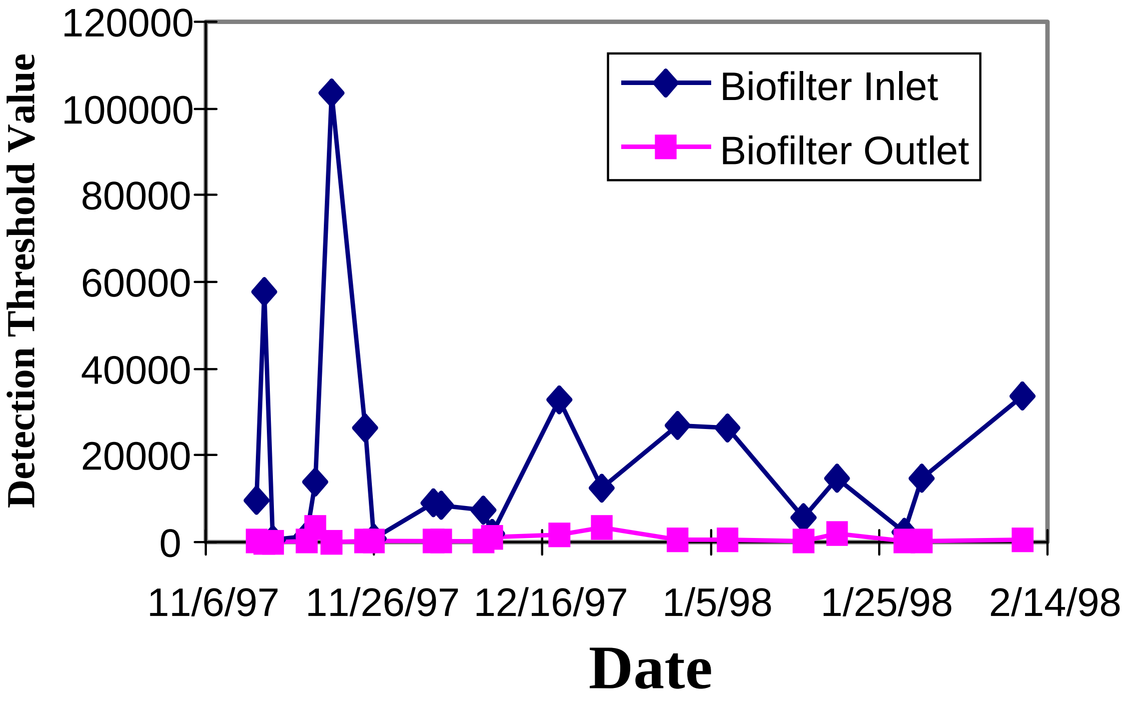

**Figure 6.** Plot of Log (Meter Reading) Versus the Log (% Zimpro Odor Concentration).

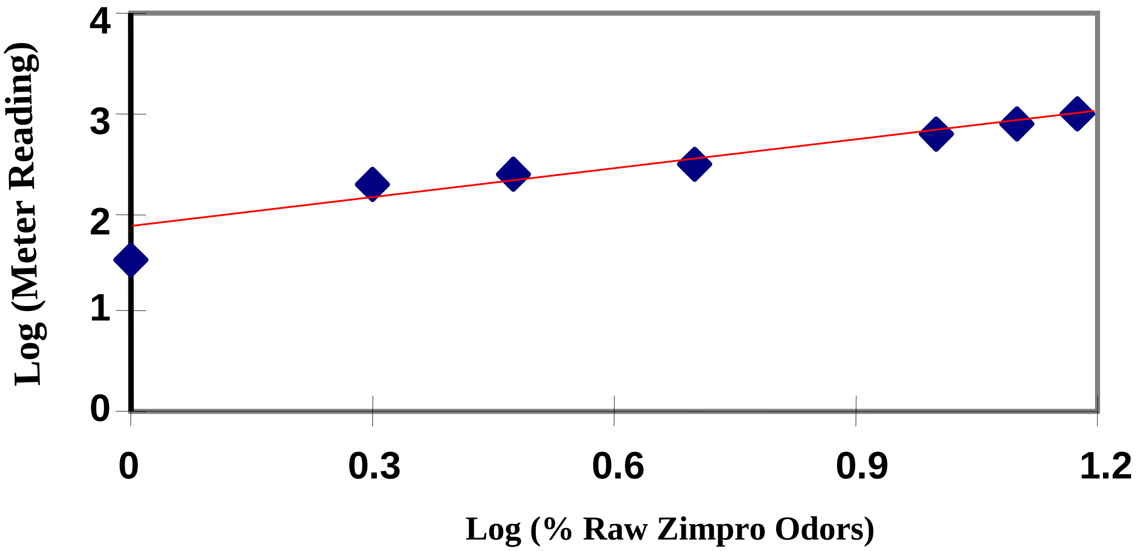

**Figure 7.** Correlation of Odor Meter Reading with the Average Odor Panel Response.

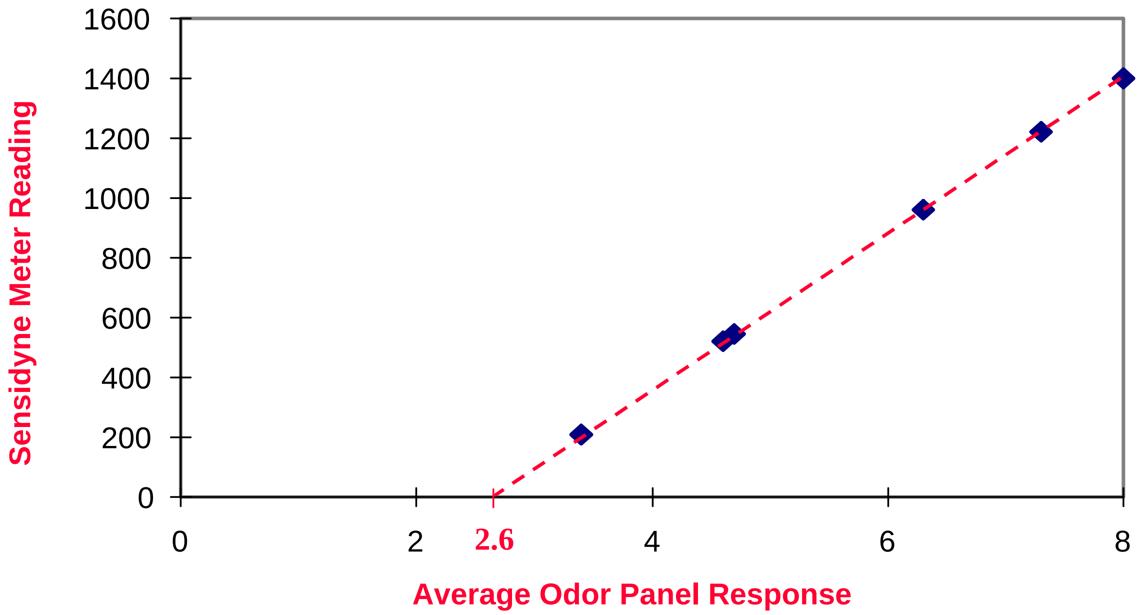

