5-31-1989

Anaerobic biodegradation of trichloroethylene by activated carbon fluidized-bed

Yeam-How Chin
New Jersey Institute of Technology

Copyright Warning & Restrictions

The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted material.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specified conditions is that the photocopy or reproduction is not to be "used for any purpose other than private study, scholarship, or research." If a, user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use" that user may be liable for copyright infringement,

This institution reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.

Please Note: The author retains the copyright while the New Jersey Institute of Technology reserves the right to distribute this thesis or dissertation

Printing note: If you do not wish to print this page, then select "Pages from: first page # to: last page #" on the print dialog screen

ABSTRACT

Title of Thesis: Anaerobic Biodegradation of Trichloroethylene by Activated Carbon Fluidized-Beds

Yeam-How Chin, Master of Science in Environmental Engineering, 1989

Thesis directed by: Yeun C. Wu
Professor of Department of Civil and Environmental Engineering

Abstract - The biodegradation of Trichloroethylene by using anaerobic activated carbon fluidized bed has been investigated in the present study. High quality effluent was obtainable when the TCE influent concentration was up to 2.4 ppm in the first stage. Glucose was introduced as a cosubstrate to determine the effects of glucose/TCE ratio on the COD, Glucose and TCE removal. The experimental data indicates that the overall TCE removal efficiency was only slightly affected by TCE loading, but the first stage performance was significantly influenced by TCE loadings. It was also found that the microbial activities were affected by TCE loadings because of higher TCE concentrations.

ANAEROBIC BIODEGRADATION OF TRICHLOROETHYLENE BY ACTIVATED CARBON FLUIDIZED-BED

by

Yeam-How Chin

Thesis submitted to the Faculty of the Graduate School of
the New Jersey Institute of Technology in partial fulfillment
of the requirements for the degree of
Master of Science in Environmental Engineering
1989

APPROVAL SHEET

Title of Thesis: Anaerobic Biodegradation of Trichloroethylene by Activated Carbon Fluidized-Bed

Name of Candidate: Yeam-How Chin
Master of Science in Environmental Engineering, 1989

Thesis and Abstract Approved:

Dr. Yeun C. Wu
Professor of
Department of Civil and
Environmental Engineering

5/2/89
Date

Signatures of other members of the thesis committee:

Dr. Su-Ling Cheng
Acting Chairman of
Department of Civil and
Environmental Engineering

5/5/89
Date

Dr. Robert Dresnack
Graduate Advisor of
Department of
Environmental Engineering

5/8/89
Date

VITA

Name: Yeam-How Chin

Permanent address:

Degreeand date to be conferred: Master of Science in En.E.
May, 1989

Date of birth:

Place of birth:

Collegiate institutions attened:	Date	Degree	Date of Degree
Taipei Institute of Technology	1979	Diploma	June, 1984
New Jersey Institute of Technology	1987	M.S.	May, 1989

Major: Environmental Engineering

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to my advisor, Dr. Yeun C. Wu for his guidance, encouragement and financial support throughout this research effort.

Also, I wish to thank Miss Suxuan Huang for her support and friendship. Her assistance makes this thesis a success.

Futhermore, I would like to express my gratitude to the respected members of the committee, Dr. Su-Ling Cheng and Dr. Robert Dresneck, whose kind consideration and guidance are most appreciated.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter I

INTRODUCTION

The problems of groundwater contaimination and hazardous waste disposal have been increasing the public awareness in recent years [1,2]. The low molecular weight halocarbons are the most widely distributed and troublesome organic contaminants. These organic contaminants can originate from various sources, such as surface impoundments, landfills, surface and subsurface disposal, underground tanks and accidental spills. This group includes trichloroethylene (TCE), a common industrial solvent, which is of interest for environment study because of its potential hazards to human health [6].

TCE is produced commercially by chlorinating ethylene or acetylene. The declining use of TCE has been resulted because of stringent regulations. However, it has been widely used as a common ingredient in many household products, dry cleaning fluids, refrigerants, industrial metal cleaners and polishers [7]. It is estimated that the annual production of TCE is 234,000 metric tons worldwide [8]. The ubiquitous use of TCE probably tells us why it has been found the most predominant chlorinated organic contaminant in groundwater.

According to the survey of contamination in industrial regions undertaken by the state of New Jersey, more than

25% of the wells sampled contained detectable concentrations of low-molecular-weight compounds such as Trichloroethylene [9]. About 10% had concentrations in excess of 10ug/l, but only 1 to 2% had concentrations more than 100ug/l. Environmental Protection Agency recommended that the imun contaminant level of TCE is zero; the maximum contaminant levels are forceable under the Safe Drinking Water Act and may range from 5 to 50ug/l. This class of TCE is hard to biodegrade under aerobic subsurface environments because of its persistence in polluted groundwaters [10], but it can be biotransformed under anaerobic conditions.

Granular activated carbon (GAC) adsorption is attractive because of its high efficiency of removing a broad spectrum of organic chemicals. However, GAC columns represent a great amount of money, and more important, operating costs are expensive. The application of biological growth on GAC columns was encourged because contaminant can be removed by both adsorption and biodegradation. This process not only increases the service life of GAC but also saves significant operating costs . Moreover, incorporation of a biological process into the treatment may lead to a desirable effluent quality and fewer problems with maintenance of water quality in the distribution system [11].

The combination of granular activated carbon and

fluidized bed was employed in this research. Except this, the addition of sugar to the systems is another important feature of this study. The glucose served as the primary substrate which supports the microbial growth to biodegrade TCE anaerobically. The scope of this study was to (1) determine the efficiency of anaerobic biodegradation of TCE, (2) obtain the optimum ratio of glucose to TCE under different TCE loading, and (3) understand the operational conditions of the biological reaction.

Chapter II

LITERATURE REVIEW

Physical and Chemical Properties of TCE

Trichloroethylene (TCE) is a low-molecular-weight, chlorinated aliphatic hydrocarbon with a molecular formular of $CHCl:Cl_2$. The molecular weight of TCE is 131 and 81% of the weight is chlorine. It has a density of 1.46 g/ml, a boiling point of $87^{o}C$ in atmosphere, a vapor pressure of 77 mm-Hg at 20^{o}, and solubility of 1,100 mg/l in water at 20^{o}.

In general, TCE is volatile, partially desolving in the water, and nonflammable in the air. These characteristics make it an effctive solvent which is popularly used in households (rug cleaner, spot remover, air freshener), industries, and even in water treatment plants for degreasing and cleaning.

Toxicities of TCE to Human Health

TCE has been classified as a suspected human carcinogen because it can cause cancer in laboratory test animals [12] . The 10^{-6} cancer risk for TCE is 2.8 ug/l [13]. The toxicity of TCE is intrinsic, and its action can be acute or chronic. When the vapor is inhaled, it is diffused through the bloodstream from the lungs. Both the liver and kindneys can be severely damaged by chronic

exposure. Drowsiness and even unconsciousness can be happened under continuous inhalation of high concentrations of TCE. TCE has also been found to have effects on the nervous system, causing in impaired vision and changes in skin sensitivity. Ingestion of high concentrations of liquid TCE have resulted in death through edema of the lungs and severe damage to the liver and kindneys [7].

Treatment Processes Available for TCE

Various techniques of removing chlorinated volatile organic compounds (VOCs) from public drinking groundwater have been investigated [14,15,16]. Adsorption with granular activated carbon (GAC) and air stripping are the two technologies successffuly utilized.

Activated carbon was utilized to purify water previouslY. With the concern of groundwater contamination since 1970s, GAC has been used to remove VOCs (such as TCE) of contaminated groundwater. Adsorption on activated carbon is a physical process by which molecules are held at the surface of the solid. The reasons make GAC an excellent adsorbent is the extensive available surface area within its structure and the ability of regenerating the carbon. GAC is often applied when organic contaminants need to be removed to nondetectable levels, and GAC should be a part of process when nonvolatile contaminants are present in the

treated water.

The air stripping process is simply the transfer of volatile compounds from the water to the surrounding air space. A sufficient amount of uncontaminated air was supplied to an aeration process for removing TCE because its high volatile characteristic. Packed tower air stripping is a means to enhance the transfer of TCE from water to air more efficient. Contaminated water introduced at the top of the tower then flows downward the packing, creating a improved contact of water and air. Clean air is forced count-currently upward through the packing, such that the air contacts the least contaminated water to optimize TCE removal. The removal efficiency may reaches 95 to 99 % if the contaminants have sufficiently high volatility than water [17].

The discharge of air stripping operation to atmosphere creates another problem (air pollution). Although air stripping process may obtain efficiently removal of VOCs, the residual contaminant is still unacceptable. In this case, GAC can be used to effectively remove the residual from the air stream just the same as removing contaminants from water. The use of air stripping as pretreatment to a carbon adsorption system can extend the service life of GAC and obtain nondetectable contaminant levels for potable water use.

Other technologies for degrading TCE have also been investigated. In 1985, Gehringer reported that trace amounts (70 to 440 ppb) of TCE in drinking water could be degraded by Gamma radiation. The doses necessary to reduce the pollutant concentration to 1 ppb are in the order of 1 KGY [18]. Another study done by Wang and Tan indicated that TCE in a water photolysis system was reduced to methan and ethane with natural sunlight irradiation [33].

Biological degradation is one of the effective processes to degrade TCE, but until now, only very little imformation is known about the microbial metabolism of TCE.

According to Montgomery and his co-worker's report, a gram-negative, rod-shaped bacterium named genus Acinetobacter was found to be responsible for the biological metabolism. The pure culture can degrade TCE to CO_2 and unidentified nonvolatile products under aerobic conditions. Oxygen and water from the original site of isolation were required for degradation [4]. It indicated that metabolism of TCE can occur under aerobic environment by the bacterial isolation mentioned above.

Study of Wilson and co-workers reported that the biotransformation of TCE in sandy soil packed column has been investigated . TCE was biodegraded aerobically to carbon dioxide when the unsaturated soil was exposed to

natural gas to enrich organisms that oxidize the other small alkanes [5].

In 1985, Kleopfer reported that TCE is definitely dechlorinated in soil to 1,2-DCE by using TCE isotopically labeled with a single ^{13}C atom [8]. But it is possible that DCE can be futher biotransformed into vinyl chloride in soil according to the report of Parsons et al. [3].

An experiment was initiated by Rutgers University in January of 1987 to examine the ability of sequential anaerobic/aerobic microbial population, in a packed bed configuration, to biodegrade leachate from the high priority Superfund site. TCE was one of the volatile compounds contained in the treated leachate, a method employing purge and trap concentration followed by gas chromatographic separation was developed for accurate identification and quantification of the volatile compounds of interest. Results obtained from application of this method to the leachate treatment process indicated that 84 to 99% of the specific volatile priority pollutants were biodegraded under anaerobic conditions, during steady-state operation [19]. In addition, previous packed column biodegradation experiments have successfully treated a wide varity of wastewater [20,21]

Another study done by McCarty et al indicated that TCE

could be biodegraded slightly under anaerobic condition. The experiment is that TCE at concentrations commonly found in surface water and groundwater were incubated aerobically in the presence of primary sewage bacterial cultures and anaerobically in the presence of mixed methanogenic bacterial cultures. No aerobic cnditions were found under which these compounds could be degraded. Anaerobic degradation was observed for TCE only slightly [22].

Microbial activity is reported to have beneficial effects on the performance of granular activated carbon (GAC) adsorbers in wastewater treatment [23]. The combination of adsorption and biodegradation that is possible with GAC permits high removal efficiency for biodegradable trace organics. But it is unclear whether organic compounds may continue to be removed through biological degradation or by adsorption which is made possible by renewal of sorption sites by biological activity [24].

A comparison was made by Bouwer et al to observe the removal of chlorinated benzenes and aliphatics in a granular activated carbon column with microbial activity VS. a control column with only bacterial growth. Both columns were under aerobic conditions. Results showed that under favorable steady-state conditions, biodegradable organics are principally removed through biofilm

utilization. During unfavorable conditions such as absence of adequate oxygen biodegradablle organics may pass through the biofilm and become adsorbed by GAC. Anyway, the presence of microbial growth on GAC gives stability and reliability to overall trace organic removal performance [25].

According to Gardner's research report indicated that the adsorptive capacity of GAC was essential for reducing the toxicity of the wastewater, thus permitting uninhibited biological treatment. Reactor performance improved with decreasing GAC particle size and when higher loading rates of the wastewater were used. This was attributed to the increased surface available for microbial attachment and the decreased diffusional resistance to adsorption that accompany a decrease in GAC particle size [26]. Activated Carbon adsorption offers one of the most efficient processes available for removing certain organics and inorganics from wastewater [27,28].

More recent work done by Dietrich et al, who added powder activated carbon to an activated sludge system, to make a process, named PACT treatment system. This combination of physical adsorption with biological oxidation and assimilation has been shown to be specially effective in treating wastewaters which contain variable concentrations and compositions. Report on that leachate

from landfill site was treated using a bench-scale PACT system, the raw leachate was spiked with high concentration of chlorinated organic compounds such as TCE. The results show the removal efficiency as high as near 100% [29].

The feasibility of combining carbon adsorption with anaerobic biological treatment greatly interests environment researchers. The phenols-bearing-wastewaters treated by the fluidized-bed granular activated carbon anaerobic reactor have demonstrated the effectiveness [30,31]. Contaminants were adsorbed on the GAC medium, then the attached biofilm efficiently biodegrade the degradable compounds.

Various techniques of wastewater detoxicification have been investigated successfully before. Fluidized bed, one of the attached-growth processes, has been used in this study because of its extraordinary efficiency and reliable management of microorganisms. Another advantage of the fluidized bed is that the maximum biomass production which depends on the diffusion properties of soluble and particulate organics, substrate utilization and microbial growth kinetics [32].

The combination of granular activated carbon (GAC) and fluidized bed was employed in the present study. GAC serves as the supporting medium for microbial growth as well as

the adsorbent of TCE in the fluidized bed system. More importantly, the addition of sugar to the synthetic graundwater containing TCE is utilized as primary substrate, which enhances TCE detoxification through substrate co-metabolism. Also, the accompanied methane gas can be expected, it is another feature of this study.

