

OXYGENATION IN COLUMN REACTOR
SEWAGE TREATMENT

by

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ABSTRACT

A bench scale secondary sewage treatment plant, which featured four packed column reactors, was constructed in an effort to study the effect of using pure oxygen gas versus air in this type of system. During the period of this study, a record of the physical, biological, and chemical conditions within the columns was kept, and a comparison of the three oxygen-fed column reactors and one air-fed column reactor was made.

The results of this study indicated that, although the ultimate treatment level was the same for both the oxygen and air-fed systems, the oxygen-fed system could have handled higher loadings with a lower gas feed rate. The biota on the column packing appeared to be generally more healthy for the pure oxygen systems as compared to the air system when operated under similar hydraulic and organic loadings.

CHAPTER I

INTRODUCTION

The study of pure oxygen treatment systems dates back to the 1950's. These studies involved the use of a separate pre-oxygenation tank and a settling tank that required mechanical agitation. The operating costs of using pure oxygen were found to be prohibitive, in spite of increased dissolved oxygen levels, generally because of the low oxygen utilization and high power costs.

The benefits to the activated sludge process gained by the use of an oxygen enriched system as reviewed by McKinney and Pfeffer (1) were: 1) the reduction of power requirements per unit of oxygen transferred; 2) the reduction in, or elimination of, periods of zero dissolved oxygen concentration; 3) the increased rate of stabilization of organic material; 4) the ability to operate high rate systems with substantial increases in organic loadings where oxygen was not limiting; 5) the increased capacity of organically overloaded plants without the need for additional aerator capacity; 6) the reduction in plant size and capital investment. These benefits were achievable because of a higher oxygen partial pressure; there was over four times more energy available for reactions using pure oxygen than for those that used an equivalent amount of air.

Interest in the use of pure oxygen in the bio-oxidation process was revived as the result of an investigation done by Union Carbide

Corporation for the Federal Water Quality Administration of the Department of the Interior (2). The experimental results obtained in the Batavia study indicated that a high percentage gas utilization can be realized using a pure oxygen system that incorporated a multi-tank, recycling, flow pattern. With high oxygen utilization their process was found to be economically competitive with the conventional activated sludge process using air. Along with the development of an economically competitive pure oxygen system there has developed a need for more information concerning the various treatment parameters, in a pure oxygen system, such as oxygen demand and oxygen utilization.

Purpose and Scope

The purpose of this thesis was to determine the values of the various operating parameters in an upflow column reactor which utilized pure oxygen gas for aeration and to compare them with similar values from a column reactor that utilized air.

The study was bench scale employing four packed column reactors, three using pure oxygen and one air. Sewage was pumped from a refrigerated reservoir through a heating coil into the tubes where contact took place. A capability of adjusting sewage and gas flow rates was also built into the system.

The primary sewage used throughout the study was obtained from the municipal waste treatment plant of the City of Tucson, Arizona.

CHAPTER II

LITERATURE SURVEY

Low cost oxygen supplies have recently become available, and this has caused a sudden rekindling of interest in the use of pure oxygen as an aid in secondary sewage treatment (3). It has been known for thirty years that dissolved oxygen (DO) levels of four times that from air could be maintained using pure oxygen gas. There have been many theories as to the value of these high DO levels, but whether it was increased biological activity, reduced oxygen tension, better oxygen utilization, or any of these, there seemed to be a distinct improvement in the load carrying capability of the treatment process with the use of oxygen enriched air.

"Bio-precipitation" is a method of sewage treatment utilizing a biological floc as the means of removing organic matter. It was first outlined by Okun (4) and Pirnie (5), who thought it might be used employing pure oxygen produced at low cost by air liquefaction and rectification. Bio-precipitation, a form of aerobic biological treatment, involves the removal and stabilization of polluting material which is either suspended or dissolved in sewage. The process is schematically presented in Figure 2.1.

Okun (6), working with Malcolm Pirnie Engineers in New York, conducted a laboratory study which used the bio-precipitation process on well-settled raw sewage. The sewage was first oxygenated using

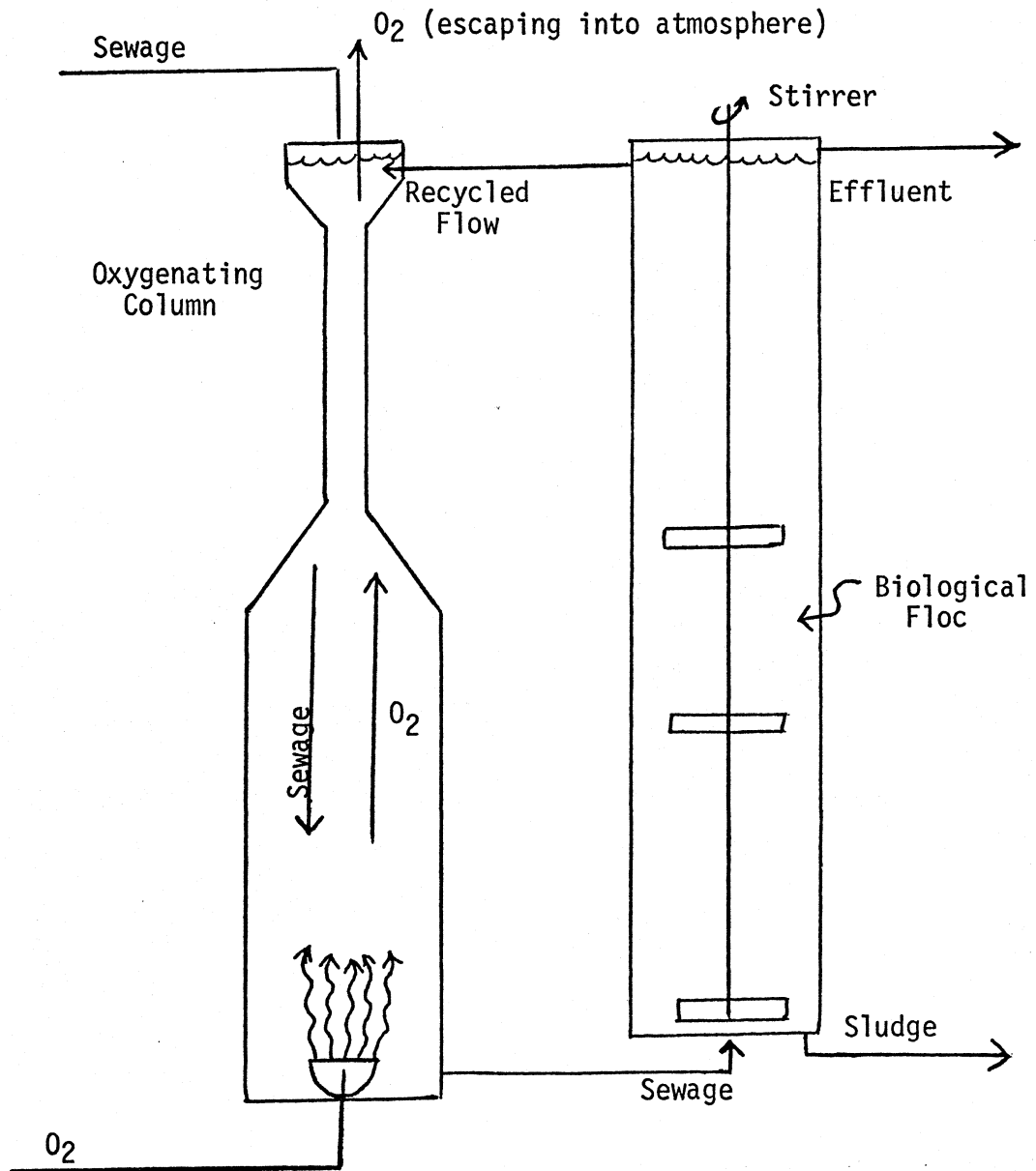


Figure 2.1 Diagram of Laboratory Bio-precipitation Apparatus (6)

bottled oxygen then fed into a precipitation unit that contained suspended biological floc. Three of the basic parameters that affected Okun's biological sewage treatment units were the amount of contact surface area, contact time, and organic load. From his studies Okun concluded that the efficiency of biochemical oxygen demand (BOD) removal was a function of volatile solids (VS) in the system rather than total solids (TS) and that the surface area could have been directly related to the sludge volume.

A summary of some of the conclusions obtained from Okun's study is as follows: 1) The concentration of the biomass in the bio-precipitation process could have been maintained at twice the level as that in the aeration tanks of activated sludge plants. 2) For equivalent sewage purification a smaller plant capacity was required for the bio-precipitation process than the activated sludge. This was due to the greater weight of biological floc maintained in the reactor which utilized pure oxygen. 3) The volume of the aeration required to hold the biological floc in bio-precipitation was approximately one-fourth that necessary for the activated sludge process to obtain an equal degree of treatment. 4) The difference in organic loadings did not result in marked differences in the microscopic life of the biomass. However, the number and activity of the protozoa was greater at higher loadings in the pure oxygen system.

These findings indicated that further study in the use of pure oxygen for biological waste treatment systems was warranted.

Lynn and Okun (7) experimented with the bio-precipitation process in an effort to discern the effects of oxygen tension on biological

sewage treatment. They found that oxygen concentration of itself had little influence on the activity of micro-organisms through the sludge settling stage and the period of aeration immediately following the addition of fresh sewage. While the oxygen fed system had much greater DO resources for the settling period, the period of zero DO which followed sewage addition was also much shorter because of a greater absorption gradient.

Lynn and Okun also found that the oxygen requirements of air-aerated sludge was greater than in the oxygen fed systems. The greater oxygen requirements may have been the result of the extended periods of zero DO in the activated sludge causing it to become "stale". Stale sludge had a greater oxygen demand because, during the period of oxygen absence, slower rate anaerobic decomposition occurred. This resulted in a net loss in stabilization as compared to a continuously aerobic system. Further loss in net stabilization was caused by substances toxic to aerobic organisms produced during anaerobic periods.

As a result of these studies, a small-scale high purity oxygen pilot plant, furnished by Dorr-Oliver, Inc., was installed at the Black River Sewage Treatment Plant in Baltimore, Maryland (3). The plant had a design flow of between 10 (0.631) and 30 gpm ($1.89 \frac{1}{\text{SEC}}$) with a 4-ft (1.22 m) diameter by 12-ft (3.66 m) side-water depth upflow clarifier. Six 13.5-ft (4.13 m) long tapered tubes connected in parallel were used as oxygenation units. The plant featured a countercurrent flow system. The flow diagram is presented in Figure 2.2. Absorption efficiencies were in the range of 20 to 25 per cent with a resulting

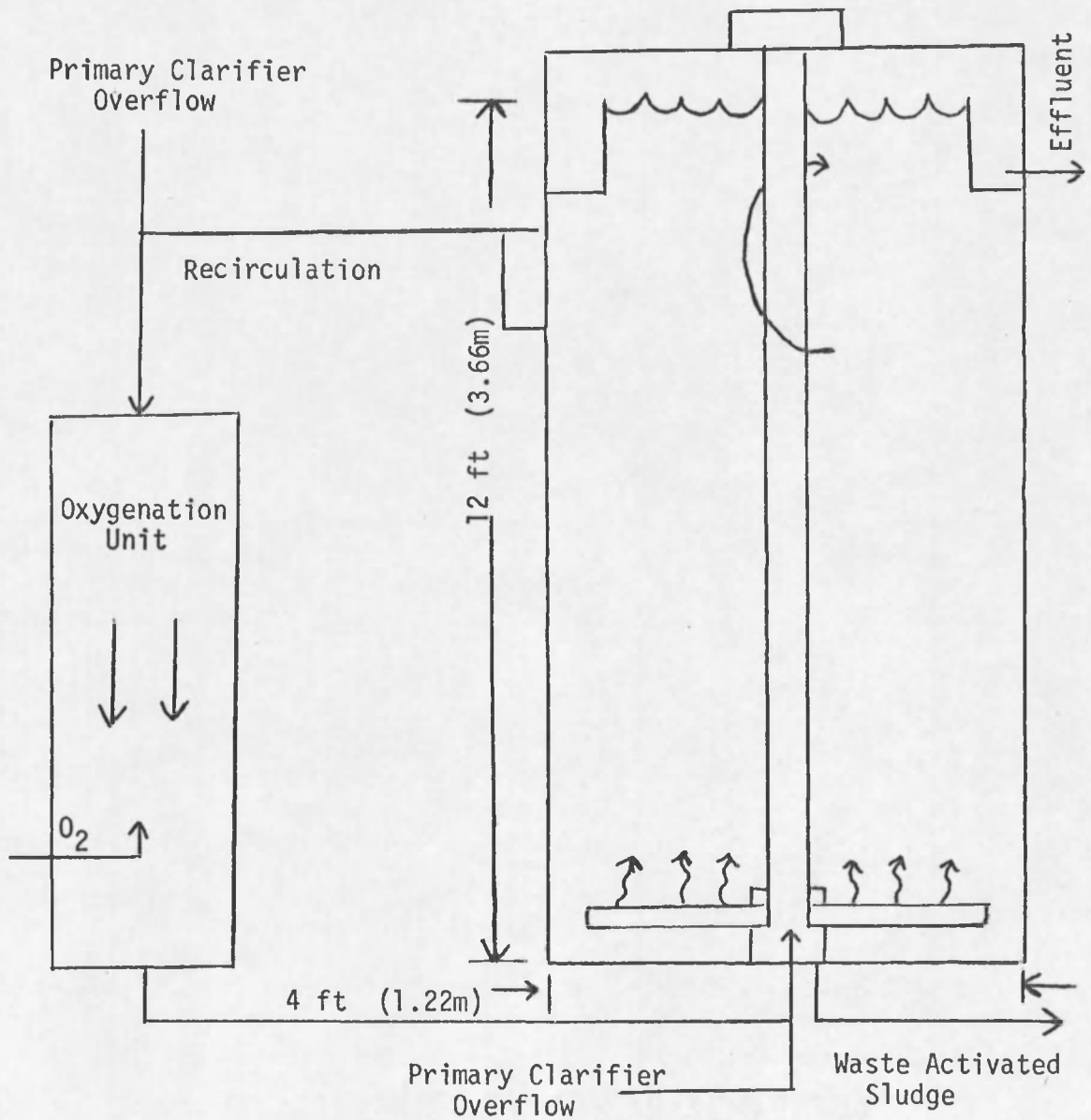


Figure 2.2 Diagram of Bio-precipitation Pilot Plant (3)

oxygen transfer rate of 1.0005 tons per million gallons (0.0060 kg/cu m) exhaust gas measured 45 to 50 per cent oxygen. This investigation indicated that economic handling and dissolving of oxygen in the sewage flow, and control of the sludge setting characteristics in the upflow unit were of great importance to a successfully run system.