**Figure 8.** Plot of Estimated Total Capital Cost of the Biotrickling Filter for Various Gas Flow Rates.

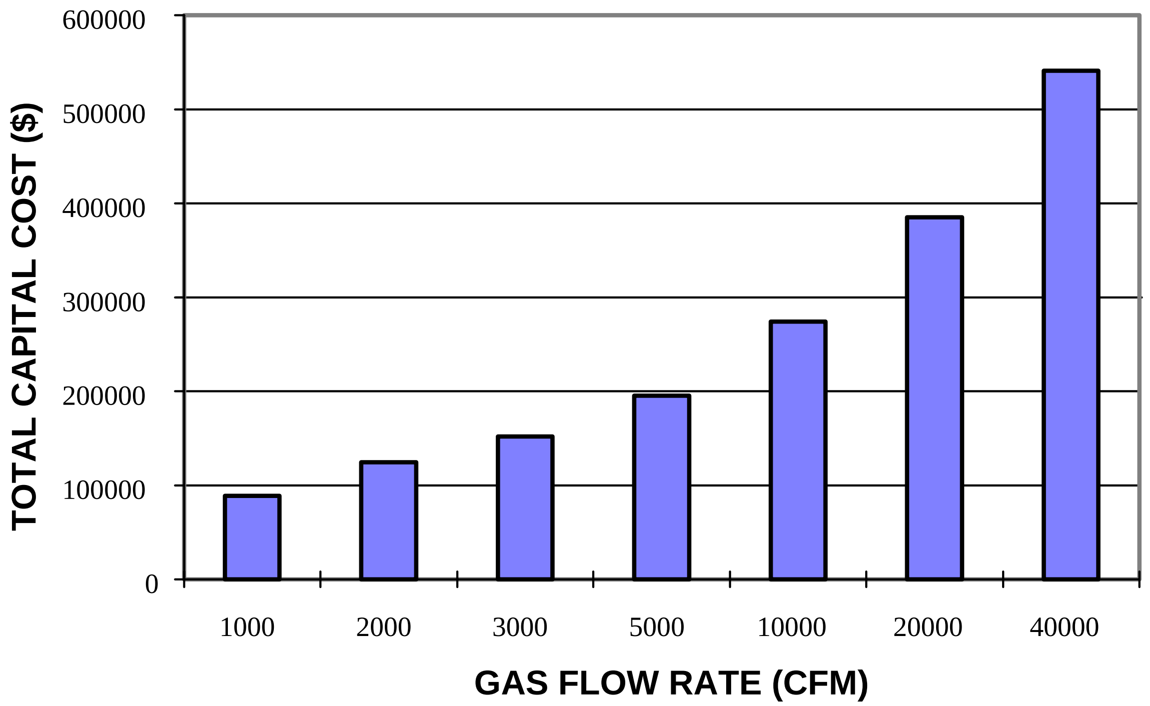

**Figure 9.** Plot of Estimated Annual Operating Cost of the Biotrickling Filter for Various Gas Flow Rates.