Chapter III

MATERIALS AND METHODS

A. Experimental Apparatus

The fluidized bed system consists of two columns, designated the first stage and the second stage, mounted with a difference in elevation of about two feet. There are two systems in operation simultaneously. The inside diameter and height of each column are two inches and five feet perspectively (See Figure 1). The columns of the two systems are all indentical.

The operation temperature is maintained at about 35^{o}C by heating tape. Bucause of the difference in the clevation of the two columns, the effluent from the to of the first stage, flows freely to the bottom of the seconod stage. The effluent from the seconod stage was pumped back to the bottom of the first stage at a rate of approximitely 0.81 liter per mintite in order to properly fluidize the activated carbon media.

500 grams of Filsotrop 400 activated carbon from Calgon Carbon Corporation used as media which were supported by a 2 inches layer of 6 mm glass beads and followed by a 2 inches layer of 18 mm glass marbles. It was approximately expanded 30% long of the original bed height.

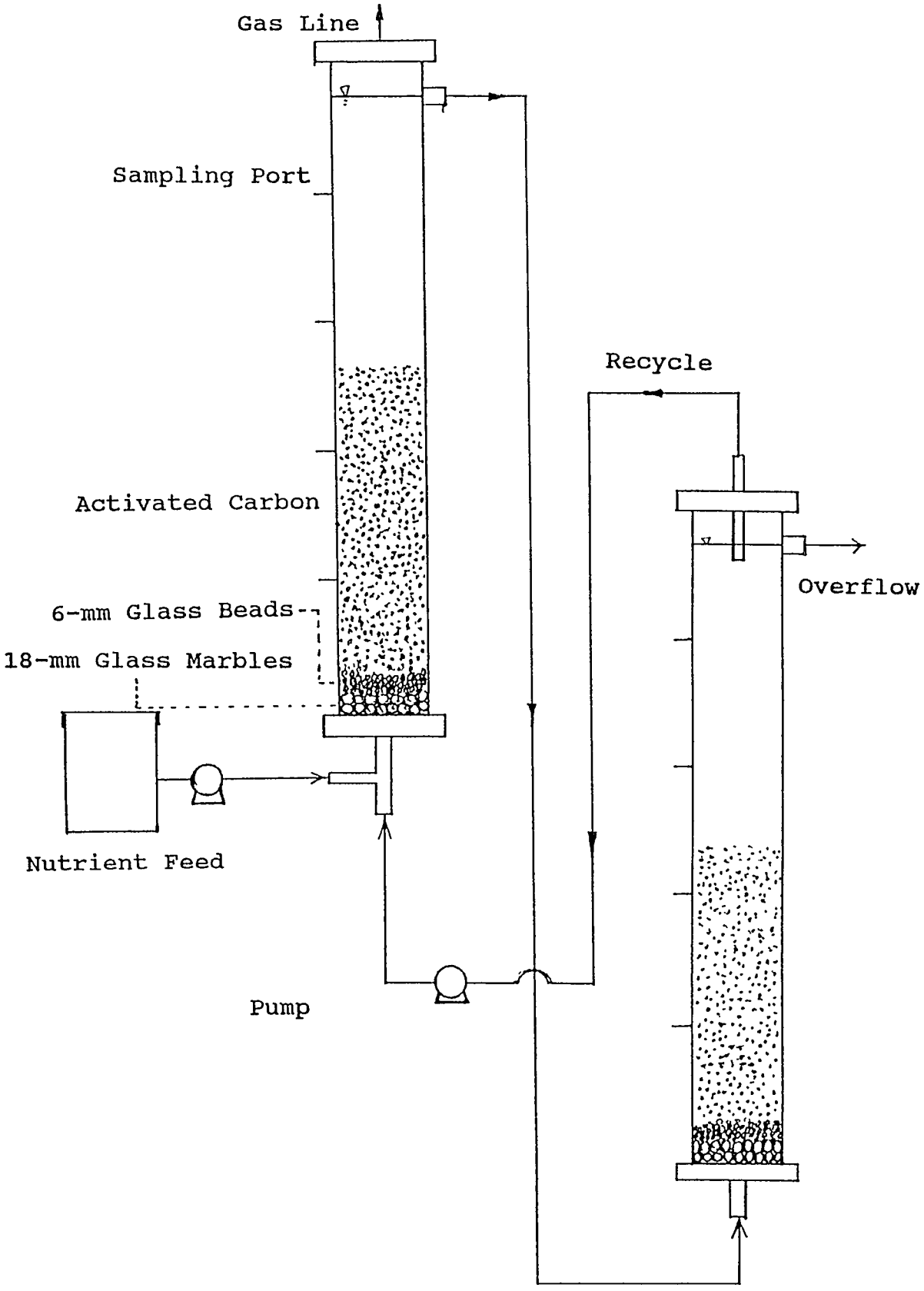

Figure 1. Schematic Flow Diagram of the Two-Stage Anaerobic Fluidized bed Biofilm Reactor

b. Seeded Culture

A mixed microbial culture, sampled from the domestic wastewater treatment plant, was seeded in the systems. The immobilized biomass was grown sucussufully on the surface of activated carbon and reached to the steady state after three months of the initial inoculation.

c. Synthetic Feed Solution

The chemical constituents of the synthetic feed solution are listed in table 1. TCE stock solution was prepared by dissolving reagent grade (99.9% purity) TCE in reagent grade methanol. The glucose concentration was fixed at 300 mg/l during the whole study. In addition, trace amounts of $MnCl_2.4H_2O$, $CuCl_2.2H_2O$, H_3BO_3, $CoCl_2.6H_2O$, $Na_2MnO_4.2H_2O$, and $ZnCl_2$ had also been added in the feeding solution. Both systems 1 and 2 were fed at the rate of 4 ml/min and 2 ml/min respectively.

The present study investigated the effect of TCE concentration on TCE reduction under various glucose/TCE ratios. The lower concentrations from trace amount to 10.8 mg/L have done by Mr. Chern, the higher concentrations from 10.8 mg/L to 500 mg/L have been discussed in this study.

Table 1. The Composition of Synthetic Feed Solution

Constituents	Concentration [mg/L]
$(NH_4)_2HPO_4$	37.00
$CaCl_2.2H_2O$	9.28
NH_4Cl	14.78
$MgCl_2.6H_2O$	66.67
KCL	48.17
$FeCl_2.4H_2O$	102.87
Biotin	0.00278
Folic Acid	0.00278

d. Sampling

The influent were sampled from each feed tank after preparation of the feed solution. Additional, it is important to cover the tank tightly for minimizing the volatilization of TCE. According to the results obtained by Huang [34], it was found that the concentration of TCE decreased exponetially with time. During the first three hours following the preparation, the concentration of TCE essentially remained constant. Samples collected at about 50 and 100 minutes after the commencement of feeding to System 1 and System 2 respectively due to the pumping rate and length of tubing leading to the columns. Effluent were sampled from the head space of both the first and second stages. Trace amount of copper sulfate was added to the sampling bottle to prevent continuous biodegradation after

sampling. All the samples were stored in refrigerator at 4^{o}.

e. Analytical Methods

To insure that the systems are under the optimum anaerobic conditions; dissolved oxygen (D.O.), pH , and temperature were examined daily to maintain the best circumstance for biodegradation. The parameters analyzed for both system 1 and system 2 are TCE, glucose, COD , ammonia nitrogen, phosphorus, pH and alkalinity. The analysis procedures of these parameter are discribed as follows:

1. Analysis of TCE [35,36]

Gas chromatograph (Hewlett Packard 5890) coupled with a purge and trap system (Tekmar Model 4000) were employed to analyze all the samples in accordance with EPA Method 601. The conditions under this analysis are:

a. Purge gas nitrogen flow-rate = 40 ml/min
b. Purge time = 11 minutes
c. Desorb time = 4 minutes
d. Bake time = 10 minutes

2. Glucose [37,38]

a. Prepare the Anthrone reagent: dissolve 0.2 grams of

anthrone in 100 ml of 95% H_2SO_4 and store in refrigerator for at least one hour

b. Filter 30 ml of sample through 0.45 um membrane filter

c. Add 5ml of anthrone reagent and 2.5 ml of sample in the test tube, then mixed thoroughly

d. Prepare a blank in which distilled water is substitute for sample, then repeat step c.

e. Prepare a calibration curve by using standard solution instead of sample in step c.

f. Place the tubes into a boiling water for 15 minutes

g. Cool the tubes down to room temperature, transfer the sample to the colorimeter tube and measure the absorbance versus a blank tube at a wavelength of 540 nm.

h. Calaulation

Glucose mg/L = Reading in calibration curve x 1000/ml sample

3. COD [39]

a. Filter 30 ml of sample through 0.45 um membrane filter

b. Preheat the COD Digestor to 150 ^{o}

c. Pipet 2.00 ml of sample into the vial and replace the cap. Swirl the vial, using a circular wrist motion, be sure the contents are mixed well

d. Place the vial in the preheated COD digestor

e. Prepare a reagent blank by repeating step "a" through "d". Using 2.00 ml of distilled water insted of sample.

f. Heat the vials for two hours at 150°C. Turn off the digestor and allow the vials cool to 120°C or less. Shake each vial and place in a cooling rack, cool to room temperature

g. Remove the cap and rinse the inside walls with less than 1ml of distilled water. Add a stirring bar and one drop of Ferroin indicator solution

h. Titrate with Ferrous Ammonium Sulfate (FAS) standard solution, 0.125 N, until the sample color changes sharply from greenish-blue to orange-brown. Record the volumes of titrant used

i. Determine the mg/l VCOD by equation indicated below:

(A-B) x N x 8000/C = mg/l COD

where:

A = ml used in test of blank

B = ml used in test of sample vial

C = ml of sample

N = concentration

4. Ammonia Nitrogen [40]

a. Prepare 10^{-2}M, 10^{-3}M and 10^{-4}M of NH_4Cl by serial dilution of the 0.1 M standard solution

b. Place electrode in the 10^{-3}M standard. Add 1ml 10 M NaOH to every 100 ml of standard. Set the function switch to REL MV. Set the reading to ooo.o by adjusting the calibration control

c. Rinse electrode and place in the 10^{-4} M standard. Add 1

ml 10 M NaOH to every 100 ml of standard. Stir thoroughly, record stable reading

d. Rinse electrode and place in the 10^{-2} M standard, then repeat the step "c"
e. Plot the reading vs concentration on standard 4-cycle semilogarithmic paper. Establish the calibration curve.
f. Rinse electrode and place in sample. Add 1ml of 10 M NaOH to each 100 ml of sample. Stir thproughly, record the stable reading and obtain the concentration of sample from the calibration curve.

5. Phosphorus [41]

The phosphorus is measured by Vanadomolybdophosphoric Acid Colorimetric method.

a. Filter 50 ml of sample through 0.45 um membrane filter
b. Place certain volume ml of sample, containing 0.05 to 1.0 mg of P, in a reagent and dilute to 50 ml with distilled water. Measure the absorbance of the sample versus a blank at a wavelength of 450 nm after waiting 10 minutes or more.
c. Prepare a blank in which distilled water is substituted for the sample
d. Prepare a calibration curve by using proper volumes of standard phosphate solution and proceed as same as in step "b"

e. Calculation:

P mg/l = P mg (in 50 ml flask) x 1000/ ml sample

6. Alkalinity [41]

The alkalinity is measured by using the potentiometric titration curve.

a. Rinse electrodes and titration vessel with distilled water and drain.
b. Measure pH of sample, add standard acid solution in an increments with a magnetic stirrer. Record pH when a Stable reading is obtained.
c. Keep adding titrant until pH value become 3
d. Construct the titration curve by plotting observed pH values versus cumulative milliliters titrant used.
e. Calculation

Alkalinity mg $CaCO_3$/L = A x N x 50,000/ml sample

where:

A = ml standard acid used

N = normality of standard acid

f. Recirulation Effects

Due to the flow recirculation from the second stage to the first stage of the fluidized bed system, the influent TCE concentration for both systems 1 and 2 was calculated as follows:

Let

Qi = influent flow rate for the system

Qo = influent flow rate from the feeding tank

Qr = recirculative flow rate (= 810 ml/ min)

Ci = influent concentration for the system

Cr = concentration from recirculation

Co = concentration from feeding tank

According to the operating condition, equation (1) and (2) can be set :

$$Qi = Qo + Qr \qquad (1)$$

$$Qi \times Ci = Qo \times Co + Qr \times Cr \qquad (2)$$

Combine equation (1) and (2), equation (3) can be obtained:

$$Ci = (Qo \times Co + Qr \times Cr) / (Qo + Qr) \qquad (3)$$

TCE loading for the first stage and the whole system can be calculated according to the influent concentration Ci.

CHAPTER IV

RESULTS AND DISCUSSION

The operation was started after 90 days acclimation of microorganisms. That is, samples were collected after the systems had reached stable conditions. During the course of the experiment, TCE concentrations were gradually increased in the first stage of both Systems 1 and 2. The range varied from 2.5 ppb to 2.4 ppm and 0.9 ppb to 1.2 ppm respectively.

Nitrogen is an essential nutrient for the cultivation of microbial cells. It was found that the ammonium ions were utilized in this study, which means that the cell reporduction was successful. Another nutrient which supports the microbial growth is phosphate; the amount of phosphate is adequate in the feed solution, although the consumption of phosphate was very small.

In order to provide an optimum operation condition, pH was also under control~~led~~. The pH values of both the influent and the effluent were measured to be in the range of 7 to 8, which insured a favorable environment for microbial growth. Even though the pH of the influent was frequently higher than the effluent, the pH of the system remained essentially constant because of the low feed rate and high recirculation.