A pilot plant (3) designed for a flow of 50 (3.15) to 75 gpm (4.73 ¹sec) was constructed at the Stamford, Conn., municipal sewage treatment facility. The flow sheet for the plant was similar to Figure 2.2. After some experimentation, it was determined that higher oxygen absorption efficiencies were obtained and less recirculation was needed with a mechanically mixed countercurrent liquid downflow unit. This type of oxygenation column provided greater flexibility of operation and a higher oxygen absorption efficiency.

This study indicated an efficiency dependent upon the time of contact and overflow rate which was inversely proportional to contact time. An overflow rate of approximately 900 gpd/sq ft (36.8 cu m/day/sq m) resulted in the best treatment efficiency. The organic load was maintained in the range of 315 lbs (143 kg) of BOD per 1,000 lb (454 kg) of suspended solids (SS) resulted in the best setting characteristics of the sludge in terms of the sludge volume index (SVI).

In comparing the pure oxygen treatment to standard activated sludge treatments it was found that with a secondary clarified overflow rate of 1000 gpd/sq ft (40.8 cu m/day/sq ft) for a conventional activated sludge treatment plant and 650 gpd/sq ft (26.6 cu m/day/sq ft) for the pure oxygen system, based on average plant flow, a reduction in

secondary treatment tank area of 50 per cent and volume of 30 per cent was possible with the pure oxygen system.

In 1965, McKinney and Pfeffer (1) reviewed the state of the art for the use of oxygen enriched air in sewage treatment. They concluded that the most important consideration in the use of oxygen enriched atmosphere was not the increased DO level obtainable, but the accelerated rate at which the pure oxygen could be utilized. This led then to the further conclusion that oxygen enriched air would be advantageous in systems operating under oxygen limiting conditions.

An additional and possibly more important advantage to the use of oxygen enriched atmosphere is the ability of the process to increase the rate of stabilization of organic material. McKinney and Pfeffer (1) illustrated in a comparison of two systems - one aerated with 20.5 per cent oxygen and the other with 28.5 per cent oxygen - that the maximum rate of chemical oxygen demand (COD) removal was 300 mg/l/hr for the 20.5 per cent oxygen system and 400 mg/l/hr for the 28.5 per cent oxygen system.

Jewell, Eckenfelder, and Cavalier (8) completed a study on the use of air and oxygen enriched atmospheres in sludge aeration of brewery wastes. Three different DO levels were investigated, 1 mg/l (air), 7 mg/l (oxygen enriched air), and 15 mg/l (pure oxygen), at mass loadings, quantity of substrate supplied per unit mass of volatile suspended solids (VSS) per day, on a COD basis of from 0.4 to 30 mg/l. The activated sludge unit with oxygen aeration, 15 mg/l, produced good settling sludge at mass loading as high as 13, but the 1 mg/l (air)

and 7 mg/l (oxygen enriched) treated activated sludge had unacceptable settlability at mass loadings above 1 and 3 respectively.

Albertson et al. (2) working for the Linde Division of Union Carbide Corporation recently completed a study at the Batavia, New York, Water Pollution Control Sewage Treatment Plant. The plant used the diffused air aerated activated sludge treatment process and was designed for an average flow of 2.5 mgd (9,460 cu m/day) with a maximum flow of 6.15 mgd (23,300 cu m/day).

The four aeration tanks at Batavia were used and connected hydraulically to form two parallel treatment systems with one of these tank systems being converted for the use of high purity oxygen. The tanks were modified by making various piping changes and adding ports, as illustrated in Figure 2.3. They were also covered with a steel structure constructed so as to hold the separate gas and water circulation equipment and trap the effluent gases for recirculation. These modifications enabled an oxygen utilization of over 90 per cent with low power requirements.

The work was conducted in three phases: the performance of the oxygenation system was compared to a parallel air aeration system in two of the phases, and in a third, the oxygenation system was used with one-fourth of the plant aeration tankage to treat the entire wastewater flow to the plant.

The oxygenation system consistently out performed the conventional air system by operating with mixed liquor volatile suspended solids (MLVSS) concentrations of as high as 4500 mg/l and achieving 90

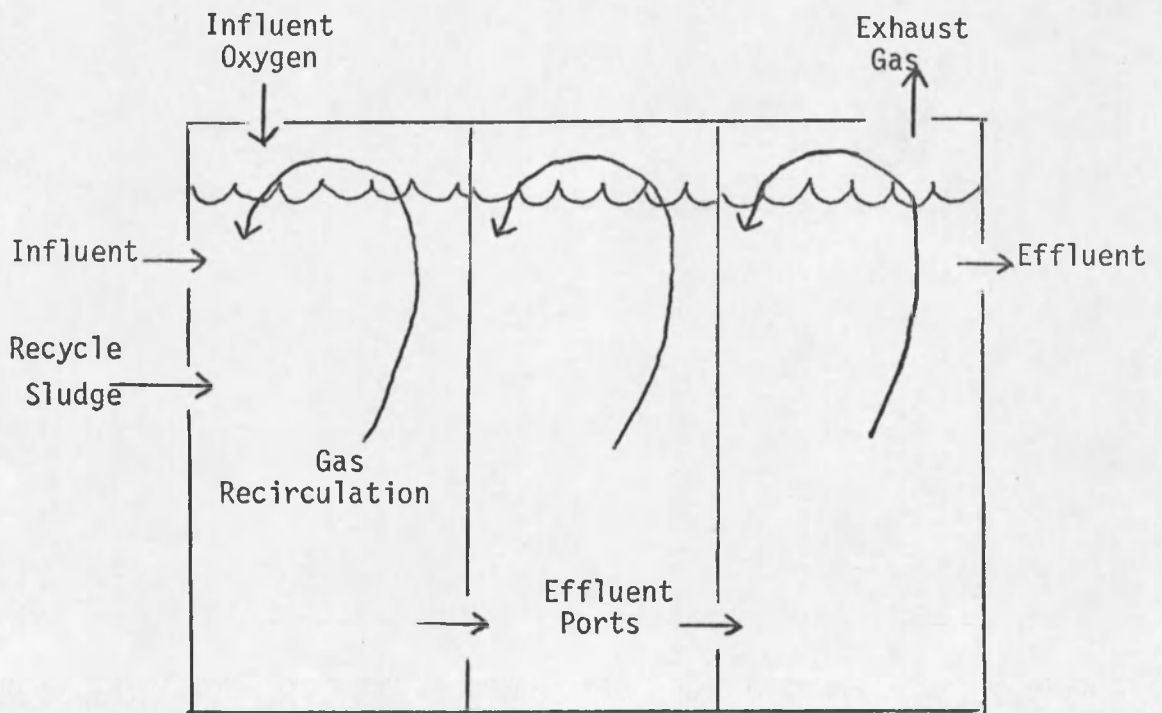


Figure 2.3 Diagram of Multi-stage Oxygenation System (2)

per cent BOD removals at aeration detention times, as low as 1.2 hr (raw flow and recycle flow) treating domestic sewage of 220 mg/l of BOD. Significant potential savings in treatment costs were attributed to the use of high purity oxygen due to the smaller aeration tank volume required for equivalent treatment and a reduction in the production of waste activated sludge.

Ball and Humerick (9), in a paper evaluating the existing data on the use of high-purity oxygen in activated sludge, concluded that it is as yet unclear when the benefits will outweigh the costs. They also concluded that, in treating very high-strength wastes, oxygen would be more feasible because of the limitations of oxygen transfer during aeration.

Other conclusions were drawn by Ball and Humerick (9, p 75), as follows:

1. There is evidence to indicate that no significant difference exists between substrate removal rates per unit weight of organism in aerated or oxygenated activated sludge systems. Increased substrate removals per unit volume of reactor for oxygenation systems as compared to aeration systems can be attributed mostly to the former's greater ease in maintaining high MLVSS concentration in an aerobic condition.
2. There may be no difference in cell yield coefficients between aerated and oxygenated activated sludge.
3. The lower production of VSS from oxygenated activated sludge compared to aerated activated sludge at Batavia may be explained in terms of the former's longer time period for aerobic digestion of solids.

From August 1970 to July 1971 a pure oxygen plant treated a strong mixture of domestic and industrial wastewaters at the Middlesex County Sewage Authority, New Jersey (10). The results of this study

indicated high BOD efficiencies and improved stability with low construction and total annual operation costs could be affected if a full scale plant were constructed.

Work is now underway in secondary sewage treatment by the Linde Division of Union Carbide at Batavia, New York, and additional demonstration plants have been installed at Cincinnati, Ohio and Washington, D.C. This work has been aided by the development of a new way to separate air- with small, automatic oxygen plants based on proprietary absorption technology, for a dependable supply of low-cost oxygen to small treatment plants (11).

These and other studies led Union Carbide (11) to predict that by the 1980's wastewater treatment facilities will become one of the nation's largest oxygen consumers.

In October 1972, the United States Environmental Protection Agency (12) published a partial listing of full-scale municipal wastewater treatment plants using or planning to use oxygen aeration.

These plants included:

Location	Size (mgd)
Detroit, Michigan	300
Brooklyn, New York	20
Louisville, Kentucky	105
Miami, Florida	55
Baltimore, Maryland	5
Wyandotte, Michigan	100
Salem, Oregon	16
Decatur, Illinois	18
New Rochelle, New York	14
New Orleans, Louisiana	122
Middlesex County, New Jersey	120
East Bay MUD, S.F., California	120
Hollywood, Florida	36

CHAPTER III

EXPERIMENTAL APPARATUS

Introduction

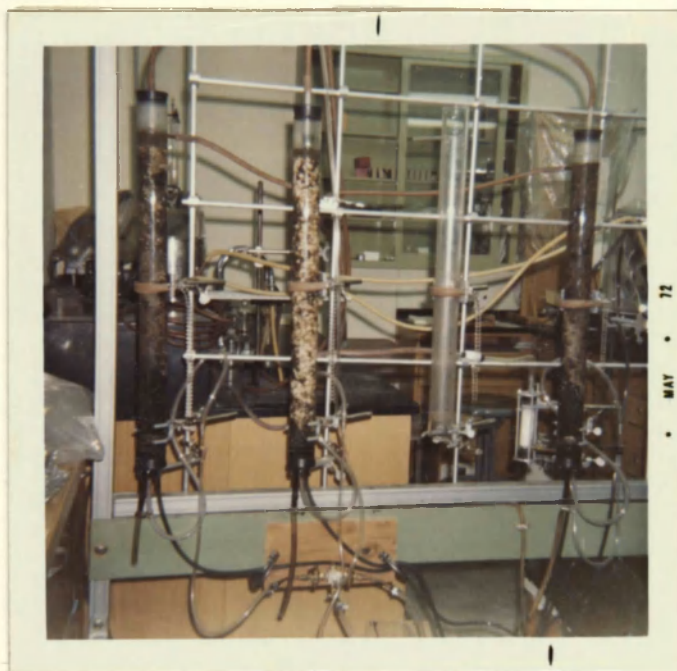
The experimental apparatus consisted of the bench scale secondary biological sewage treatment plant with three oxygen fed column reactors, and one air fed column reactor pictured in Figure 3.1.

Column Reactors

The column reactors diagramed in Figure 3.2 consisted of four 2 1/8-in. (5.40 cm) diameter glass tubes randomly packed with 3/4-in. (1.905 cm) Intalox saddles and sealed on both ends with rubber stoppers which contained holes for influent and effluent flows. The packing was submerged, with gas and sewage passing concurrently through it from bottom to top.

Wastewater Supply

The wastewater was supplied by a 20-gal (75.7 l) refrigerated reservoir located near the columns. It was stirred by a 2.0-in. (5.08 cm) magnetic stirrer while in the reservoir to keep the solids in suspension and mix newly added wastewater. It was then pumped by the means of three Zeromax Sigma pumps rated at 10-in. lbs (11.52 cm kg) of torque through a 1/8-in. (0.318 cm) mesh wire filtering screen into the tubing and then through the columns.