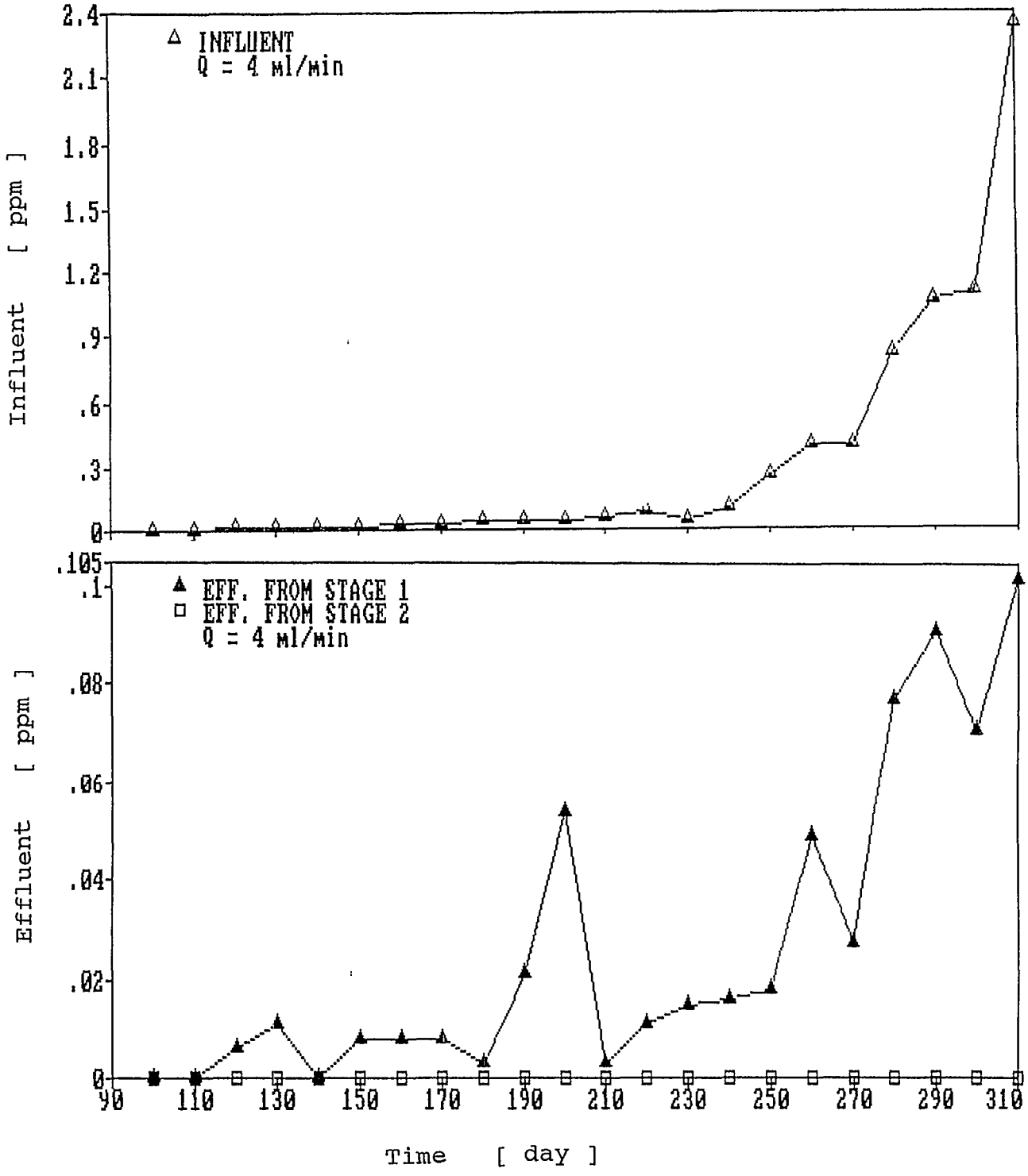

Figure 2. TCE Reduction in System 1

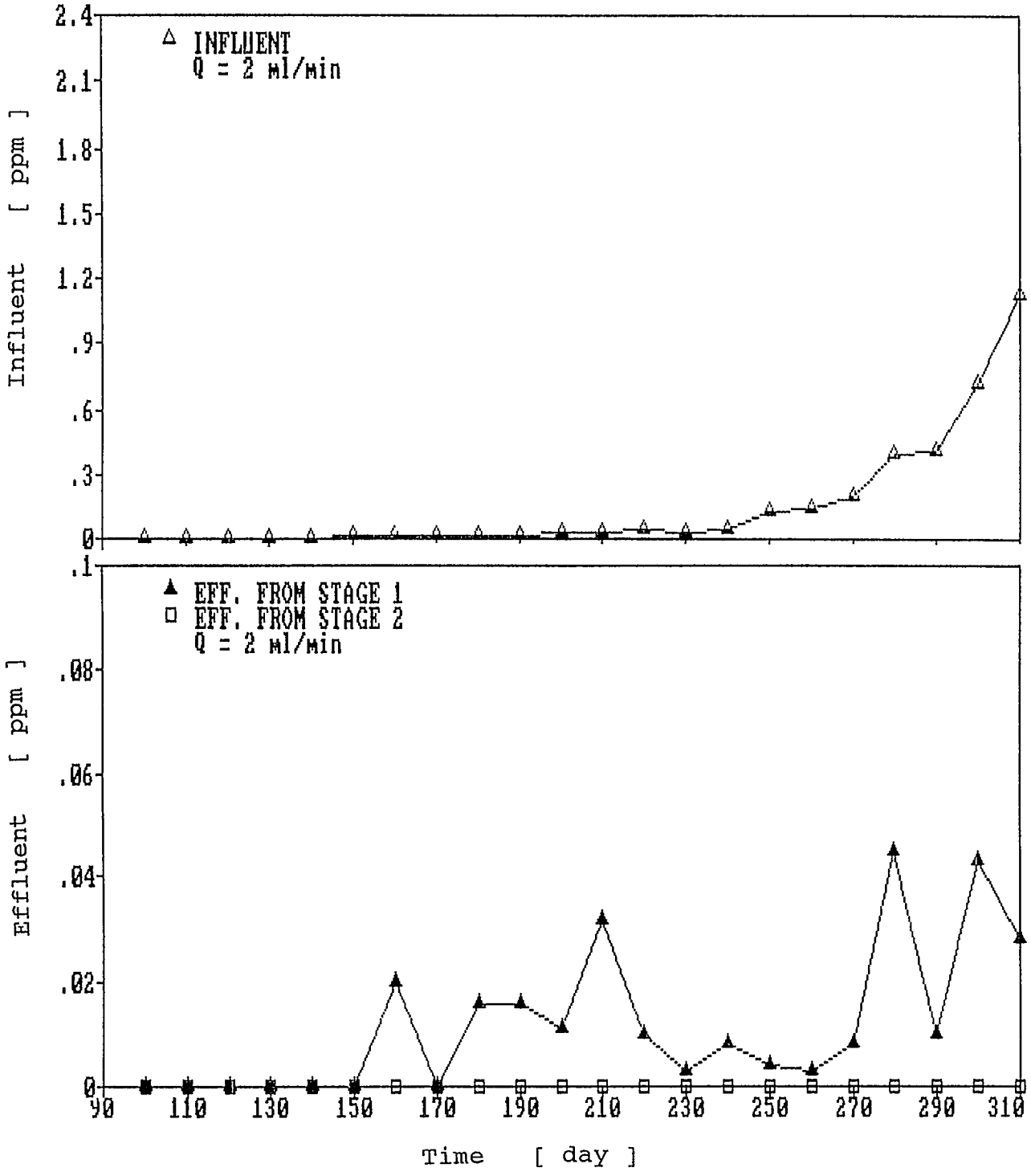

Figure 3. TCE Reduction in System 2

The data shown in Table 5 and 6 indicates that, in the low influent TCE concentration range the TCE concentrations from the effluent of the first stage were too low to be detected. However, TCE can be detected from the first stage effluent after the influent concentration was increased to 4.7 ppm (in feeding tank). It was found that the higher the influent TCE concentration, the higher the TCE concentration detected in the effluent of Stage one.

Since most of the TCE introduced to the System was degraded in Stage 1, the rest became less toxic to the microbial population in Stage 2 due to the decrease in concentration. According to the flowchart of the system, the effluent from the first stage which contains lower concentration of TCE is the influent of the second stage. The result obtained from the effluent of Stage 2 showed that the TCE residues of Stage 1 were completely degraded in Stage 2, no TCE was detected in the effluent of the second stage. Therefore, the TCE reduction efficiencies were 100 % for the entire system.

Glucose removal also occurred primarily in the first stage. In low TCE concentrations, the toxicity produced from TCE would not affect the microbial activity. That is why the glucose consumption was very large during the low TCE concentration runs. According to Figures 4 and 5, we observed that large amount of glucose was detected in the

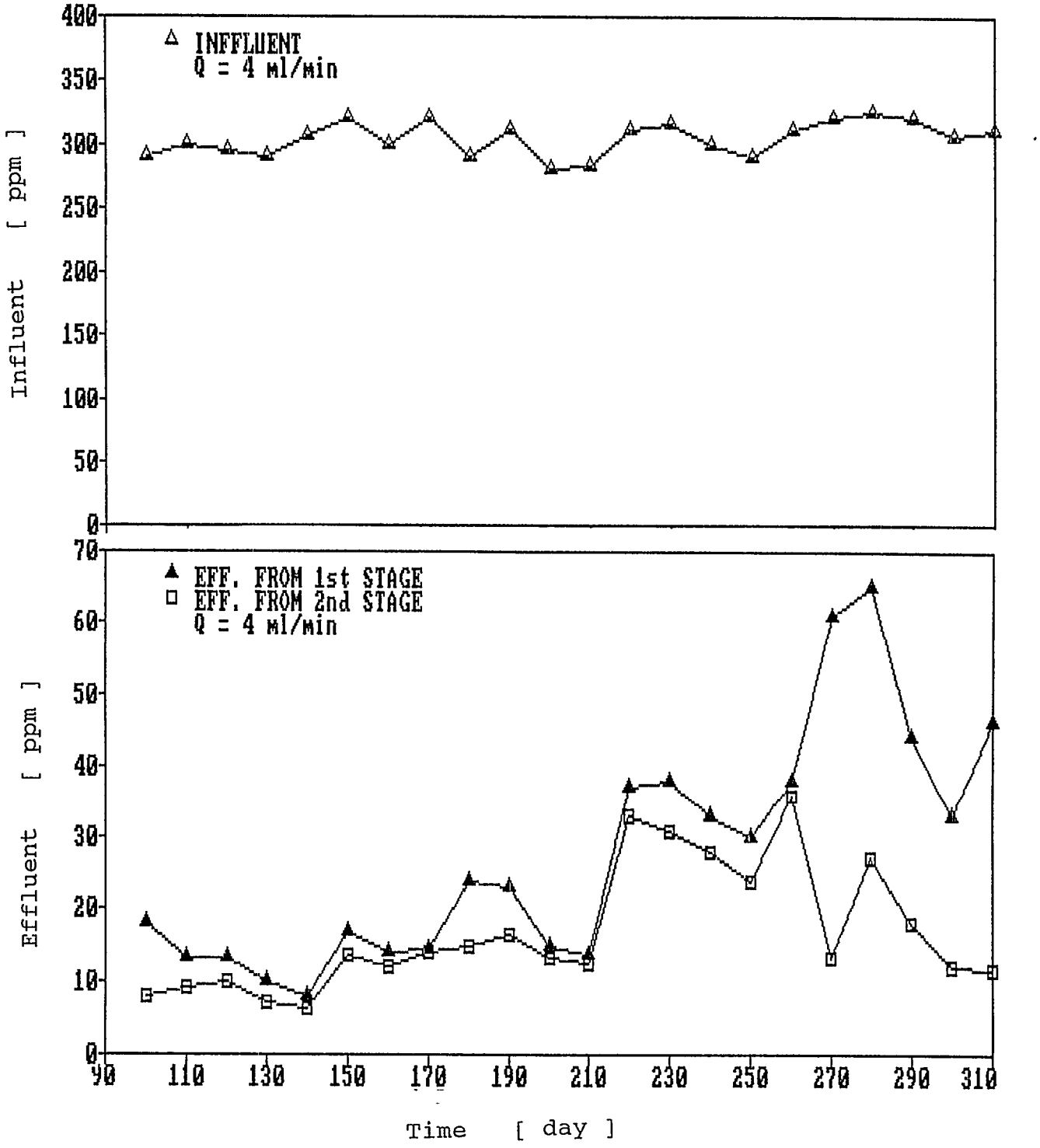

Figure 4. Glucose Reduction in System 1

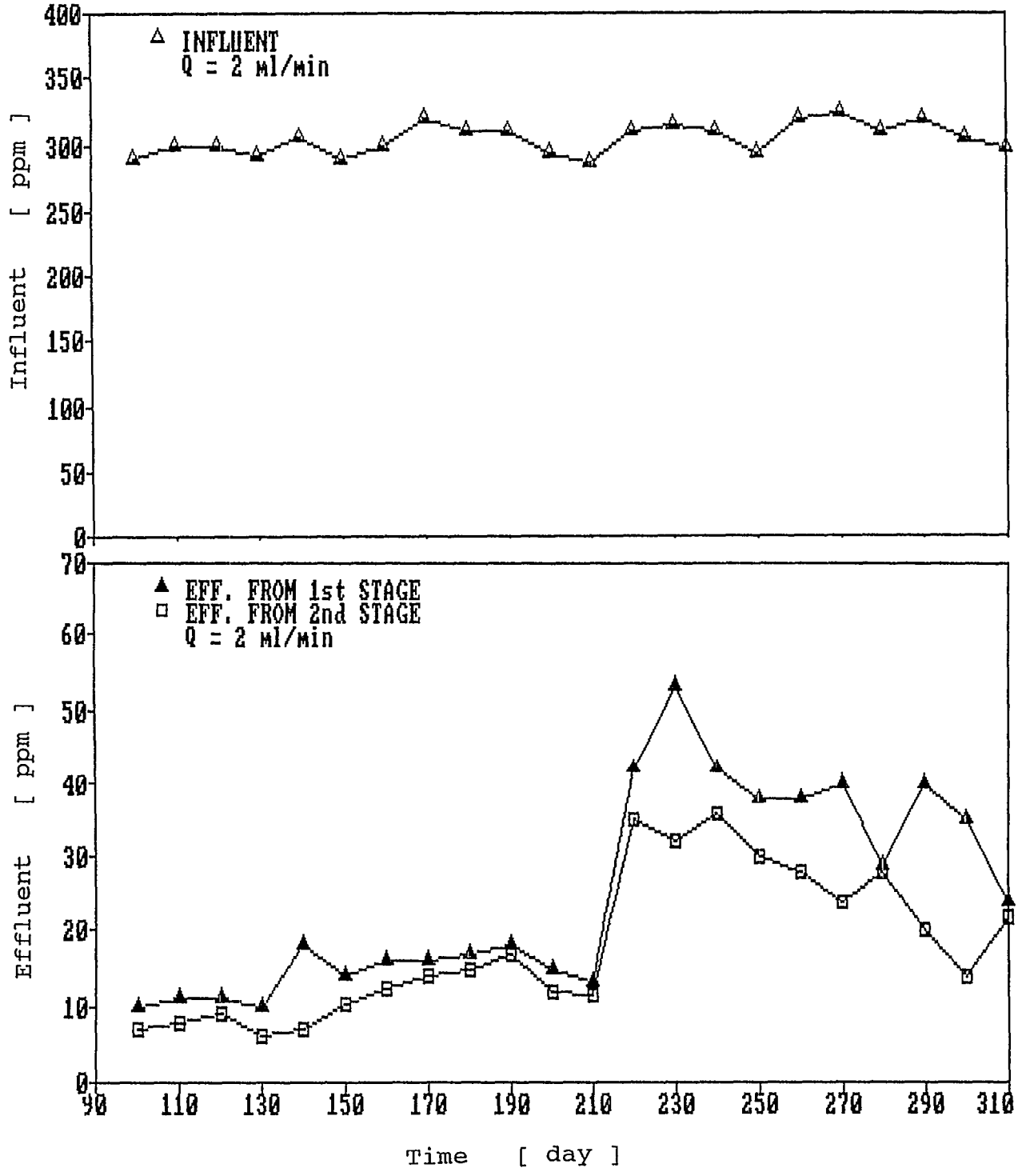

Figure 5. Glucose Reduction in System 2

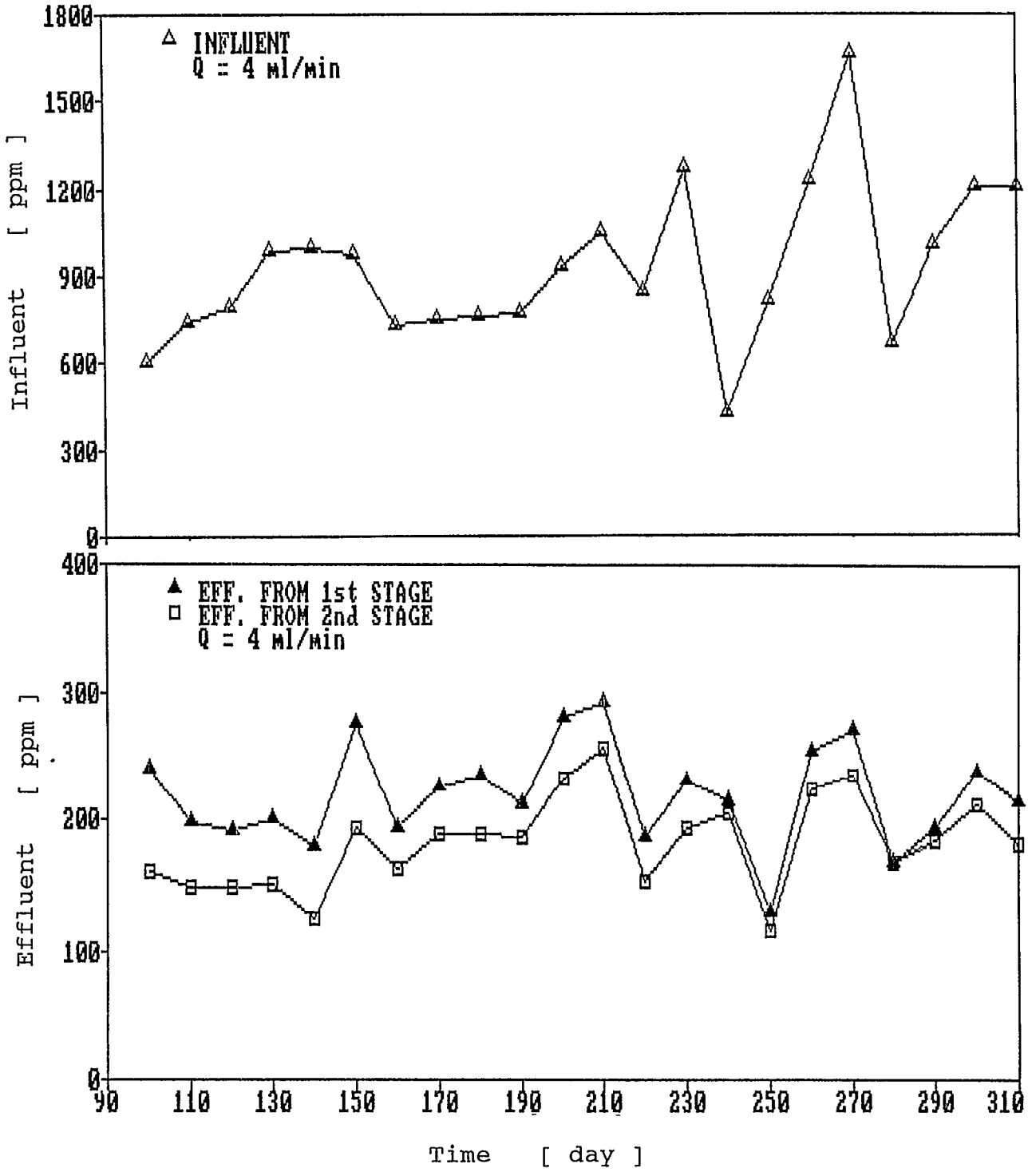

Figure 6. COD Reduction in System 1

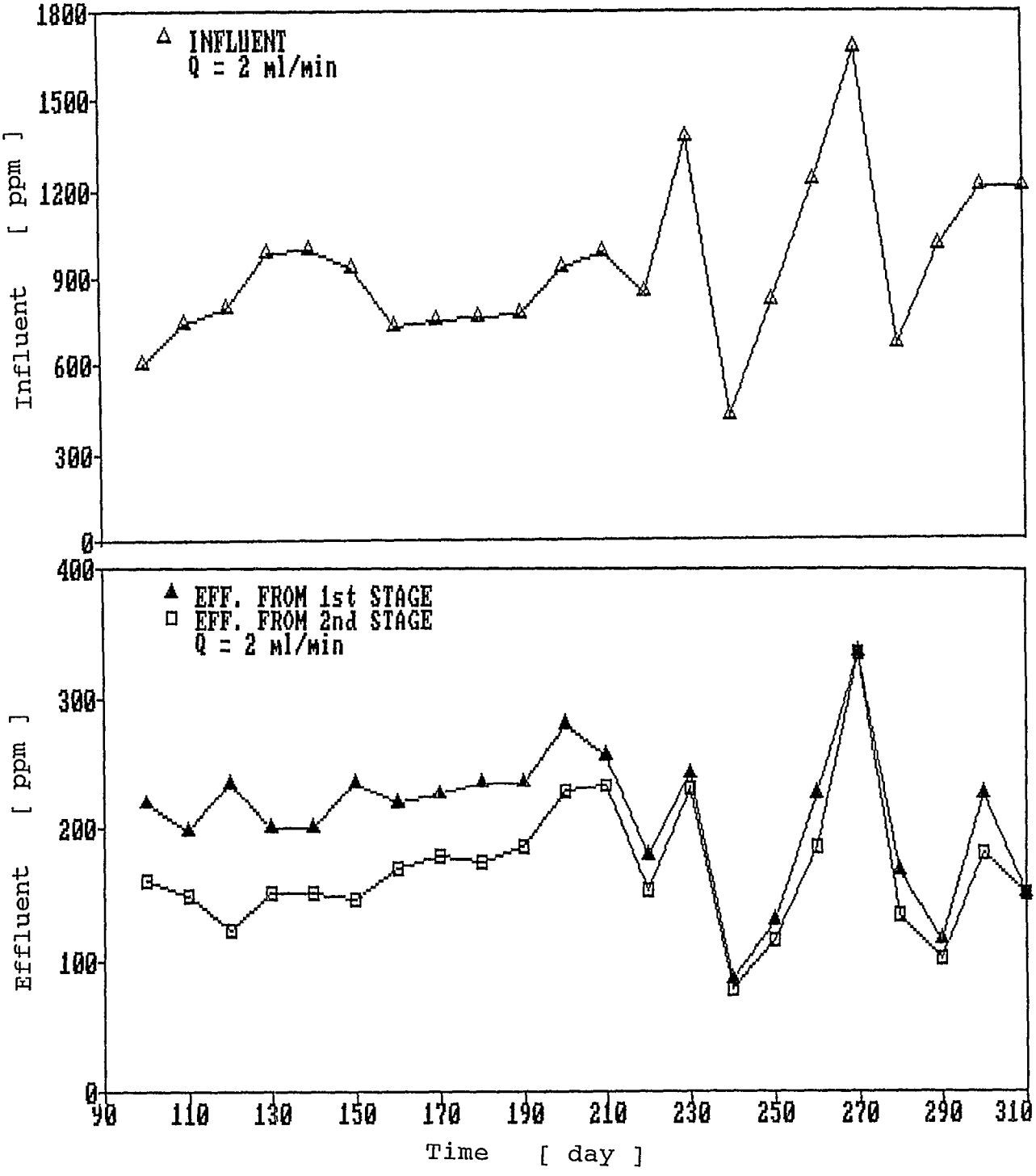

Figure 7. COD Reduction in System 2

effluent after Day 220. When the microorganisms can not stand such an increasingly toxic environment, the biodegradation becomes slow and the glucose utilization decreases. This is the reason for the peaks illustrated in Figures 4 and 5, the glucose digestion was affected by TCE concentration. On Day 220, the influent TCE concentration was increased from 10 ppm to 16 ppm, the glucose in the effluent increased sharply from 13.5 ppm to 37 ppm. The same situation occured in the latter experiments, that apparently tells us the glucose utilization decreased with the TCE concentration increased.

As time goes by, the microorganisms enhance their toxic resistance and adapt to the external environment. Under this condition the microbial activity is recovered. The above phenomenon is clearly discovered from the figure which shows that the amount of glucose in the effluent decreased gradually from 65 ppm to 46 ppm in the first stage of System 1 and from 40 ppm to 24 ppm of System 2 . Glucose utilization was affected by TCE concentrations in both Systems 1 and 2. The inhibition might have produced because of the high toxicity of TCE. It can be reflected from the increasing amount of glucose and TCE in the effluent. The feeding rate of System 1 is twice that of System 2, this is why System 1 was affected in a greater extent than System 2.

The major sources of COD in this experiment come from

the convertion of glucose and methanol (used as solvent). In the latter half of the study, COD values were extremely changeable because of the additions of different concentrations of methanol. In order to dissolve higher TCE concentrations, more methanol was used causing high COD value. In the whole study, COD as well as glucose was mainly utilized in Stage 1. Some intermediate products such as dichloroethylene (DCE) and vinyl chloride (VC) were produced. These compounds were highly resistant to biodegradation. Because of their toxicity, a lower reduction of COD was obtained in Stage 2 than in Stage 1.

TCE Loading Effects

a. Effects on TCE

From Figures 9 and 10, it was found that TCE concentration in the effluent of Stage 1 increased with an increase of TCE loading and TCE concentration. But no TCE was detected in the effluent of stage 2 within the TCE loadings of 0.021 to 55.518 mg/hr-L. According to the above observation, the following conclusion can be deduced: (a) Stage 1 was affected by TCE loading; increasing the TCE loading causes an increase in the TCE concentration in the effluent of stage 1. (b) The overall TCE removal was not affected by increasing the TCE loading because no TCE was detected in the effluent of Stage 2 during the entire course of the experiment.