The air fed column reactor #4 is located at the far right.

All piping used for sewage and gas transport was 1/4 in. (0.635 cm) ID, 3/8 in. (0.953 cm) OD, Van-Lab vinyl tubing.

Figure 3.1 Bench Scale Secondary Sewage Treatment Plant

Scale

1"=2"
(2.54 cm=5.08 cm)

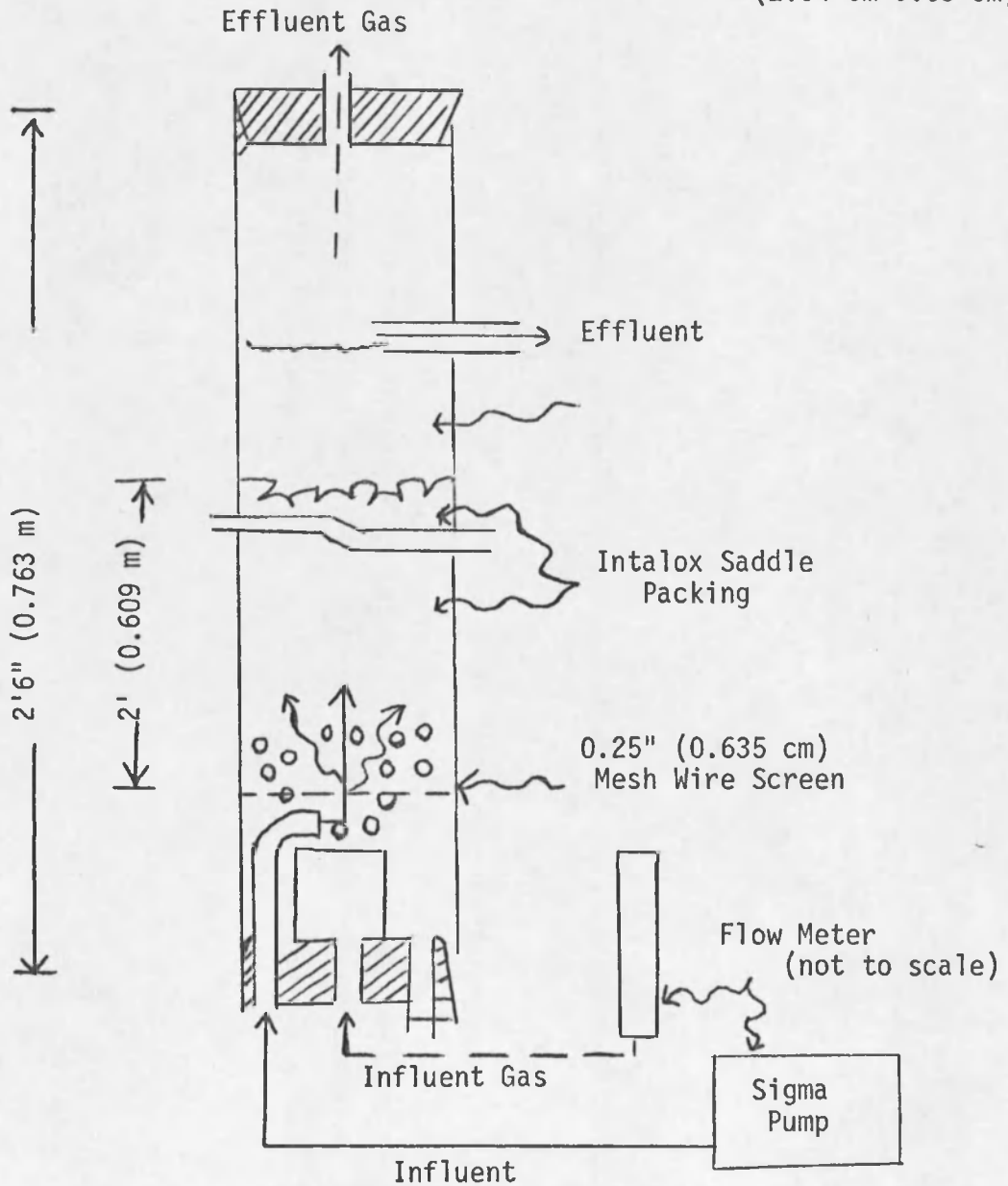


Figure 3.2 Diagram of Bench Scale Column Reactor

Gas Supplies

The gas used for three of the column reactors was commercially bottled pure oxygen, fed through a regulator at line pressures ranging from 5 (0.351) to 10 psi (0.703 kg/sq cm). Air, used for the fourth column was taken from a laboratory compressed air source with a flow regulator in the line. The gas flows were measured by Fm1043B Manostat flow meters and then passed into the column through a gas diffuser stone.

CHAPTER IV

EXPERIMENTAL PROCEDURES

Feed Source

The primary sewage used in this study was collected at the City of Tucson Municipal Waste Treatment Plant. Sewage samples of 45 (170.4) to 60 gal (227.0 l) were obtained from the inlet ditch to the aeration tanks after they had been processed through primary treatment which included screening and grit removal. The samples were stored in 5-gal (18.9 l) plastic carboys in a 4° C refrigerator for not more than four days. One or two carboys of sewage per day were poured through a 1/4-in. (0.635 cm) meshwire screen into a 20-gal (75.7 l) container kept at 11° C in a refrigerator located next to the experimental apparatus.

The samples were collected at approximately 1500 hours on weekdays. This sampling schedule was pursued in order to maintain as constant a quality influent as possible.

Schedule of Experimental Analyses

The schedule of analyses was governed by column reactor operation, visual observations and results of analyses for COD. If the columns appeared to be operating properly by visual observation under steady flow conditions with a constant supply of gas, COD's and/or total organic carbon's (TOC's) were run on the column effluents. If the results were equal within 5 per cent over at least a 24-hr period for

any one column, that column was assumed to be in equilibrium and a battery of analyses run as illustrated in Appendix A.

A condition of equilibrium was defined as that point at which a constant treatment level was reached for a given set of operating conditions.

Analytical Methods

The samples used for analyses were filtered through a 0.45 micron Millipore filter and analyzed immediately or preserved for not more than 7 days with a 40 mg/l concentration of Hg Cl_2 , (13). The analyses were in accordance with Standard Methods for the Examination of Waste and Wastewater (14), unless otherwise noted.

Chemical Oxygen Demand

The COD determination standard procedure was followed as outlined in Standard Methods (14), except that the normality of the Ferrous Ammonium Sulfate titrant was changed from 0.25 to 0.12 N when it was discovered that greater accuracy was needed to distinguish small differences in COD.

pH

A Beckman glass electrode pH meter calibrated with a buffer solution of pH 7.0 was used for pH determination on unfiltered samples. The pH was measured as soon as possible in order to prevent errors due to sample deterioration and changes in temperature.

Phosphate

According to the procedure described in Standard Methods (14), the total, ortho, plus meta-phosphate was read directly by use of ammonium molybdate and the Beckman B Spectrophotometer, using a red filter and a red sensitive photocell. All glassware used in this test was washed in weak hydrochloric acid to eliminate error due to phosphate absorption by glass.

Nitrogen

The percentages of the various nitrogen forms present in the samples tested were of importance as an indicator of the progress of biological oxidation. Standard Methods (14) was used as a reference in all the nitrogen tests except nitrate.

Nitrogen (Ammonia). The distillation method was used to obtain the ammonia-nitrogen concentration. This method was chosen over direct Nesslerization because of fewer errors due to color, turbidity, and organic matter, and also because the sample must be free of ammonia in order to make subsequent determinations. A 100-ml sample was considered adequate for the accuracy desired.

Nitrogen (Organic). The organic-nitrogen was determined by use of the Kjeldahl method on the sample remaining after the ammonia distillation had been completed.

Nitrogen (Nitrite). Nitrite-nitrogen was determined by the diazotization method.

Nitrogen (Nitrate). Nitrate-nitrogen was determined by use of the modified Brucine method as described by Jenkins and Medsker (15).

Due to the inaccuracy of the test for concentrations greater than 10 $\mu\text{g NO}_3\text{-N}$, solutions ranging from 2.5 to 100 percent were used.

Temperatures

Temperature readings of the sewage in the refrigerator and in the carboys were read at 7 to 10 cm below the liquid surface. Column temperature readings were taken by setting the thermometer on top of the packing.

Gas Flow Rates

The gas flow rates were determined by the use of Predictability Flowmeters, FM1043B, corrected for air and oxygen flow (16).

Sewage Flow Rates

The sewage flows to the reactors were supplied by Sigma pumps. The resulting flows were difficult to measure directly, so a method of determining flow rates was devised. The sewage flow rate entering the column reactors was calculated by closing off the effluent tube and allowing effluent to fill a known volume of column freeboard. The flow rate could then be calculated by dividing the known volume by the time it took to fill that volume.

Carbon Analyses

The carbon analyses were run on a Beckman Model 915 Total Organic Carbon Analyzer, which had the capability of rapid processing large numbers of samples. The operation of the carbon analyzer is based

on converting sample carbon to carbon dioxide and measuring this with a non-dispersive infrared analyzer. Calibration curves were constructed using samples of known total inorganic carbon content. 200 μ l samples were injected into the analyzer which was operating with an oxygen carrier gas flow rate of 200 cc/min, a carrier gas pressure of 5 psi (0.352 kg/sq cm) a temperature of 950⁰ C, and a gain of 070 for the total carbon test. Samples of 100 μ l were injected with oxygen carrier gas flow of 200 cc/min, a carrier gas pressure of 5 psi (0.352 kg/sq cm) a temperature of 150⁰ C, and a gain of 200 for the inorganic test. The total organic carbon (TOC) was determined by calculating the difference between the total carbon (TC) and inorganic carbon (IC) concentrations, $TOC=TC-IC$.

The carbon tests were used along with the COD's to monitor the conditions in the column.

Samples collected were filtered through a 0.45 micron Millipore filter and stored in 50-ml flasks. The samples were analyzed as soon as possible after collection, as the samples stored in the 4⁰ C refrigerator showed signs of deterioration after overnight storage.

Carbon Dioxide

Pettenkofer's method (17) of determining carbon dioxide in air was chosen as a convenient means of determining the carbon dioxide in the exhaust gas from the columns. The sample gas was collected in 1-gal (3.78 l) plastic jugs that were stoppered after at least one hour

of continuous filling from a gas effluent hose. The gas was then treated with barium hydroxide to form barium carbonate which was titrated with oxalic acid.

Dissolved Oxygen

Dissolved oxygen readings were obtained directly by use of a Delta Scientific Model 106 Dissolved Oxygen Analyzer. The samples were collected in a standard DO bottle and stirred with a 1.5-in (3.82 cm) magnetic stirrer.

Where the DO readings were off-scale of the Dissolved Oxygen Analyzer the Alsterburg Azide modification of the Winkler method was used.

Solids

Total residue, dry residue, and volatile residue determinations were made on the column reactor packing to determine sludge buildup. These tests were run in accordance with Standard Methods (14) except that the packing was included in the weight determinations, then cleaned, dried and weighed separately. The packing weight was then subtracted from the total weights.

Total suspended solids (TSS), and VSS were determined on the same sample as the DO's to obtain oxygen uptake rates.

Biological Examination

A record of day-to-day biological observations was made. This was done by observing the growth build up in the column reactor packing

at various flow rates. Any difference between the oxygen and air column reactors was also noted.

The biologic examinations (18) were not intended to be a complete survey of the growth in the columns, but were a qualitative attempt to identify the organisms and the relative proportions in which they existed in the oxygen and air fed column reactors. Random grab samples were taken with a 1.1 - ml pipet and examined with a compound microscope at 200-400X. The samples were taken from areas demonstrating the different growth patterns encountered.

CHAPTER V

EXPERIMENTAL RESULTS AND DISCUSSION

Introduction

One air fed and three oxygen fed column reactors were operated continuously for three and one-half months. The oxygen feed rates were kept at 80 ml/min and the air feed rate at 370 ml/min, and the gas supply to the air fed column reactor was increased from 80 ml/min to 370 ml/min when septic odors were detected in the effluent gas. Every effort was made to keep the operating parameters constant while changing only the sewage flow rates. A tabulation of the results of the experimental analyses is presented in Appendix A.

Column Reactor Operational Performance

The column reactors functioned very well with the only problems resulting from the clogging of the tubing used for the influent sewage. To remedy this a 1/8-in. (0.318 cm) mesh wire screen was placed over the tubing inlet to prevent the line from clogging. The portion of the tubing subjected to the action of the Sigma pumps was changed periodically to prevent it from collapsing due to fatigue.

After the plant had been in operation for more than a month algae growth was observed in the column reactors. The growth was located on the column reactor packing on the side facing the fluorescent lighting in the laboratory. Since algae produce oxygen and consume

carbon dioxide, its growth would have given erroneous results in the oxygen-carbon dioxide analyses. The growth was eliminated by placing removable strips of aluminum foil around the column reactors to block out light.

After a few days of operation, it was observed that solids from the sewage and sludge growth had begun to gather at the bottom of the column reactors. An outlet was installed in the bottom of each column reactor and used to drain approximately 250 ml of liquid and solids each day.