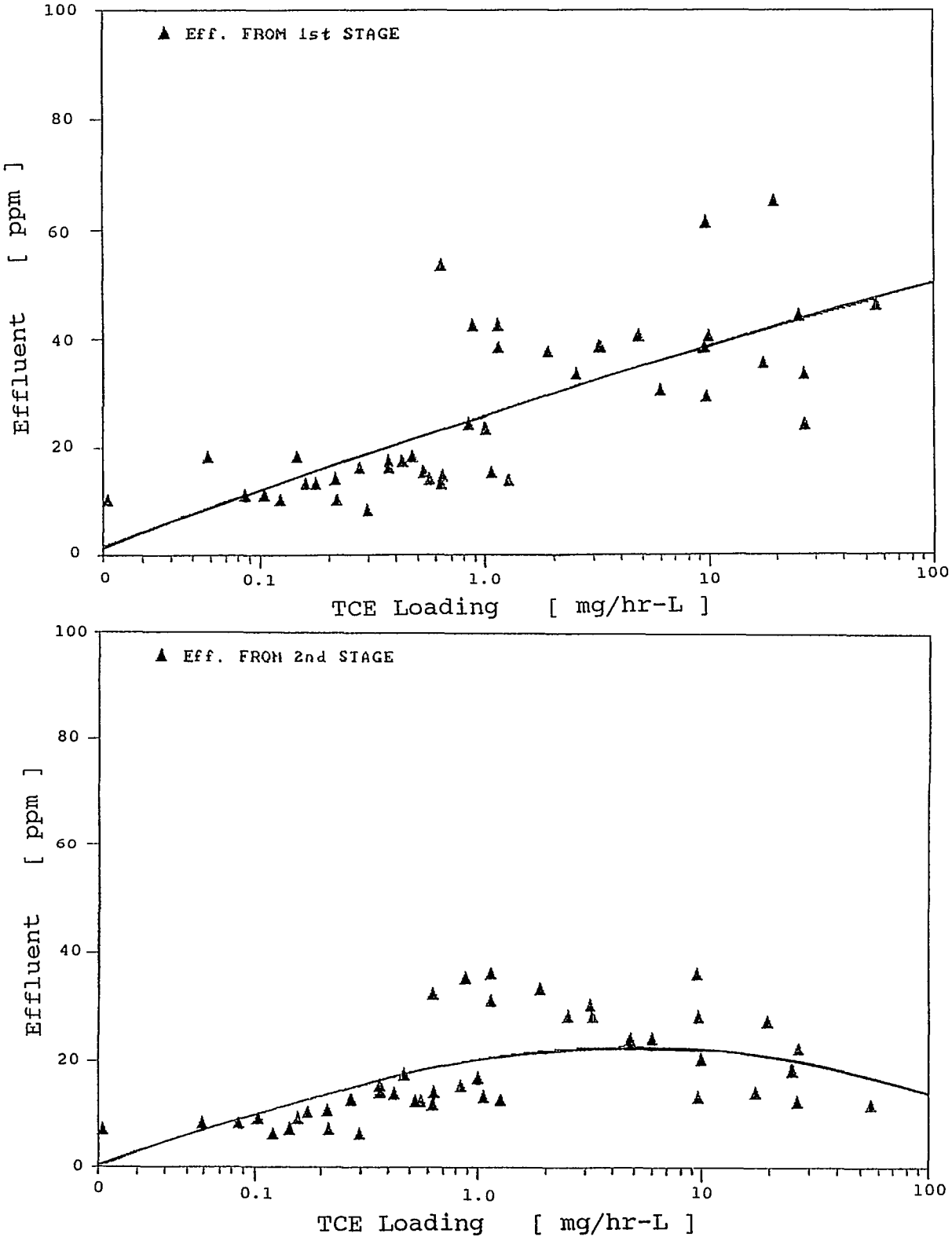

Figure 8. Glucose in Effluent as a Function of TCE Loading

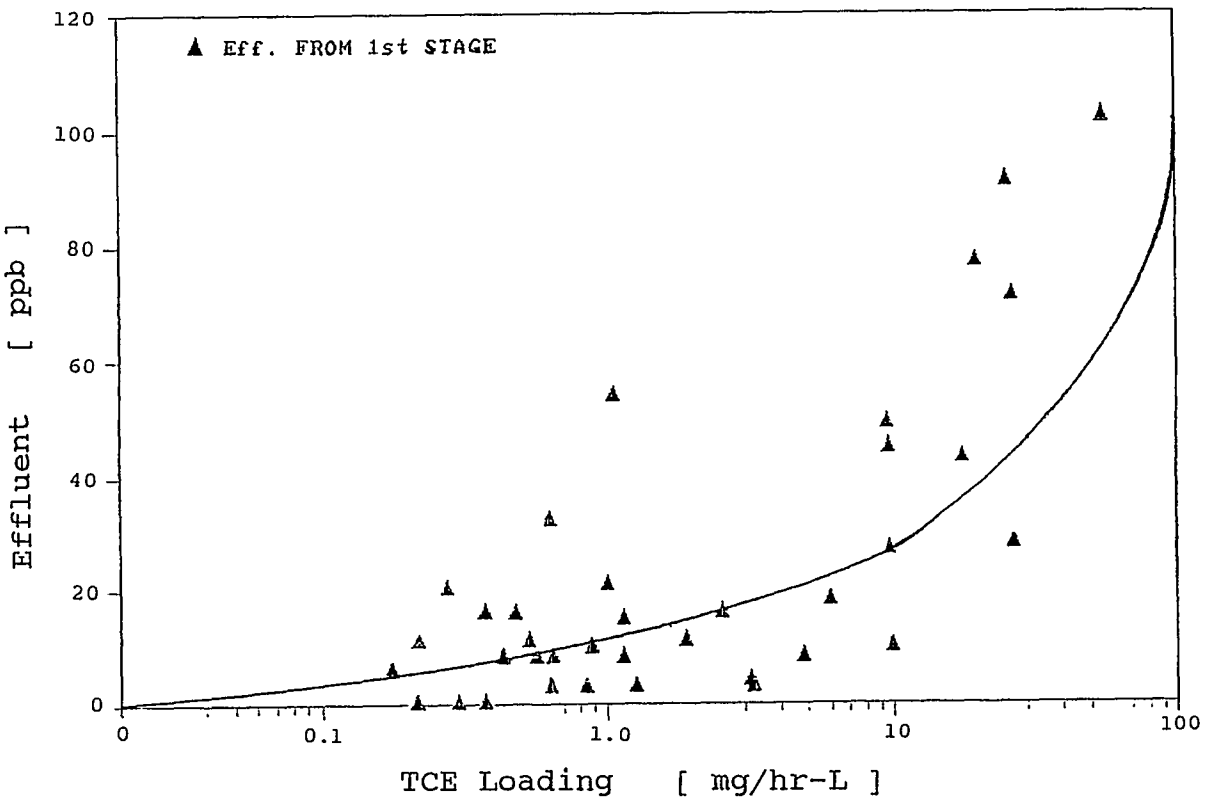

Figure 9. TCE in Effluent as a Function of TCE Loading

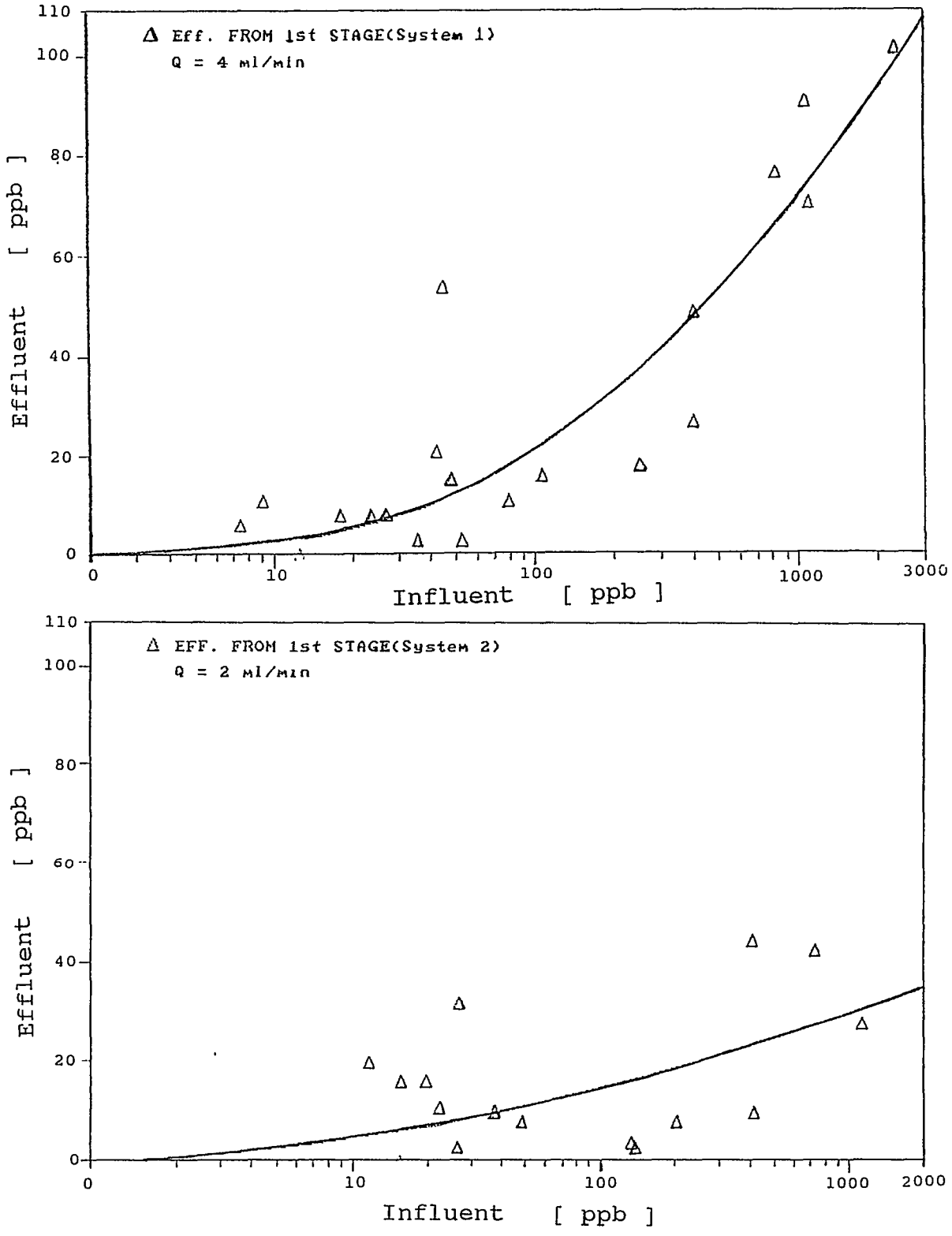

Figure 10. The Influence of TCE Influent on TCE Effluent

b. Effects on glucose

It was also found that glucose utilization was greatly affected by TCE loading as shown in Figure 8. Glucose concentration in the effluent increased with an increase of TCE loading. Thus, the glucose removal declined when TCE loading increased. In the present study, both Stages 1 and 2 were influenced by the change of TCE loading and the effect on Stage 1 was stronger than that on Stage 2.

The microorganisms were inhibited to digest glucose in high TCE loading. This effect is especially senere in the 1st stage. This explains why the glucose concentration increased gradually in the effluent. In the second stage, the environment is less toxic because of lower TCE level. The microbes can adapt to the external environment and recover their degradative activity soon. Hence the glucose concentration in the effluent of Stage 2 decreased slowly.

Glucose/TCE Ratio Effects

a. Effects on TCE

Within the glucose/TCE ratio of 0.6 to 805.5, the overall removal efficiency was close to 100%. According to the experimental data, the TCE concentration in the effluent of the first stage increased with the decrease in the glucose/TCE ratio. However, the second stage was not affected by glucose/TCE ratio.

b. Effects on glucose

The glucose removal efficiency ranged from 88.4% to 97.9% within the glucose/TCE ratio of 0.6 to 805.5. During higher glucose/TCE ratios, the glucose reduction efficiency remained essentially constant at about 94%. Then the reduction efficiency declined abruptly when the glucose/TCE ratio decreased to 20. With increasing TCE concentration (decreasing glucose/TCE ratio), the resistance of microorganisms became stronger, so the glucose reduction was enhanced gradually.

c. Effects on COD

In Figure 11, the COD removal efficiency varied clearly in higher glucose/TCE ratio. In the range of glucose/TCE from 805 to 78.3, the removal efficiency increased with a decrease of glucose/TCE ratio and then decreased gradually. The optimal removal occured in this range. The obvious decline in the COD reduction efficiency within the ratio from 78.4 to 26.3 was attributed to the antagonistic effect of TCE. Moreover, the intermediate products produced by TCE such as vinyl chloride and dichloroethylene were recalcitrant to biodegradation. The activities of the microorganisms to degrade COD were also inhibited by these compounds. As the glucose/TCE ratio decreases, the COD removal efficiency increases smoothly again as the same as glucose within the ratio from 26.2 to

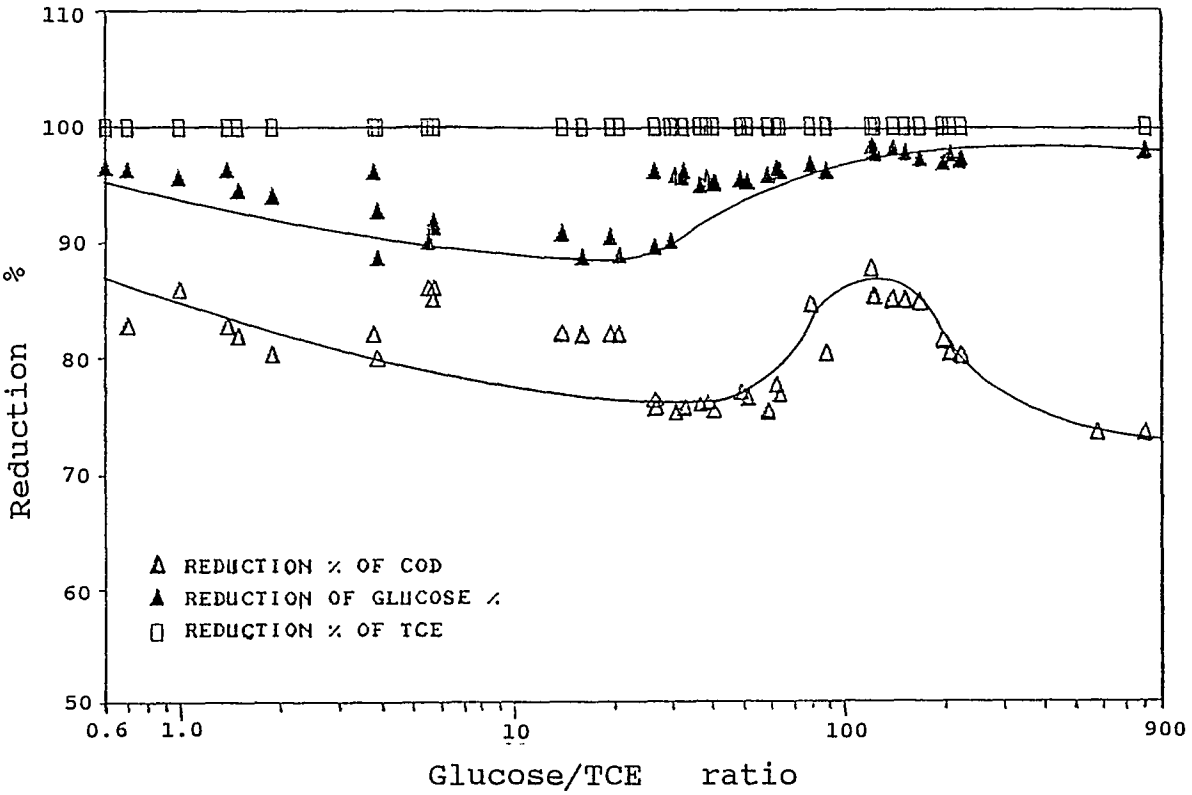

Figure 11. The Effect of Glucose/TCE Ratio on TCE, Glucose and COD Reduction

0.6.

Kinetics of Substrate Removal

According to the Figure 12, the kinetic of TCE removal can be discribed as Monod equation.

$$r = r_m S/K_S+S$$

The reaction rate r, defined as consumption of substrate concentration within solid retention time (mg/L-min), was applied in this calculation. The maximum reaction rate (r_m) obtained from this calculation is 833.3 ug/l-min, and the half-velocity constant (K_S) is 41.7 ug/l.

The result indicates that when the substrate (TCE) concentration is low compared to K_S, the reaction rate is directly proportional to S. Therefore the reaction can be discribed as first-order. However, when S is much greater than K_S, the reaction rate is a maximum and independent of the concentration S. The purpose of utilizing reaction kinetic constants is to illustrate (1) the development of microorganism and substrate balances, (2) the prediction of effluent microorganism and substrate concentrations, (3) the development of process design factors, and (4) the effects of kinetics on process design, performance and stability.

Also, the kinetic of glucose utilization was observed from Figure 13. It was found that the reaction is described

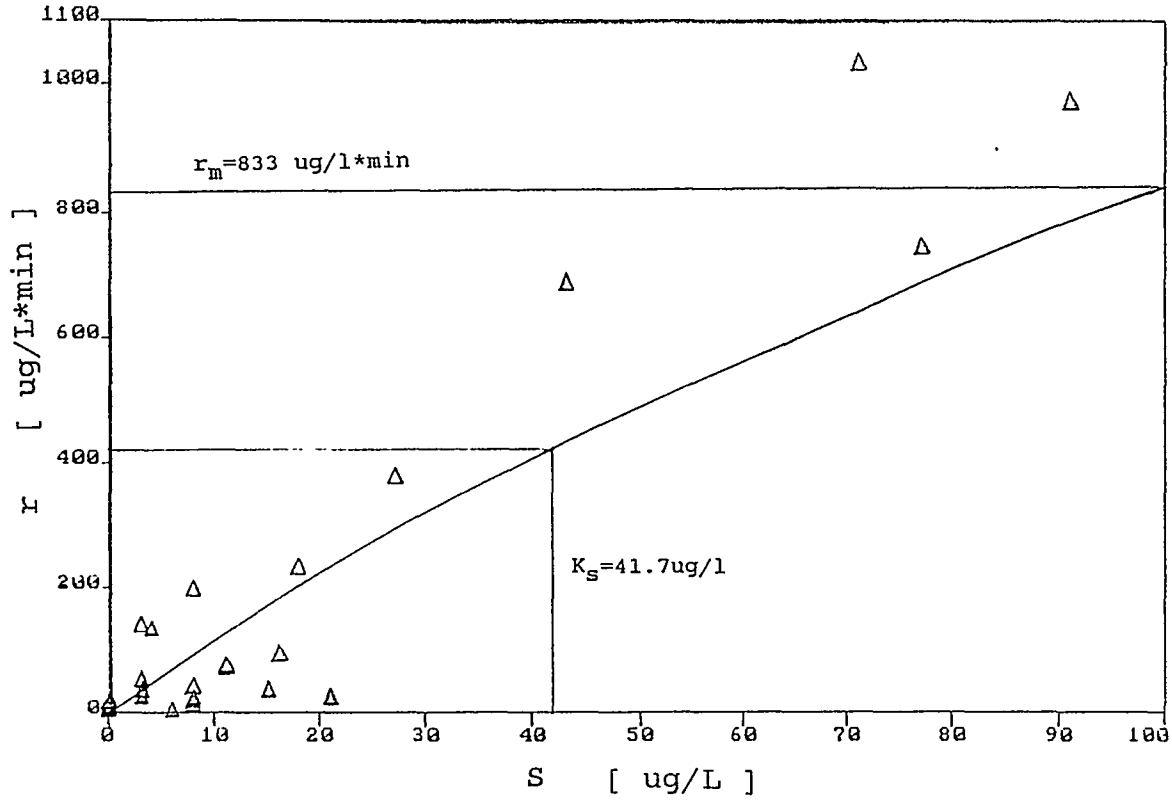

Figure 12. TCE Removal Rate during the Course of the Experiment

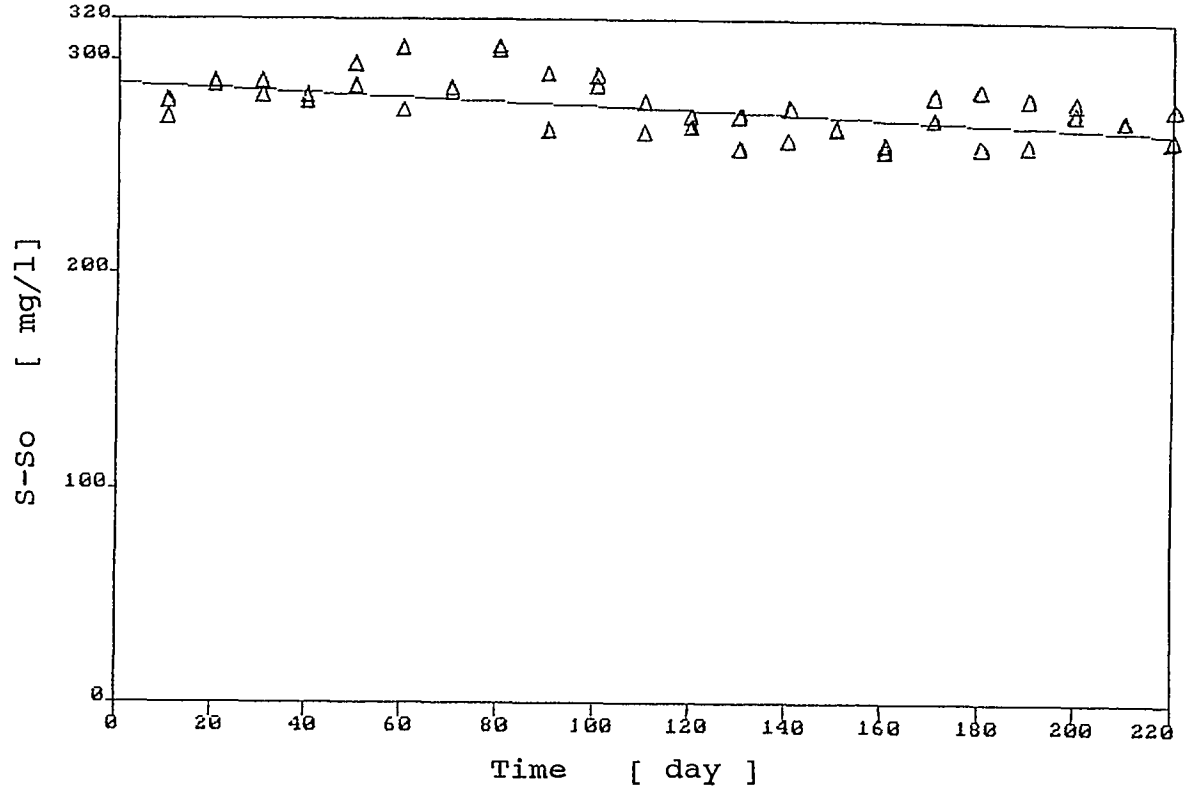

Figure 13. Glucose Utilization Rate during the Course of the Experiment

as zero-order. Many biologically induced reaction, particularly those involving soluble substrates, appear to occur in a linear manner over fairly large ranges of concentrations. Glucose was utilized as cosubstrate in the present study. Thus, the rate of glucose consumption is independent of glucose concentration.

CHAPTER V

CONCLUSION

The biodegradation of TCE by using anaerobic bioprocess has been successfully investigated in the present study. High quality effluent was obtainable when the TCE influent concentration was up to 2.4 ppm in the 1st stage. The microbial cultures, originated from conventiional anaerobic digestor, had been developed to degrade TCE in the anaerobic carbon fluidized bed.

In the present study, the overall TCE removal efficiency was not affected by TCE loadings, but the first stage was obviously influenced by TCE loadings. More TCE was detected in the effluent under higher TCE loadings. It was also found that the microbial activities were influenced by TCE loadings, the ability to digest glucose decreased when TCE loading increased. On the other hand, the inhibitory effect was stronger enough to affect microbes, which resulted a decline in TCE and glucose reductions.

The intermediate products such as vinyl chloride and dichloroethylene were produced in this study. These compounds are hardly biodegraded, which lowers the COD removal efficiency.

In order to obtain satisfied experimental results, it is important that the reactor temperature must be maintained at 35°C and the pH should be controlled around 7. Moreover, nitrogen and phosphate have to be sufficient for microbial growth.

The kinetic of TCE removal can be discribed as Monod equation. The maximum reaction rate obtained is 833.3 ugTCE/L*min and the half-velocity is 41.7ug/l. It was also found that the glucose utilization kinetic is zero-order, which proved that the present study is a typical biologically induced reaction. Particularly glucose was utilized as a soluble cosubstrate in this experiment. As a result, the glucose consumption rate is independent of glucose concentration.

APPENDIX: EXPERIMENTAL DATA

Table 2. Glucose Reduction in System 1

Run No.	Time [Day]	Inf. [ppm]	Eff 1 [ppm]	Eff 2 [ppm]	Reduction % 1st	System
1	100	290.0	18.0	8.0	93.8	97.2
2	110	300.0	13.0	9.0	95.6	97.0
3	120	295.0	13.0	10.0	95.6	96.6
4	130	290.0	10.0	7.0	96.5	97.5
5	140	305.0	8.0	6.0	97.3	98.0
6	150	321.0	17.0	13.5	94.7	95.8
7	160	300.0	14.0	12.0	95.3	96.0
8	170	320.0	14.5	14.0	95.4	95.6
9	180	290.0	24.0	15.0	91.7	94.8
10	190	310.0	23.0	16.5	92.5	94.6
11	200	280.0	15.0	13.0	94.6	95.3
12	210	282.0	13.5	12.2	95.2	95.6
13	220	310.0	37.0	33.0	88.0	89.3
14	230	315.0	38.0	31.0	87.9	90.2
15	240	300.0	33.0	28.0	89.0	90.6
16	250	290.0	30.0	24.0	89.6	91.7
17	260	310.0	38.0	36.0	87.7	88.4
18	270	320.0	61.0	13.0	80.9	95.9
19	280	325.0	65.0	27.0	80.0	91.7
20	290	319.0	44.0	18.0	86.2	94.3
21	300	305.0	33.0	12.0	89.2	96.0
22	310	310.0	46.0	11.5	85.2	96.3

Table 3. Glucose Reduction in System 2

Run No.	Time [Day]	Inf. [ppm]	Eff 1 [ppm]	Eff 2 [ppm]	Reduction % 1st	system
1	100	290.0	10.0	7.0	96.5	97.6
2	110	300.0	11.0	8.0	96.3	97.3
3	120	300.0	11.0	9.0	96.3	97.0
4	130	292.0	10.0	6.0	96.5	97.9
5	140	305.0	18.0	7.0	94.0	97.7
6	150	290.0	14.0	10.3	95.1	96.4
7	160	300.0	16.0	12.5	94.6	95.8
8	170	320.0	16.0	14.0	95.0	95.6
9	180	310.0	17.0	15.0	94.5	95.1
10	190	310.0	18.0	17.0	94.1	95.1
11	200	295.0	15.0	12.0	94.9	95.9
12	210	286.0	13.0	11.5	95.2	95.8
13	220	310.0	42.0	35.0	86.4	88.7
14	230	315.0	53.0	32.0	83.2	89.8
15	240	310.0	42.0	36.0	86.5	88.4
16	250	295.0	38.0	30.0	87.1	89.8
17	260	320.0	38.0	28.0	88.1	91.2
18	270	325.0	40.0	24.0	87.7	92.6
19	280	310.0	29.0	28.0	90.6	90.9
20	290	320.0	40.0	20.0	87.5	93.7
21	300	305.0	35.0	14.0	88.5	95.4
22	310	300.0	24.0	22.0	92.0	92.6

Table 4. COD Reduction in System 1

Run No.	Time [Day]	Inf. [ppm]	Eff 1 [ppm]	Eff 2 [ppm]	Reduction % 1st	system
1	100	600.0	240.0	160.0	60.0	73.3
2	110	742.5	198.0	149.0	73.3	79.9
3	120	790.0	190.5	148.5	75.8	81.2
4	130	980.0	200.0	150.0	79.6	84.6
5	140	1000.0	180.0	125.0	82.0	87.5
6	150	970.0	180.0	194.0	71.6	80.0
7	160	728.0	194.0	163.0	73.3	77.6
8	170	750.0	225.0	187.5	70.0	75.0
9	180	760.0	235.0	188.4	69.0	75.2
10	190	770.0	212.0	187.0	72.4	75.7
11	200	934.0	280.0	233.0	70.0	75.0
12	210	1051.0	292.0	257.0	72.2	75.5
13	220	846.1	185.0	153.8	78.1	81.8
14	230	1269.2	230.0	192.3	81.8	84.5
15	240	1057.0	215.0	205.0	81.0	81.8
16	250	814.8	130.0	115.4	84.0	85.8
17	260	1223.0	255.0	223.0	79.1	81.7
18	270	1677.0	270.5	234.9	83.8	86.0
19	280	671.1	167.7	167.7	75.0	75.0
20	290	1006.5	192.5	184.5	80.8	81.6
21	300	1212.0	237.5	212.0	80.4	82.5
22	310	1212.0	215.0	181.0	82.2	85.0