Column Reactor Sludge Buildup Observations

Since the columns were made of glass and provided an excellent opportunity to observe column reactor behavior visually, a chronological record of observations of sludge growth patterns was kept. A summary of this record is presented in the following paragraphs.

Sludge growth in the column reactor packing was first noticed two days after the column reactors were placed in operation. The grey-brown growth appeared at the bottom of the packing in all four column reactors. It appeared as though it was trapped in, rather than attached to, the packing. The buildup continued for ten days at which time conditions appeared to reach steady state as indicated by visual observations. This condition was confirmed by a stabilizing of the effluent COD readings. Sludge was present throughout the packing, but appeared to be thicker near the bottom of those columns operating at low sewage flow rates. The column reactors with the higher sewage flow rates had a thick growth of sludge dispersed equally throughout the packing.

Figure 5.1 illustrates some VS profiles for the oxygen fed column reactors showing an increased solids buildup at shorter detention times.

The air fed column reactor seemed to have a greater sludge buildup upon visual observation, but it was a slime growth on the column wall that gave this impression. Actually the oxygen fed column reactors had a greater sludge buildup. Figure 5.2 illustrates the quantity of VS present in the air fed column reactor and an oxygen fed column reactor with identical influent sewage flow rates.

At detention time of less than approximately 130 min for the air fed column reactor and 60 min for the oxygen fed column reactors the sludge growth in the packing would begin to gather into masses grey-brown on the outside and black on the inside. This caused channeling of the sewage and gas as it passed through the packing. This condition became worse as detention times were reduced.

As the biological growth built up, channeling developed, causing simultaneous aerobic and anaerobic growth in the air fed column reactor. This occurred at detention times of from 95 to 120 min.

At detention times of approximately 45 min for the air fed column reactor and 30 min for the oxygen fed column reactor, there were large zones of black sludge conglomerates surrounded by grey filamentous growth in all of the column reactors.

The oxygen fed column reactor effluent consisted of a clear liquid with large floc which settled readily upon standing. The air fed column reactor had a slightly turbid effluent with a less readily settleable floc. The effluent from all of the column reactors became turbid and more difficult to filter as the detention time was reduced.

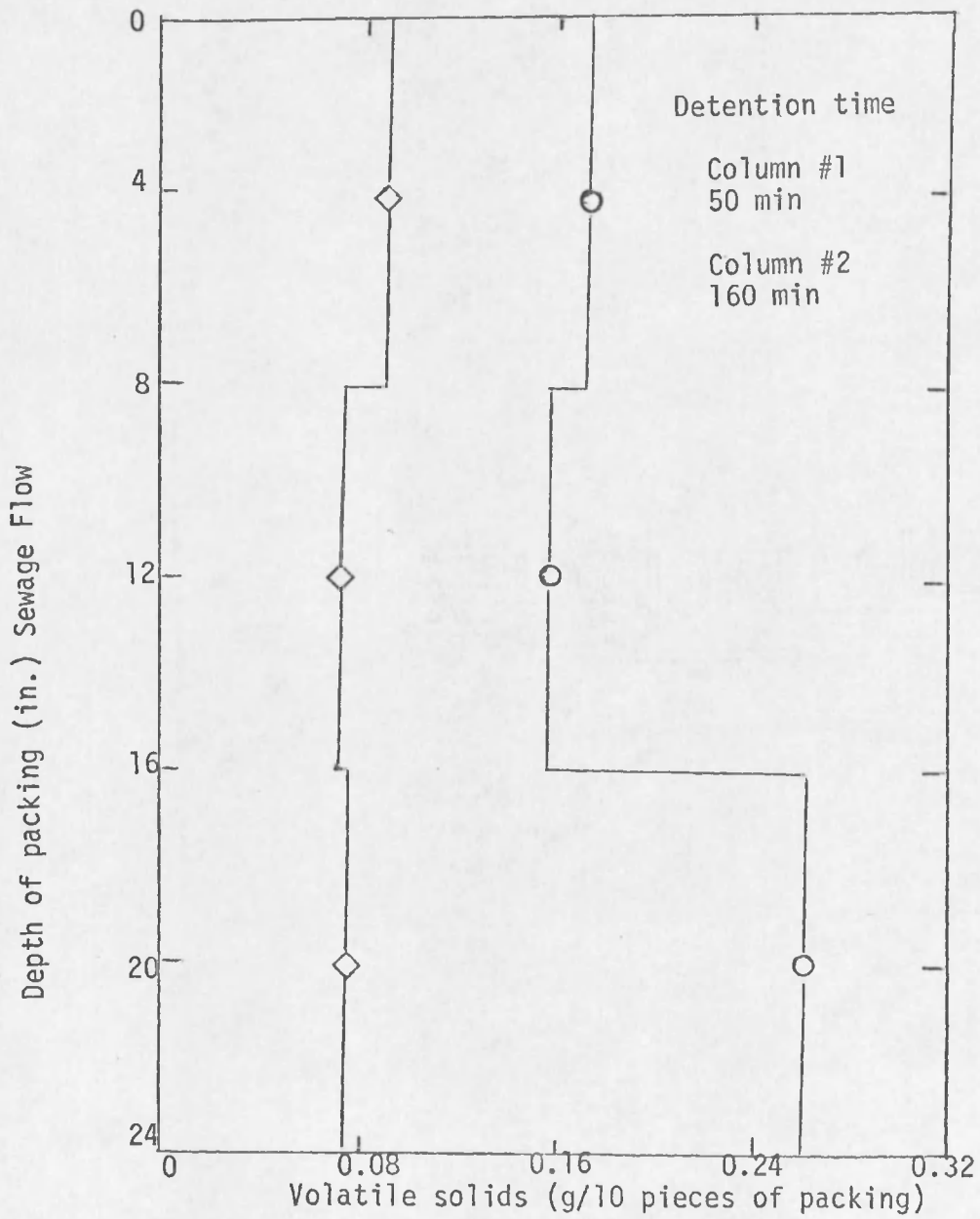


Figure 5.1 Volatile Solids Profiles on Packing for Oxygen Fed Systems

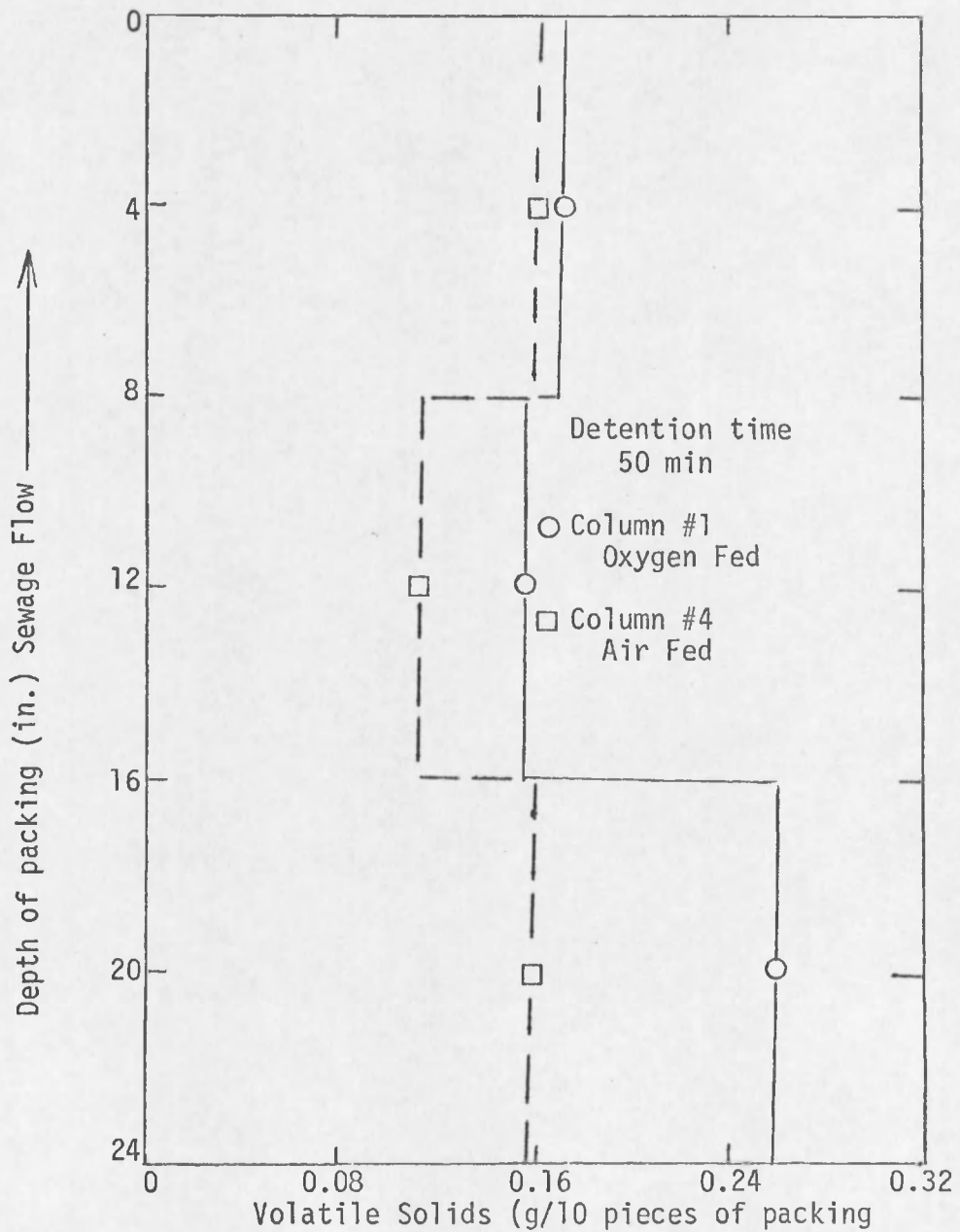
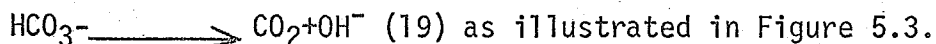


Figure 5.2 Volatile Solids Profiles on Packing for Oxygen and Air Fed Systems

Higher pH values were maintained in the air fed column reactor because carbon dioxide was stripped out of solution during aeration,



Samples of the biological growth from the air fed column reactor and the #1 oxygen fed column reactor were taken for microscopic observation. This was done at a time when the sewage loading was 19.5 ml/min and all conditions were assumed to be stable for both column reactors.

The samples from both column reactors contained numerous protozoa with the oxygen fed organisms appearing to be the most active. The protozoa consisted mostly of Paramecium, with some Vorticella also present. Small numbers of Sphaerotilus were present in each column. Beggiatoa was also present in both columns, but the air fed column reactor's samples contained larger numbers of this organism.

After two month's operation, the growth in reactor #3, an oxygen fed column, underwent a change during which a loss of growth as compared to the other column reactors was observed. After several more weeks, the column reactor growth still had not returned to its original state so the column was drained. The quantity of volatile suspended solids in column reactor #3 as compared to another oxygen fed column reactor operated at a slower flow rate is shown in Figure 5.4. The volatile solids profile shown in Figure 5.4 verified the visual observations that column reactor #3 should have had greater solids concentrations.

Results of Chemical Analyses

The results of chemical analyses of the treated effluent as compared to the influent sewage provide a direct comparison between the