Table 5. COD Reduction in System 2

Run No.	Time [Day]	Inf. [ppm]	Eff.1 [ppm]	Eff.2 [ppm]	Reduction % 1st	System
1	100	600.0	220.0	160.0	63.3	73.3
2	110	742.5	198.0	148.5	73.3	80.0
3	120	790.0	235.0	123.0	70.2	84.4
4	130	980.0	200.0	150.0	79.4	84.6
5	140	1000.0	200.0	150.0	80.0	85.0
6	150	928.0	235.8	145.0	74.6	84.3
7	160	728.0	220.0	169.0	69.7	76.7
8	170	750.0	225.0	177.7	70.0	76.3
9	180	760.0	235.8	175.0	68.9	76.9
10	190	770.0	235.8	185.0	69.3	75.9
11	200	934.0	280.0	228.8	70.0	75.5
12	210	980.0	257.0	233.0	73.7	76.2
13	220	846.1	180.0	153.8	78.7	81.8
14	230	1380.0	242.5	230.7	82.4	83.3
15	240	423.0	85.0	76.9	79.9	81.8
16	250	814.8	130.0	115.4	84.0	85.8
17	260	1223.0	225.0	185.0	81.6	84.8
18	270	1677.0	335.0	335.0	79.9	79.9
19	280	671.1	167.0	134.2	75.0	80.0
20	290	1006.6	115.5	100.6	88.5	90.0
21	300	1212.0	225.0	181.0	81.4	85.0
22	310	1212.0	225.0	150.0	81.4	87.6

Table 6. TCE Reduction in System 1

Run No.	Time [day]	Inf. [ppm]	Inf.1 [ppb]	Eff.1 [ppb]	Eff.2 [ppb]	Reduction % 1st	System
1	100	0.50	2.5	ND	ND	100.0	100.0
2	110	1.35	6.6	ND	ND	100.0	100.0
3	120	1.50	7.4	6	ND	23.3	100.0
4	130	1.85	9.1	11	ND	-----	100.0
5	140	2.56	12.5	ND	ND	100.0	100.0
6	150	3.65	17.9	8	ND	55.3	100.0
7	160	4.80	23.6	8	ND	66.1	100.0
8	170	5.45	26.8	8	ND	70.2	100.0
9	180	7.18	35.3	3	ND	91.5	100.0
10	190	8.50	41.8	21	ND	49.8	100.0
11	200	9.07	44.6	54	ND	-----	100.0
12	210	10.70	52.6	3	ND	94.3	100.0
13	220	16.00	78.6	11	ND	86.0	100.0
14	230	9.75	47.9	15	ND	68.7	100.0
15	240	21.53	105.8	16	ND	84.9	100.0
16	250	50.74	249.3	18	ND	92.8	100.0
17	260	81.06	398.3	49	ND	87.7	100.0
18	270	81.70	401.5	27	ND	93.3	100.0
19	280	166.48	818.0	77	ND	90.6	100.0
20	290	216.35	1063.0	91	ND	91.4	100.0
21	300	223.66	1099.0	71	ND	93.5	100.0
22	310	476.41	2341.0	102	ND	95.6	100.0

Table 7. TCE Reduction in System 2

Run No.	Time [day]	Inf. [ppm]	Inf.1 [ppb]	Eff.1 [ppb]	Eff.2 [ppb]	Reduction % 1st	System
1	100	0.36	0.9	ND	ND	100.0	100.0
2	110	1.45	3.5	ND	ND	100.0	100.0
3	120	1.80	4.4	ND	ND	100.0	100.0
4	130	2.10	5.1	ND	ND	100.0	100.0
5	140	2.50	6.1	ND	ND	100.0	100.0
6	150	3.70	9.1	ND	ND	100.0	100.0
7	160	4.70	1.6	20	ND	-----	100.0
8	170	6.30	5.5	ND	ND	100.0	100.0
9	180	6.35	5.6	16	ND	-----	100.0
10	190	8.05	9.8	16	ND	19.2	100.0
11	200	9.07	2.3	11	ND	50.7	100.0
12	210	10.80	6.6	32	ND	-----	100.0
13	220	15.02	37.0	10	ND	73.0	100.0
14	230	10.72	26.4	3	ND	88.6	100.0
15	240	19.42	47.8	8	ND	83.3	100.0
16	250	54.07	133.2	4	ND	92.6	100.0
17	260	55.77	137.4	3	ND	94.6	100.0
18	270	81.76	201.4	8	ND	90.2	100.0
19	280	163.65	401.5	45	ND	88.8	100.0
20	290	168.43	414.8	10	ND	97.6	100.0
21	300	294.08	724.3	43	ND	94.1	100.0
22	310	457.52	1126.9	28	ND	97.5	100.0

Table 8. TCE Loading in System 1 and 2

Run No.	Time [day]	Loading to System 1 [mg/hr-L]	Loading to System 2 [mg/hr-L]
1	100	0.058	0.021
2	110	0.157	0.084
3	120	0.174	0.103
4	130	0.216	0.122
5	140	0.298	0.145
6	150	0.425	0.214
7	160	0.559	0.273
8	170	0.634	0.367
9	180	0.837	0.369
10	190	0.990	0.469
11	200	1.056	0.528
12	210	1.246	0.628
13	220	1.864	0.874
14	230	1.135	0.624
15	240	2.509	1.131
16	250	5.913	3.150
17	260	9.445	3.249
18	270	9.520	4.764
19	280	19.399	9.537
20	290	25.212	9.814
21	300	26.064	17.137
22	310	55.518	26.661

Table 9. Experimental Results of System 1 (Run 1)

Parameter		Inf.	Eff. of 1st	Eff. of 2nd
TCE	[ppm]	0.500	ND	ND
COD	[ppm]	600.0	240.0	160.0
Glucose	[ppm]	290.0	18.0	8.0
PO_4^{-3}	[ppm]	980.0	920.0	800.0
NH_4^+	[ppm]	12.6	---	1.5
Alkalinlity	[ppm]	1200.0	---	950.0
pH		8.2	7.45	7.3
V.S.S.	[ppm]	50.0	---	22.0

Glucose/TCE = 580.0

Table 10. Experimental Results of System 1 (Run 2)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	1.35	ND	ND
COD	742.0	198.0	149.0
Glucose	300.0	13.0	9.0
PO_4^{-3}	665.0	924.0	788.0
NH_4^+	40.6	---	30.1
Alkalinity	1026	1150	1308
pH	8.44	7.35	7.22
V.S.S.	27	---	19

Glucose/TCE = 222.2

Table 11. Experimental Results of System1 (Run 3)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	1.5	0.006	ND
COD	790	190.5	148.5
Glucose	295	13	10
PO_4^{-3}	1090	960	1040
NH_4^+	32.9	---	26.6
Alkalinity	1050	1100	1210
pH	8.3	7.1	7.05
V.S.S.	53	---	48

Glucose/TCE = 196.6
All units except pH are ppm.

Table 12. Experimental Results of System 1 (Run 4)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	1.850	0.011	ND
COD	980	200	150
Glucose	290	10	7
PO_4^{-3}	530	710	790
NH_4^+	42	---	19.6
Alkalinity	1120	---	1065
pH	8.33	7.32	7.26

Glucose/TCE = 156.7

Table 13. Experimental Results of System 1 (Run 5)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	2.56	ND	ND
COD	1000	180	125
Glucose	305	8	6
PO_4^{-3}	640	565	735
NH_4^+	39.2	---	18.9
Alkalinity	1090	---	1035
pH	8.21	7.22	7.10

Glucose/TCE = 119.1

Table 14. Experimental Results of System 1 (Run 6)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	3.65	0.008	ND
COD	970	275	194
Glucose	321	17	13.5
PO_4^{-3}	834	735	980
NH_4^+	42	---	25
Alkalinity	1465	---	1380
pH	8.49	7.4	7.21

Glucose/TCE = 87.9
All units except pH are ppm.

Table 15. Experimental Results of System 1 (Run 7)

Parameter	Inf.	Eff. of1st	Eff. of 2nd
TCE	4.8	0.008	ND
COD	728	194	163
Glucose	300	14	12
PO_4^{-3}	1050	945	980
NH_4^+	42	---	45
Alkalinity	1980	---	1820
pH	8.7	7.45	7.28

Glucose/TCE = 62.5

Table 16. Experimental Results of System 1 (Run 8)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	5.45	0.008	ND
COD	750	225	187.5
Glucose	320	14.5	14
PO_4^{-3}	1325	1265	1142
NO_4^+	53	---	46
Alkalinity	2010	---	1915
pH	8.89	7.39	7.26

Glucose/TCE = 58.7

Table 17. Experimental Results of System 1 (Run 9)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	7.18	0.021	ND
COD	770	212	187
Glucose	310	23	16.5
PO_4^{-3}	890	1055	875
NH_4^+	52	---	50
Alkalinity	1882	---	1876
pH	8.45	7.41	7.17

Glucose/TCE = 40.3
All units except pH are ppm.

Table 18. Experimental Results of System 1 (Run 10)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	8.5	0.021	ND
COD	770	212	187
Glucose	310	23	16.5
PO_4^{-3}	890	1055	875
NH_4^+	52	---	50
Alkalinity	1882	---	1876
pH	8.45	7.41	7.17

Glucose/TCE = 36.4

Table 19. Experimental Results of System 1 (Run 11)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	9.07	0.054	ND
COD	934	280	233
Glucose	280	15	13
PO_4^{-3}	955	995	1160
NH_4^+	49	---	52
Alkalinity	1978	---	1895
pH	8.41	7.33	7.12

Glucose/TCE = 30.8

Table 20. Experimental Results of System 1 (Run 12)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	10.7	0.003	ND
COD	1051	292	257
Glucose	282	13.5	12.2
PO_4^{-3}	940	1038	985
NH_4^+	57	---	51
Alkalinity	1850	---	1811
pH	8.36	7.17	7.05

Glucose/TCE = 26.3
All units except are ppm.

Table 21. Experimental Results of System 1 (Run 13)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	16.0	ND	ND
COD	846.1	185	153.8
Glucose	310.0	37	33
PO_4^{-3}	1150.0	1433	1375
NH_4^+	119.7	---	11.1
Alkalinity	522	---	963
pH	7.09	---	7.84

Glucose/TCE = 19.4

Table 22. Experimental Results of System 1 (Run 14)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	9.75	0.015	ND
COD	1269.2	230	192.3
Glucose	315	38	31
PO_4^{-3}	950	833	1070
NH_4^+	40.9	---	10.7
Alkanility	1035	---	846
pH	7.84	---	7.9

Glucose/TCE = 32.3

Table 23. Experimental Results of System 1 (Run 15)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	21.53	0.016	ND
COD	1057	215	205
Glucose	300	33	28
PO_4^{-3}	1050	1170	1400
NH_4^+	33.7	---	10.7
Alkalinity	639	---	927
pH	7.64	---	8.03

Glucose/TCE = 13.9
All units except pH are ppm.

Table 24. Experimental Results of System 1 (Run 16)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	50.74	0.018	ND
COD	814.8	130	115.4
Glucose	290	30	24
PO_4^{-3}	1340	1466	1490
NH_4^+	58.6	---	18.5
Alkalinity	1193	---	1202
pH	7.6	---	7.39

Glucose/TCE = 5.7

Table 25. Experimental Results of System 1 (Run 17)

Parameter	Inf.	Eff. of 1st	Eff.of 2nd
TCE	81.06	0.049	ND
COD	1223	255	223
Glucose	310	38	36
PO_4^{-3}	1700	866	1960
NH_4^+	19.4	---	33.8
Alkalinity	963	---	990
pH	7.92	---	7.73

Glucose/TCE = 3.8

Table 26. Experimental Results of System 1 (Run 18)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	81.70	0.027	ND
COD	1667	270.5	234.9
Glucose	320	61	13
PO_4^{-3}	850	600	900
NH_4^+	44.8	---	53.5
Alkalinity	1334	---	791
pH	7.15	---	7.21

Glucose/TCE = 3.9
All units except pH are ppm.

Table 27. Experimental Results of System 1 (Run 19)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	166.48	0.077	ND
COD	671.1	167.7	167.7
Glucose	325	65	27
PO_4^{-3}	1050	900	1150
NH_4^+	15.5	---	16.9
Alkalinity	1012	---	1196
pH	7.14	---	7.21

Glucose/TCE = 1.9

Table 28. Experimental Results of System 1 (Run 20)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	216.35	0.091	ND
COD	1006.5	192.5	184.5
Glucose	319	44	18
PO_4^{-3}	980	1040	1250
NH_4^+	34.4	---	27.5
Alkalinity	1316	---	1260
pH	7.64	---	7.28

Glucose/TCE = 1.5

Table 29. Experimental Results of System 1 (Run 21)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	223.66	0.071	ND
COD	1212	237.5	212
Glucose	305	33	12
PO_4^{-3}	1100	820	855
NH_4^+	70.9	---	78
Alkalinity	1790	---	1665
pH	7.62	---	8.01

Glucose/TCE = 1.4
All units except pH are ppm.

Table 30. Experimental Results of System 1 (Run 22)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	476.41	0.102	ND
COD	1212	215	181
Glucose	310	46	11.5
PO_4^{-3}	1370	1460	1120
NH_4^+	60.4	---	49.3
Alkalinity	1790	---	2067
pH	7.43	---	7.45

Glucose/TCE = 0.7

Table 31. Experimental Results of System 2 (Run 1)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	0.36	ND	ND
COD	600	220	160
Glucose	290	10	7
PO_4^{-3}	950	908	850
NH_4^+	26.6	---	7.8
Alkalinity	1130	---	1054
pH	8.1	7.18	7
V.S.S.	69	---	55

Glucose/TCE = 805.5

Table 32. Experimental Results of System 2 (Run 2)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	1.45	ND	ND
COD	742.5	198	148.5
Glucose	300	11	8
PO_4^{-3}	665	470	492
NH_4^+	40.6	---	14
Alkalinity	1093	1168	1200
pH	8.4	7.15	7.39
V.S.S.	27	---	29

Glucose/TCE = 206.8
All units except pH are ppm.

Table 33. Experimental Results of System 2 (Run 3)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	1.8	ND	ND
COD	790	235	123
Glucose	300	11	9
PO_4^{-3}	1090	830	795
NH_4^+	32.9	---	17.2
Alkalinity	1040	982	948
pH	8.35	7.1	7.22
V.S.S.	53	---	74

Glucose/TCE = 166.6

Table 34. Experimental Results of System 2 (Run 4)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	2.1	ND	ND
COD	980	200	150
Glucose	292	10	6
PO_4^{-3}	530	848	510
NH_4^+	42	---	21.4
Alkalinity	1195	---	1200
pH	8.33	7.05	7.1

Glucose/TCE = 139.0

Table 35. Experimental Results of System 2 (Run 5)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	2.5	ND	ND
COD	1000	200	150
Glucose	305	18	7
PO_4^{-3}	640	620	624
NH_4^+	39.2	---	13.3
Alkalinity	1100	---	980
pH	8.21	7.19	7.09

Glucose/TCE = 122.0
All units except pH are ppm.

Table 36. Experimental Results of System 2 (Run 6)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	3.7	ND	ND
COD	928	235.8	145
Glucose	290	14	10.3
PO_4^{-3}	810	510	548
NH_4^+	30.1	---	16.4
Alkalinity	1350	---	1237
pH	8.51	7.4	7.32

Glucose/TCE = 78.3

Table 37. Experimental Results of System 2 (Run 7)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	4.70	0.020	ND
COD	728.0	220	169
Glucose	300	16	12.5
PO_4^{-3}	1050	1120	1140
NH_4^+	58	---	50
Alkalinity	1950	---	1870
pH	8.62	7.43	7.3

Glucose/TCE = 63.8

Table 38. Experimental Results of System 2 (Run 8)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	6.3	ND	ND
COD	750	225	177.7
Glucose	320	16	14
PO_4^{-3}	1325	1266	1340
NH_4^+	52	---	41
Alkalinity	2115	---	1950
pH	8.65	7.45	7.27

Glucose/TCE = 50.7
All units except pH are ppm.

All units except pH are ppm.

Table 39. Experimental Results of System 2 (Run 9)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	6.35	0.016	ND
COD	760	235.8	175
Glucose	310	17	15
PO_4^{-3}	890	960	1100
NH_4^+	53	---	46
Alkalinity	1927	---	1891
pH	8.7	7.28	7.16

Glucose/TCE = 48.8

Table 40. Experimental Results of System 2 (Run 10)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	8.05	0.016	ND
COD	770	235.8	185
Glucose	310	18	17
PO_4^{-3}	970	1055	1145
NH_4^+	53	---	43
Alkalinity	1882	---	1796
pH	8.45	7.41	7.17

Glucose/TCE = 38.5

Table 41. Experimental Results of System 2 (Run 11)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	9.07	0.011	ND
COD	934	280	228.8
Glucose	295	15	12
PO_4^{-3}	1050	1200	1170
NH_4^+	45	---	46
Alkalinity	1874	---	1792
pH	8.5	7.28	7.15

Glucose/TCE = 32.5

All units except pH are ppm.

Table 42. Experimental Results of System 2 (Run 12)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	10.8	0.032	ND
COD	980	257	233
Glucose	286	13	11.5
PO_4^{-3}	945	1050	1220
NH_4^+	50	---	47
Alkalinity	1921	---	1893
pH	8.61	7.28	7.10

Glucose/TCE = 26.4

Table 43. Experimental Results of System 2 (Run 13)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	15.02	0.010	ND
COD	846.1	180	153.8
Glucose	310	42	35
PO_4^{-3}	1050	1350	1283
NH_4^+	60	---	49.5
Alkalinity	909	---	1314
pH	7.63	---	8.11

Glucose/TCE = 20.6

Table 44. Experimental Results of System 2 (Run 14)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	10.72	0.003	ND
COD	1380	242.5	230.7
Glucose	315	53	32
PO_4^{-3}	1025	935	1120
NH_4^+	67.3	---	35.1
Alkalinity	945	---	1071
pH	7.8	---	8.11

Glucose/TCE = 29.4

All units except pH are ppm.

Table 45. Experimental Results of System 2 (Run 15)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
COD	423	85	76.9
Glucose	310	42	36
PO_4^{-3}	1045	1255	975
NH_4^+	51.5	---	81.5
Alkalinity	837	---	1054
pH	7.82	---	7.95

Glucose/TCE = 15.9

Table 46. Experimental Results of System 2 (Run 16)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	54.07	0.004	ND
COD	814.8	130	115.4
Glucose	295	38	30
PO_4^{-3}	1350	1285	1400
NH_4^+	25.6	---	10.7
Alkalinity	615	---	1257
pH	7.14	---	7.76

Glucose/TCE = 5.5

Table 47. Experimental Results of System 2 (Run 17)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	55.77	0.003	ND
COD	1223	225	185
Glucose	320	38	28
PO_4^{-3}	1650	1385	1370
NH_4^+	9.7	---	12.2
Alkalinity	1018	---	918
pH	7.59	---	7.69

Glucose/TCE = 5.7

All units except pH are ppm.

Table 48. Experimental Results of System 2 (Run 18)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	81.76	0.008	ND
COD	1677	335	335
Glucose	325	40	24
PO_4^{-3}	975	1015	1095
NH_4^+	44.8	---	53.5
Alkalinity	1297	---	736
pH	7.02	---	7.13

Glucose/TCE = 3.9

Table 49. Experimental Results of System 2 (Run 19)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	163.65	0.045	ND
COD	671.1	167	134.2
Glucose	310	29	28
PO_4^{-3}	970	1100	1250
NH_4^+	17.7	---	11.8
Alkalinity	1177	---	1196
pH	7.08	---	7.22

Glucose/TCE = 1.9

Table 50. Experimental Results of System 2 (Run 20)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	168.43	0.010	ND
COD	1006.6	115.5	100.6
Glucose	320	40	20
PO_4^{-3}	1120	985	1126
NH_4^+	42.8	---	24.1
Alkalinity	1288	---	1545
pH	7.63	---	7.35

Glucose/TCE = 1.9

All units except pH are ppm.

Table 51. Experimental Results of System 2 (Run 21)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	294.08	0.043	ND
COD	1212	225	181
Glucose	305	35	14
PO_4^{-3}	1050	875	890
NH_4^+	65.5	---	49.3
Alkalinity	2080	---	1457
pH	7.71	---	7.64

Glucose/TCE = 1.0

Table 52. Experimental Results of System 2 (Run 22)

Parameter	Inf.	Eff. of 1st	Eff. of 2nd
TCE	457.52	0.028	ND
COD	1212	225	150
Glucose	300	24	22
PO_4^{-3}	1420	1510	1250
NH_4^+	62.9	---	68.2
Alkalinity	2150	---	2205
pH	8.01	---	7.79

Glucose/TCE = 0.6
All units except pH are ppm.

CHAPTER VI

REFERENCES

1. Evans, R. B.; Schweitzer, G. E.; Environmental Science & Technology, (1984), 330A-339A

2. Page, G. W.; Environmental Science & Technology, (1981), 1475-1481

3. DeMarco, J.; and Parsons F.;"Transformations of Tetrachloroethene and Trichlorethene in Microcosms and Groundwater", J. AWWA,(1984) 56.

4. Nelson, M. J. K., Montgomery, S. O., O'Neill, E. J., and ritchard, "Aerobic Metabolism of Trichloroethylene by A Bacterial Isolate", Applied and Environmental Microbiology, (1986) 383-384

5. Wilson, J. T. and Wilson, B. H.,"Biotransformation of Trichloroethylene in Soil", Applied and Environmental Biology, (1985) 242-243

6. Estes, T. J., Shah, R. V. and Vllker, V. L.,"Adsorption of Low Molecular Weight Halocarbons by Montmorillonite", Environmental Science & Technology, (1988) 377-381

7. Petura, J.C.; "Trichloroethylene and Methyl Chloroform in Groundwater: A Problem Assessment", J. AWWA, April (1981)

8. Kleopfer, R. D., Jackson, D. E. and Wurrey, C. J.,"Anaerobic Degradation of Trichloroethylene in Soil", Environmental Science& Technology, (1985) 277-279

9. Tucker, R. K.; "Groundwater Quality in New Jersey: an investigation of toxic contaminants", Office of Cancer and Toxic Substances Research, New Jersey Department of Environmental Protection, Trenton, N.J.

10. U.S.Environmental Protection Agency, 1984; National revised primary drinking water regulations: volatile synthetic organic chemicals: proposed rulemaking Fed. Reg. 49:24329-24355

11. Speitel, G. E. Jr. and DiGiano, A;"The Bioregeneration of GAC Used to Treat Micropollutants", J. Research and Technology, AWWA (1987), Vol.79, No.1

12. Memoradum on 1,1,1 Trichloroethane and Trichloroethylene from W. L. Marcus to R.G. Lee, Criteria and Standards Div. US Environmental Protection Agency, (1978)

13. Wilson, B. H.; Smith, G. B. and Rees, J. F.; "Biotransformations of Selected Alkylbenzenes and Halogenated Aliphatic Hydrocarbon in Methanogenic Aquifer Material: A Microcosm Study", Environmental Science & Technology, (1986), 997-1001

14. Guswa, J. H., Patrick, I., Donigian, A.s., and Lo, T. Y. R.; "Groundwater Contamination and Emergency Responsse Guide", Pollution Technology Review, (1984) No. 111

15. Wilson, J. T., and McBabb, J. F.; "Biological Transformation of Organic Pollutants in Groundwater", EOS, (1983) 64

16. Singhal, A. K.;"Tying up TCE", Water Engineering and Management, (1981) 56-61

17. Stenzel, M. H. And Gupta, U. S.;"Hazardous Waste Management: Treatment of Contaminated Groundwaters with Granular Activated Carbon and Air Stripping", Journal of the Air Pollution Control Association, (1985) 1304-1309

18. Gehringer, P.; Proksch, E. and Szinovatz, W.; "Radiation-Induced degradation of trichloroethylene and tetra chloroethylene in drinking water", Int'l J. Appl. Radiat. Isotopes, (1985)

19. Sikkema, S. et al., " Identification and Quantification of Volatile Organic Species During Microbial Treatment of Leachate", Environmental Progress, (1988) Vol.7, No.2

20. Kosson, D. S. and R. C. Ahlert, "In-Situ and ON-Site Biodegradation of Industrial Landfill Leachate", Environmental Progress, (1984) Vol.3, 176-183

21. Dienmann, E. A., J. F. Magee II, D. S. Kosson and R. C> Ahlert; "Rapid Renovation of A Sludge Lagoon", Environmental Progress, (1987) Vol.3, 158-165

22. McCarty P. L., Rittmann, B. E. and Bouwer, E. J.,"Anaerobic Degradation of Halogenated 1- and 2-Carbon Organic Compounds", Environmental Science & Technology, (1981) 506-599

23. Weber, W. J., Jr; Hopkins, C. B.; Bloom, J. Jr.; J. Water Pollution Control Federation, (1970)

24. Andrews, G. F.; Tien, C.; AIChE J. (1981) 27, 396-403

25. Bouwer, E. J. and McCarty P. L.,"Removal of Trace Chlorinated Organic Compounds by Activated Carbon and Fixed Film Bacteria", Environmental Science & Technology, (1982) 836-843

26. Gardner, D. A.; Suidan, M. T. and Kobayashi, H. A.,"Role of GAC activity and particle size during the fluidized-bed anaerobic treatment of refinery sour water stripper bottoms", J. WPCF, (1988) Vol.60, No.4

27. Peel, R.G. and Benedek, A.,"Biodegradation and adsorption within activated carbon adsorbers", J. WPCF, (1983), Vol.55, No.9

28. Clark, R. M. et al,"Removing organic contaminants from groundwater-- A cost and performance evaluation", Environmental Science & Technology, (1988),1126-1130

29. Dietrich, M. J.; Copa, W. M.; Chowdhury A. K. and Randall T. L., "Removal of Pollutants from ilute Wastewater by the PACT Treatment Process", Environmental Progress, (1988), Vol.7, No.2

30. Suidan, M. T., et al; "Continuous Bioregeneration of Granular Activated Carbon During the Anaerobic Degradation of Catechol", Prog. Water Treatment (1981)

31. Khan, K. A. et al; "Anaerobic Activated Carbon Filter for the Treatment of Phenol Bearing Wastewaters",J. Water Pollution Control Federation, (1981) 1519

32. Jewell, W.J., "Anaerobic Attached Film Expanded Bed Fundamentals", Proceedings of the 1984 International Conference on Fixed Film Biological Processes, Yeun C. Wu et al. Eds., April (1982)

33. Wang, T. C. and Tan, C. K., "Reduction of Chlorinated Hydrocarbons with Natural Sunlight in a Platinum-Catalyzed Water Photolysis System", Environmental Science & Technology, (1988), 916-919

34. Suxuan Huang, "Co-Metabolism of Trichloroethylene with Sugar Using Two-Stage Activated Carbon Fluidized Beds", Paper Presented in the Conference on Physicochemical and Biological Wastewater Treatment, Altalantic City, N.J. (May, 1988)

35. Tekmar Company, "Tekmar Purge and Trap Model 4000 Application Manual", TEK/DATA B011587

36. "Method 601-Purgeable Halocarbons", Federal Register, Vol. 49, No. 209 (1984)

37. Koehler, L. H.; "Differentiation of Carbonhydrates by Anthron Reaction Rate and Color Density", Analytical Chemistry 24, 1576 (1952)

38. Dreywood, R. "Qualitative Test for Carbonhydrate Material", Industrial and Engineering Chemistry, 18, 499 (1946)

39. HACH Company, "Procedure for Water & Wastewater Analysis", part 2, pp. 79-82 (1984)

40. Orion Research Incoporated, "Instruction Manual of Ammonia Electrode Model 95-12", pp. 10-13 (1984)

41. "Standard Method for the Examination of Water and Wastewater", 16th Ed. American Public Health Association, Washington D.C. pp.445-446, 271-273 (1985)