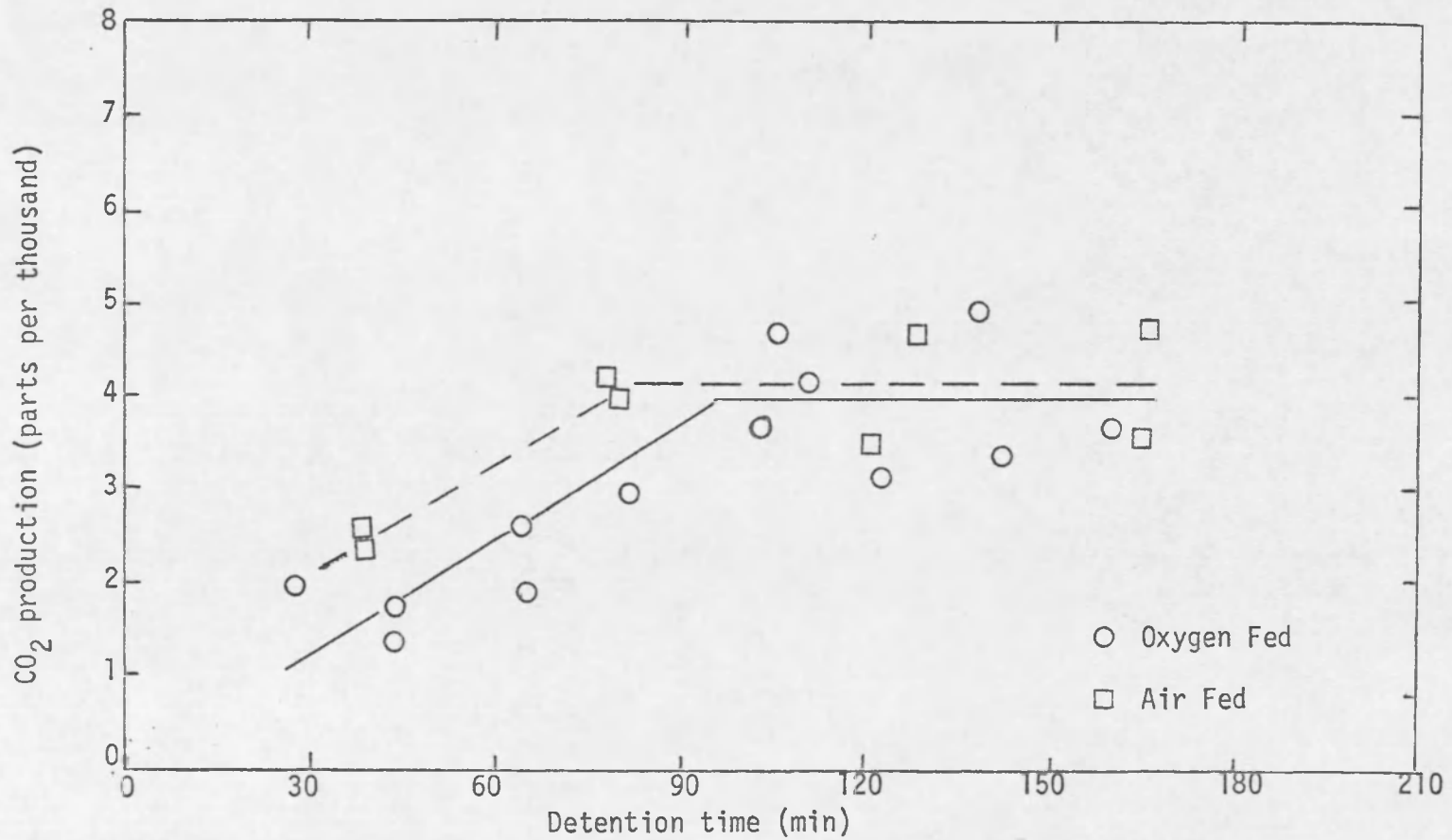


Figure 5.3 CO₂ Production Curves for Oxygen and Air Fed Column Reactors

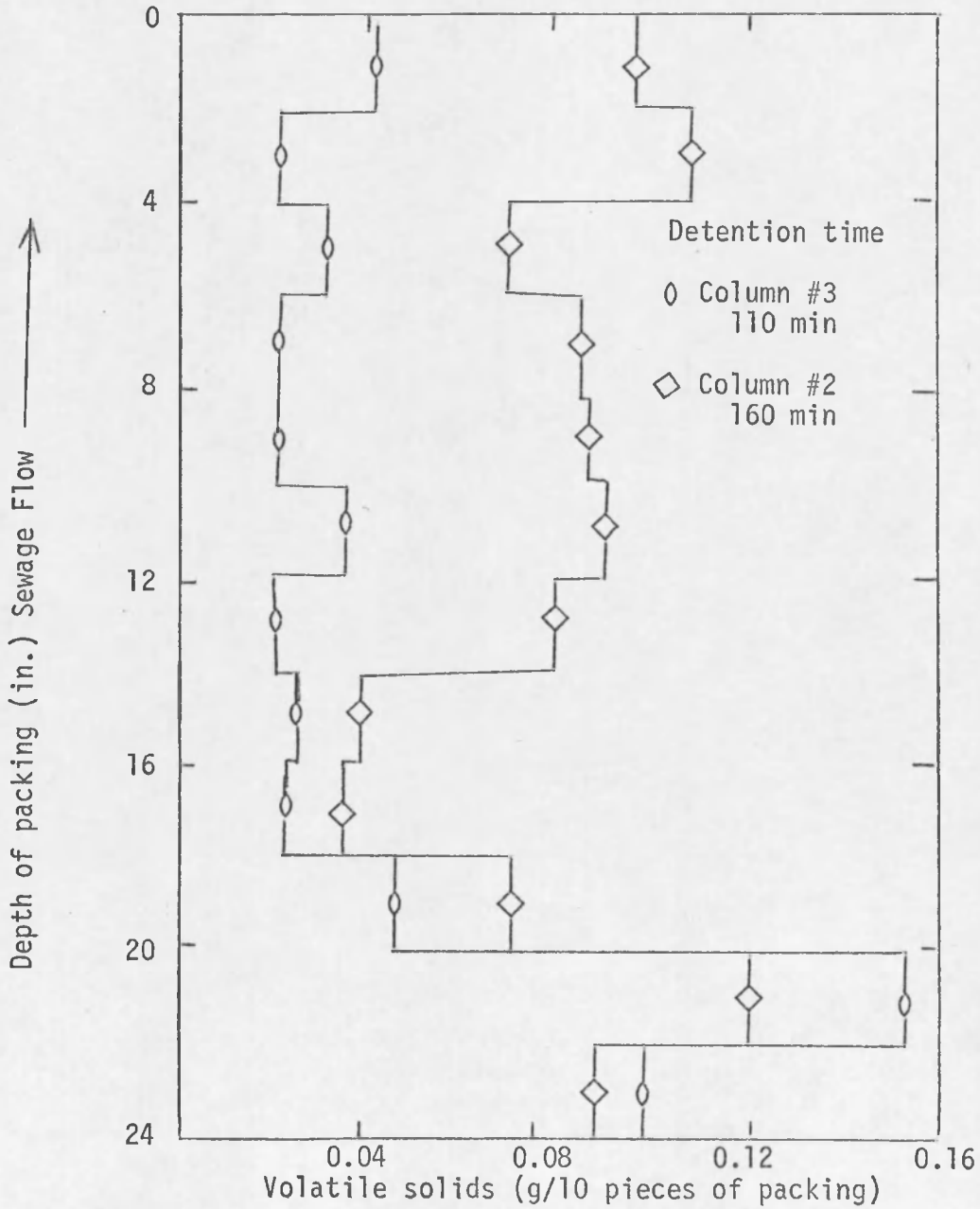


Figure 5.4 Comparative Volatile Solids on Packing for Oxygen Fed Systems

air fed column reactor and oxygen fed column reactors for the various flow rates studied in this project. The results of these are presented in the following paragraphs.

The reductions in COD for the oxygen and air fed column reactors for various hydraulic detention times are illustrated in Figure 5.5. The oxygen fed column reactors showed greater reductions in COD for detention times between 40 and 80 min. The oxygen fed column reactors reached the ultimate 75 per cent reduction level at detention times of 85 min, approximately the same time as the air fed column reactor. COD reductions of greater than 75 per cent were not possible due to incomplete mixing of the sewage and gas which was caused by channeling. The results were similar to those obtained by Poon and Wang (19) who obtained greater substrate removal using oxygen rather than air on a bench scale at process loadings from 1 to 3 g COD/g MLVSS/day.

The pH in the column reactors showed only slight changes during operation. As illustrated in Figure 5.6, the pH remained near the optimum, for biological activity, of 6.5 to 7.5 (20).

No reductions in total phosphate could be detected in the reactor effluents by the sampling methods used. As illustrated in Figure 5.7, a scattering of total phosphate concentrations was found. This occurred because of sample contamination during the filtering process as discussed in Standard Methods (14). Also, due to the delicate nature of this test, other sources of contamination, such as that from soap film on glassware may not have been completely eliminated.

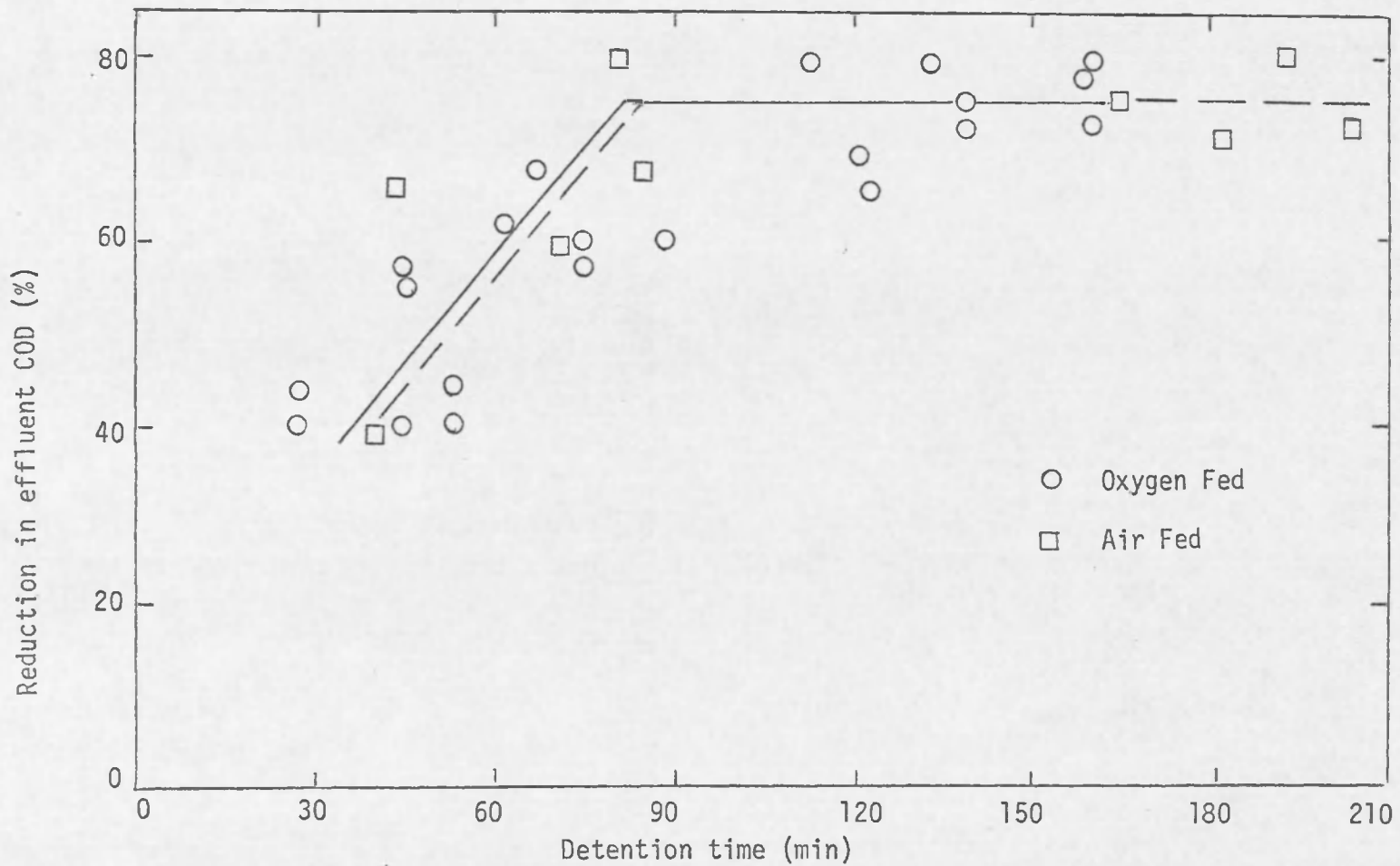


Figure 5.5 Per Cent Reduction in Effluent COD from Oxygen and Air Fed Column Reactors

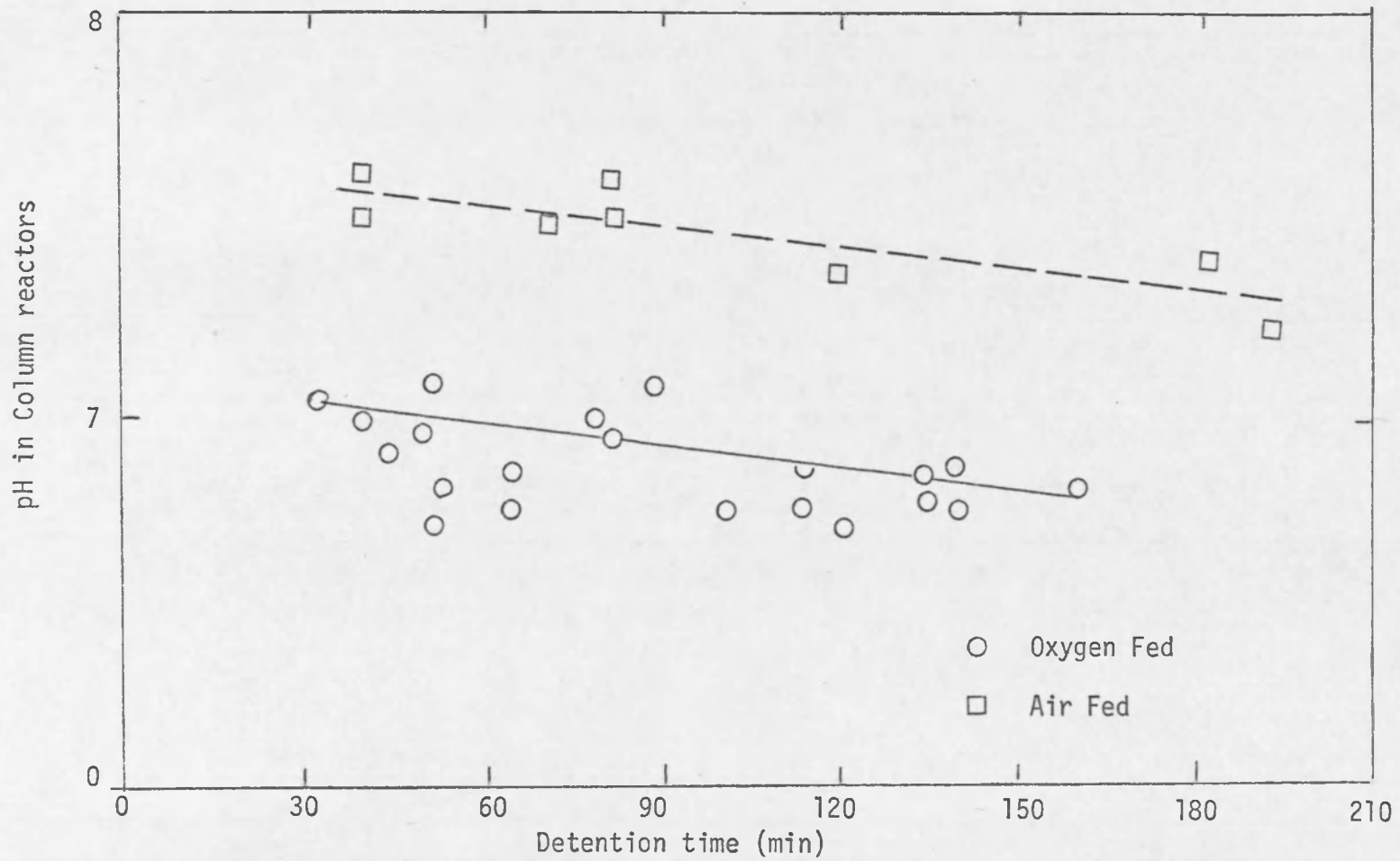


Figure 5.6 pH in Oxygen and Air Fed Column Reactors

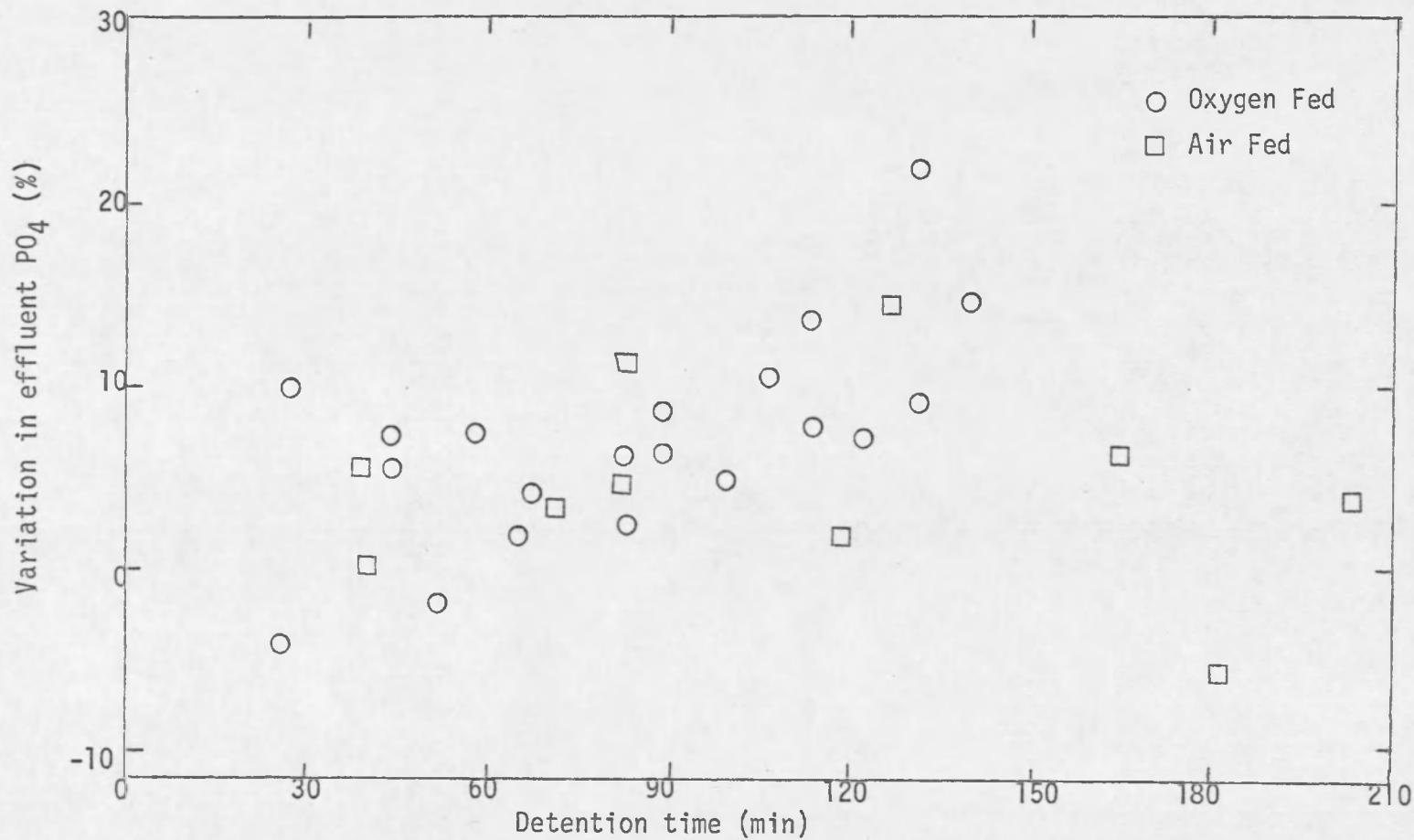


Figure 5.7 Per Cent Variation in Effluent Total Phosphate from Oxygen and Air Fed Column Reactors

In comparing nitrification in the oxygen and air fed reactors as illustrated in Figures 5.8 to 5.11, the oxygen fed column reactors showed greater initial reductions in organic and ammonia nitrogen for a detention time of up to 110 and 95 min respectively. The oxygen fed column reactors also showed a complete conversion of $\text{NO}_2\text{-N}$ to $\text{NO}_3\text{-N}$ within the 210 min maximum detention time used during the experimental analyses.

During a similar study Haug and McCarty (21), using a submerged filter reactor, achieved 90 per cent oxidation of 20 mg/l $\text{NH}_3\text{-N}$ in 30 min at 25° C. A synthetic waste was used which consisted of tap water to which ammonium sulfate was added. Haug and McCarty's oxidation times were considerably shorter than the 120 min for 90 per cent oxidation obtained in this project. This can be explained by the fact that in this project, primary effluent with an average concentration of 30 mg/l $\text{NH}_3\text{-N}$ was used. Channeling problems, which caused a reduction in the probability of oxygen contact, also affected the oxidation times.

The results of rapid analyses of the carbon content of grab samples are illustrated in Figures 5.12 to 5.14. A greater reduction in TOC throughout the operating range was obtained in the oxygen fed columns.

VanHall and Stenger (22) referred to the Infrared Carbon Analyzer as a useful general indicator of organic pollution. They were able to obtain a positive correlation between BOD and COD results in the absence of inorganic reducing agents and/or varying amounts of interfering organic materials. For sewage the ratio of COD to organic carbon

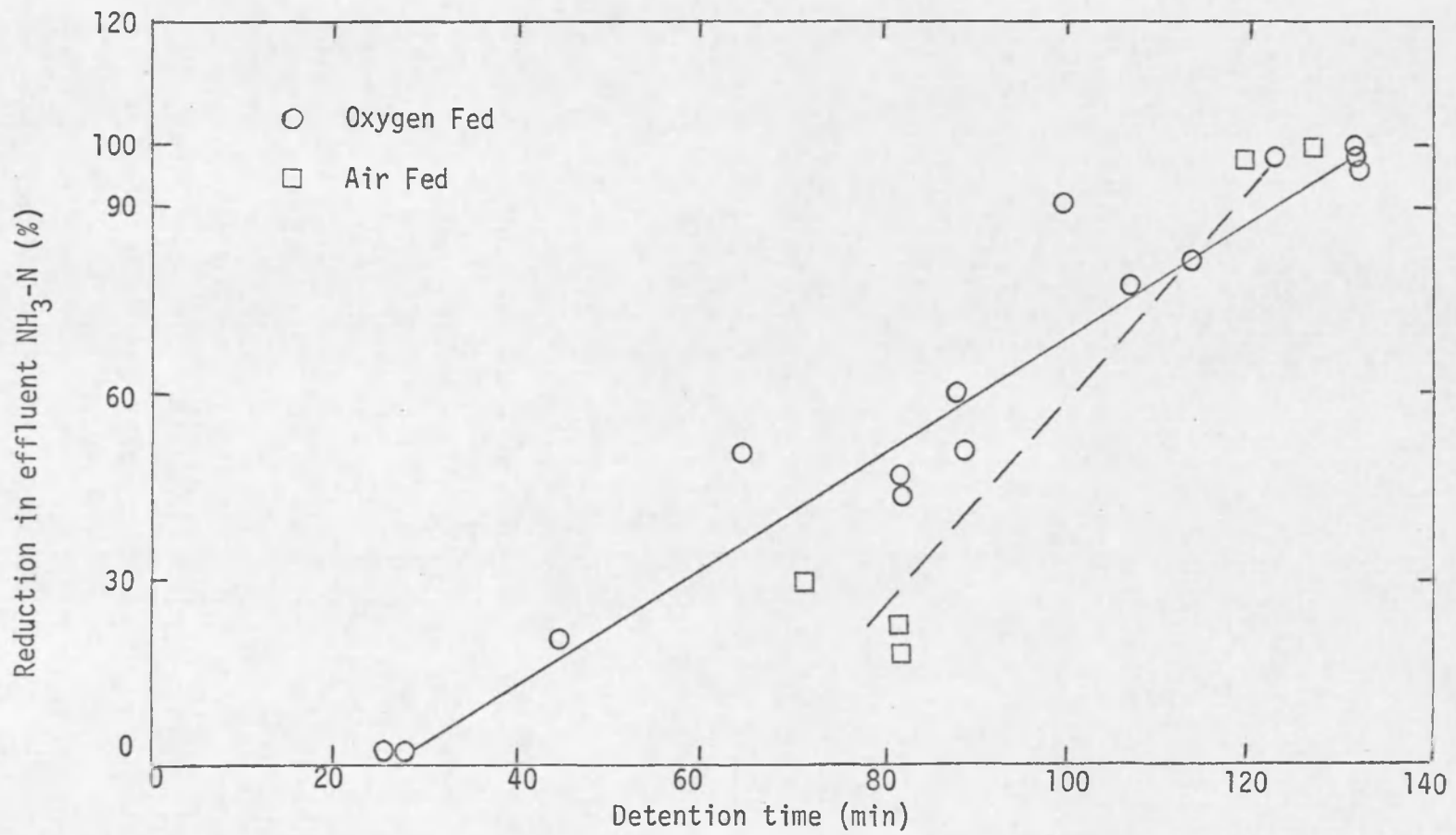


Figure 5.8 Per Cent Reduction in Effluent NH₃-N from Oxygen and Air Fed Column Reactors

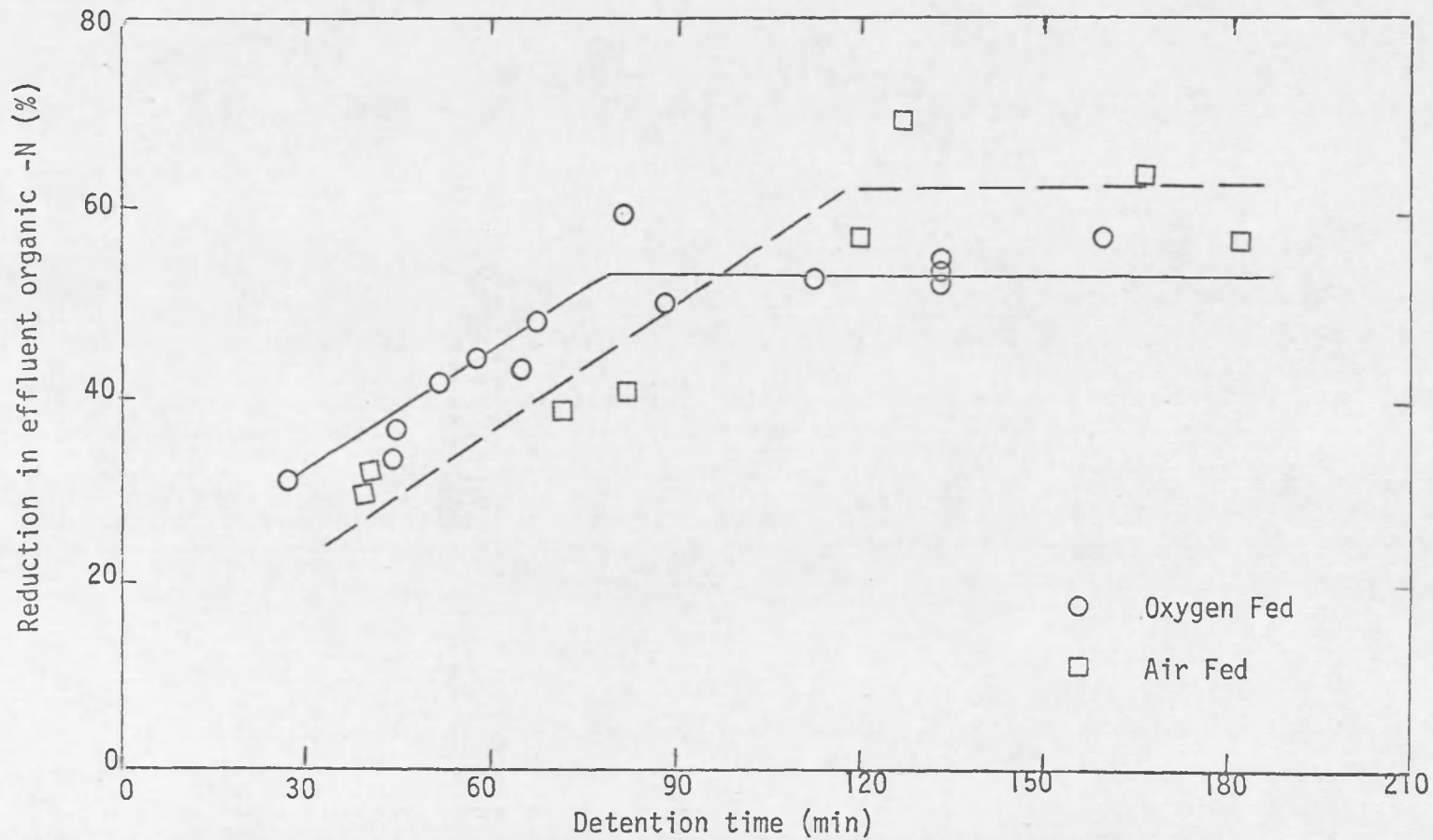


Figure 5.9 Per Cent Reduction in Effluent Organic -N from Oxygen and Air Fed Column Reactors

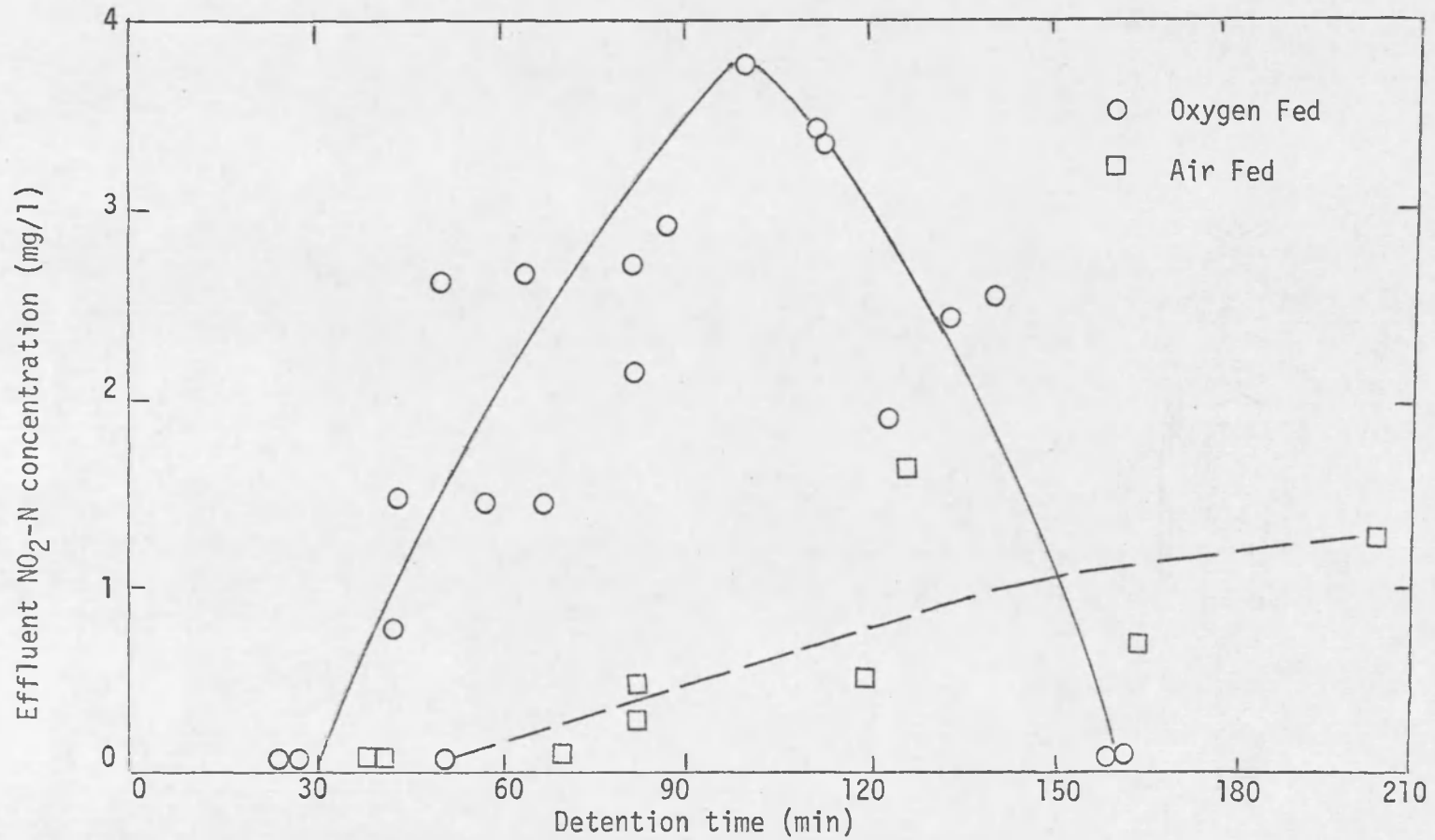


Figure 5.10 $\text{NO}_2\text{-N}$ Levels in Effluent from Oxygen and Air Fed Column Reactors

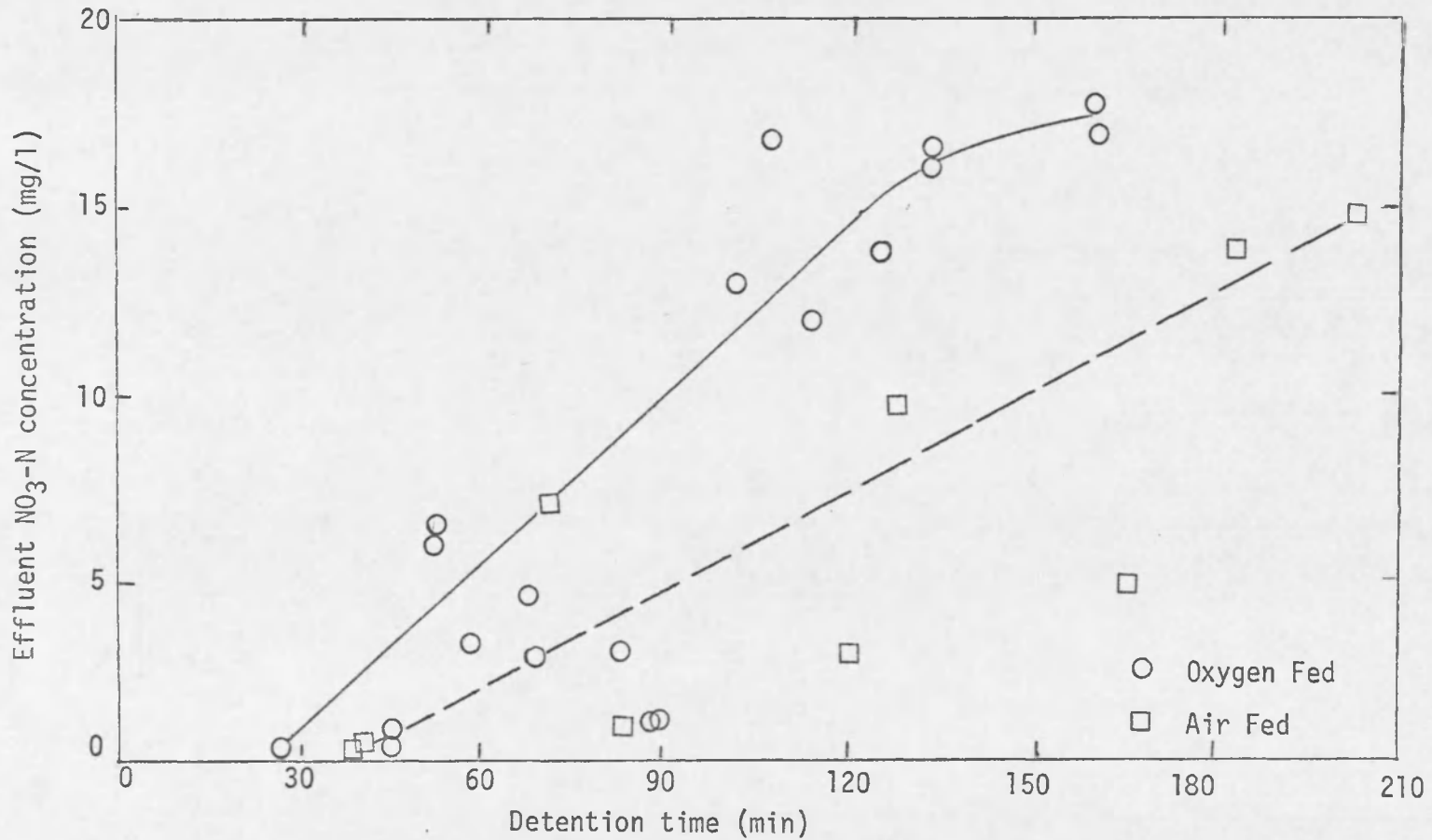


Figure 5.11 NO₃-N Levels in Effluent from Oxygen and Air Fed Column Reactors

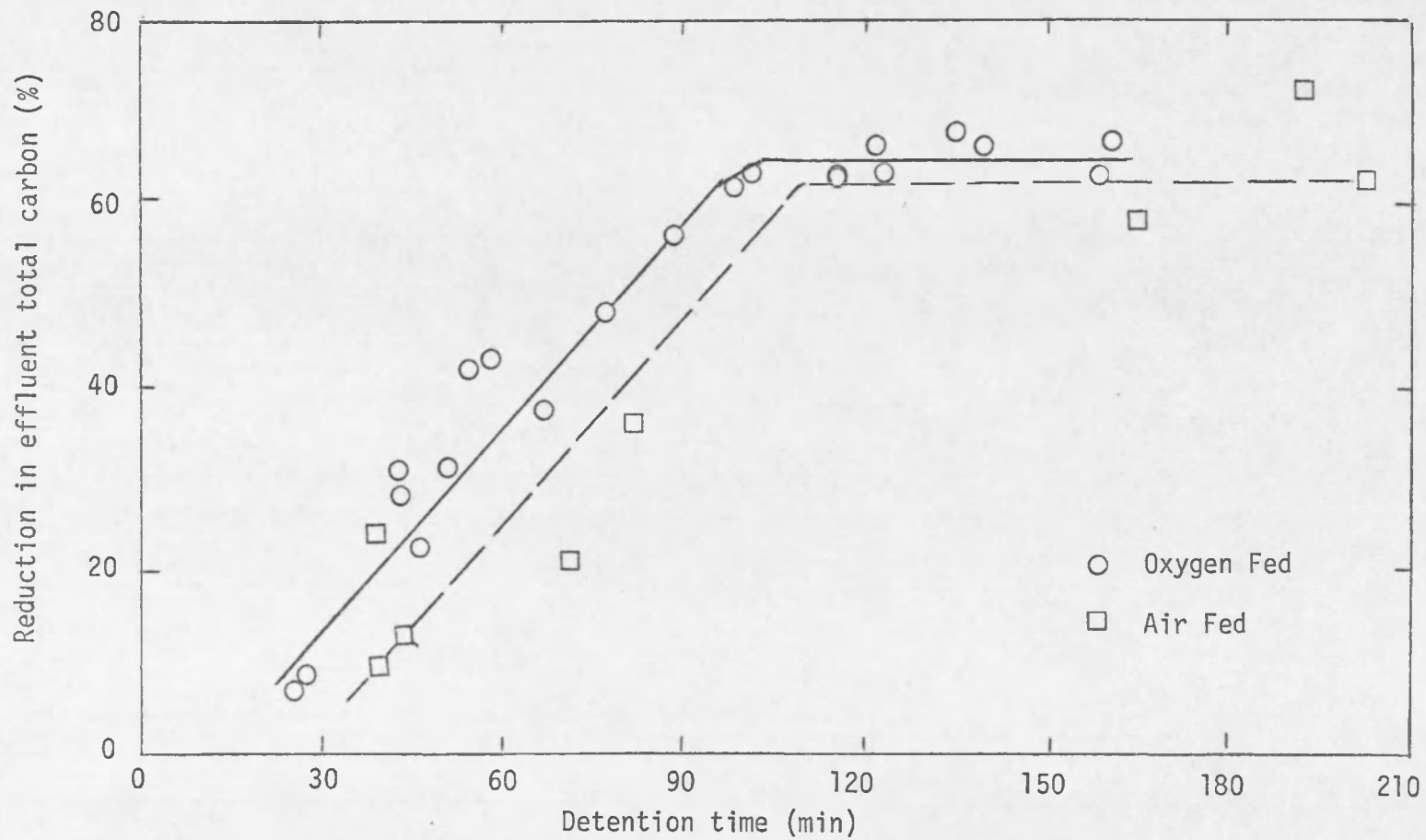


Figure 5.12 Per Cent Reduction in Effluent Total Carbon from Oxygen and Air Fed Column Reactors

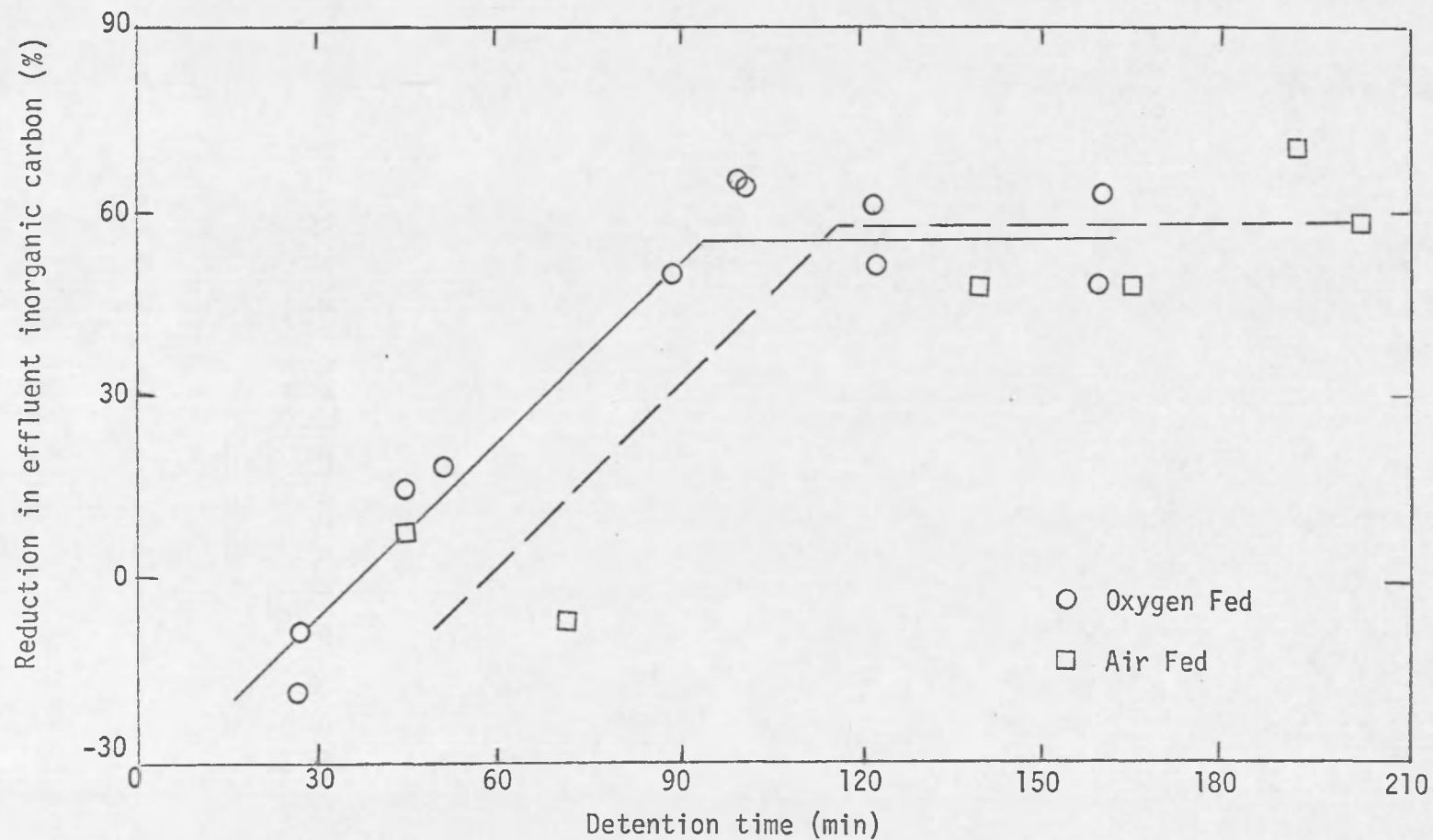


Figure 5.13 Per Cent Reduction in Effluent Inorganic Carbon from Oxygen and Air Fed Column Reactors

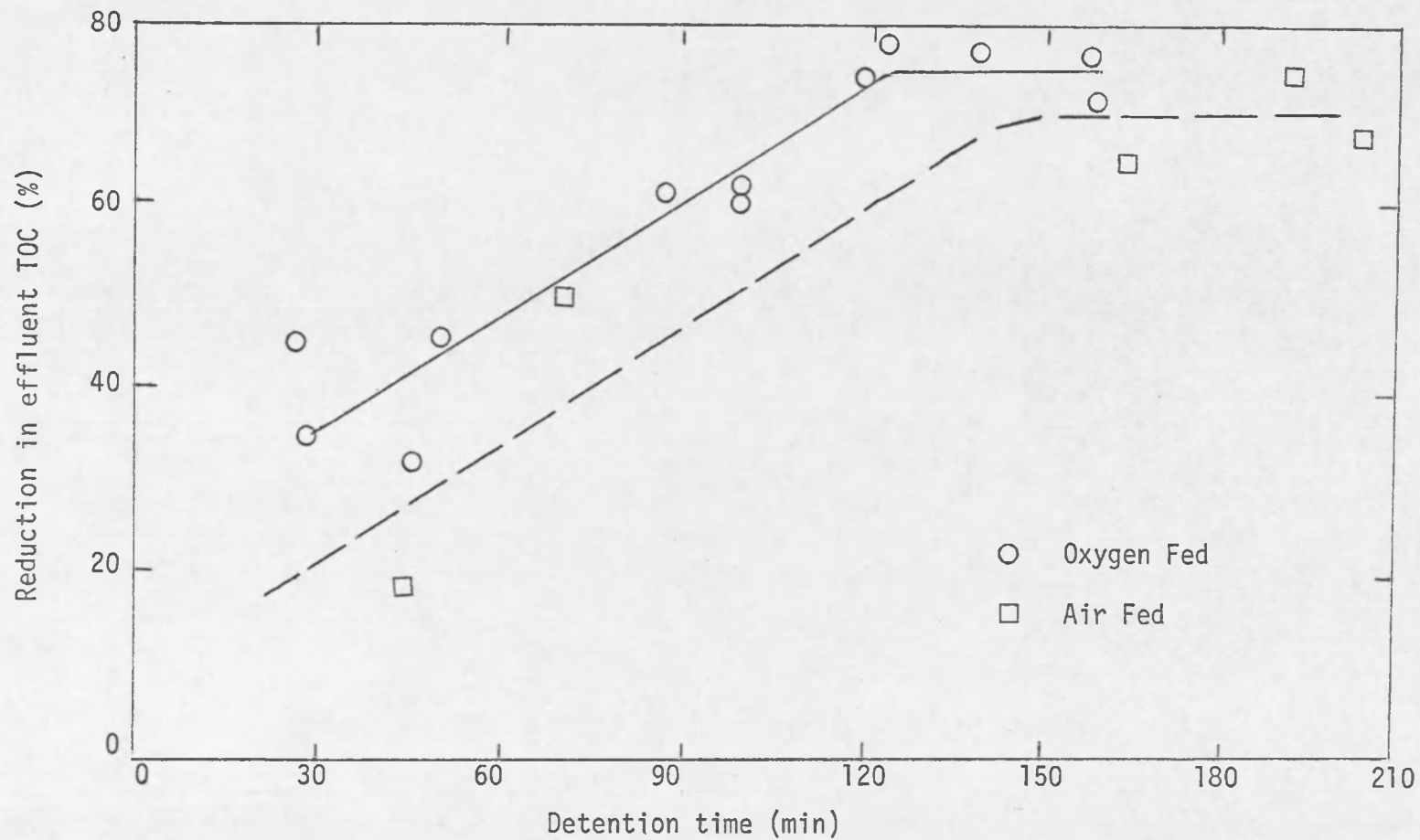


Figure 5.14 Per Cent Reduction in Effluent Total Organic Carbon from Oxygen and Air Fed Column Reactors

was found to be in the neighborhood of three or slightly higher (5). The raw sewage used in this project had a ratio of 3:1. Figure 5.15 illustrates the COD to TOC ratios for the column reactors used in this project.

The results of the determination of the carbon dioxide produced during column reactor operation are illustrated in Figure 5.13. Assuming that carbon dioxide was the only gas produced in the columns, the ultimate percentage of the oxygen supply that entered into reaction was approximately 0.4 per cent for both the oxygen and air fed column reactors.

The low percentages of oxygen entering into reaction were due to the channeling of the gas bubbles as they passed through the column reactor packing.

Analyses were run on the column reactor effluent to determine if the oxygen fed column reactor effluent had a greater DO level than that from the air fed column reactor. The DO level in the influent sewage was found to be zero while the effluent from the oxygen fed column reactors averaged approximately 21.5 mg/l DO and the air fed column reactor effluent approximately 2.0 mg/l DO at detention times of 45 min.

Oxygen Utilization

The changes in dissolved oxygen over time for sludge samples from air and oxygen fed column reactors are reported in Figure 5.16. The oxygen utilization rates were calculated from the slopes of the straight line portion of these curves. The oxygen utilization rate of sludge from both the oxygen and air fed column reactors was 26.6 ppm O_2 /g (hr).

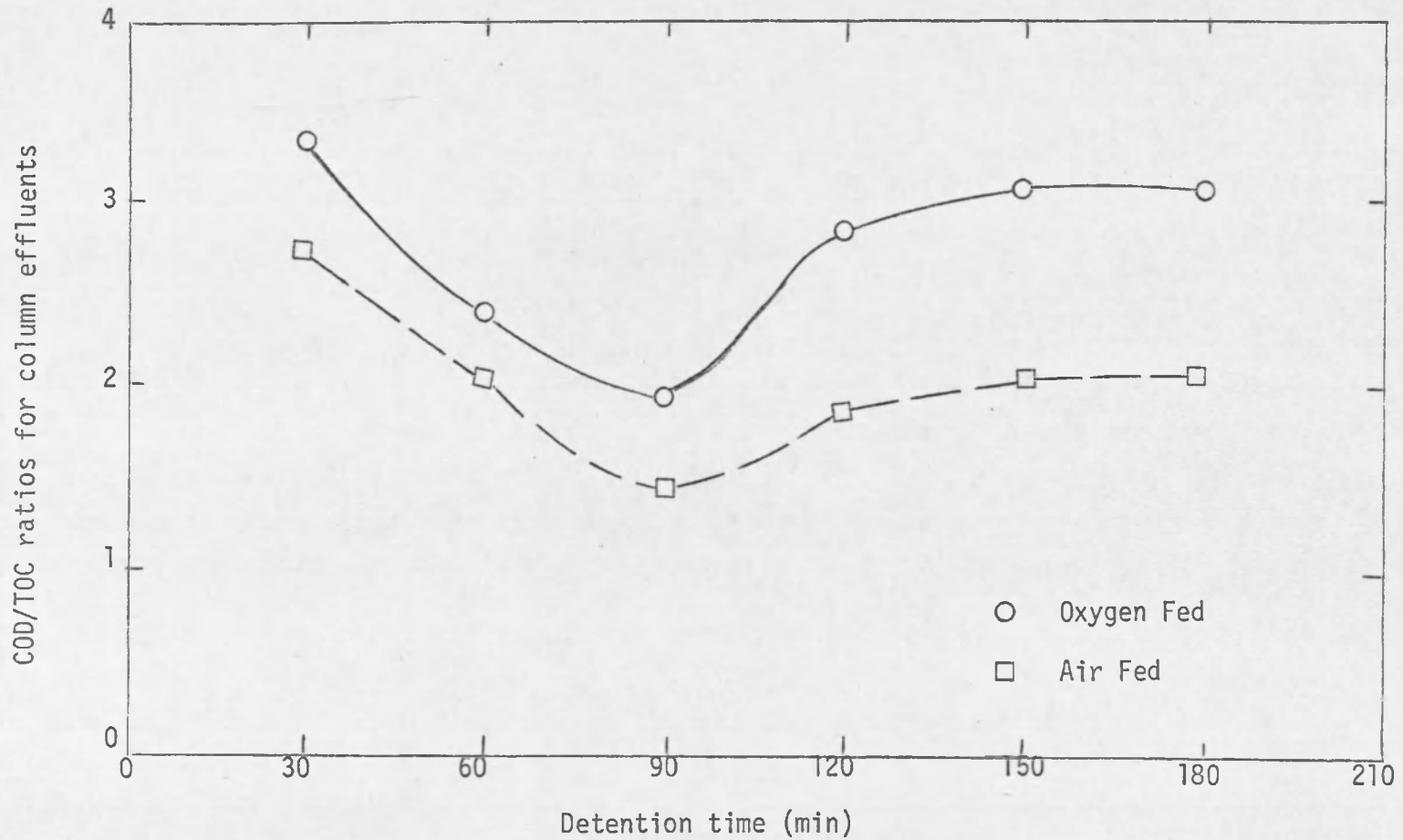


Figure 5.15 COD/TOC Ratios for Column Effluent as a Function of Time for Oxygen and Air Fed Column Reactors

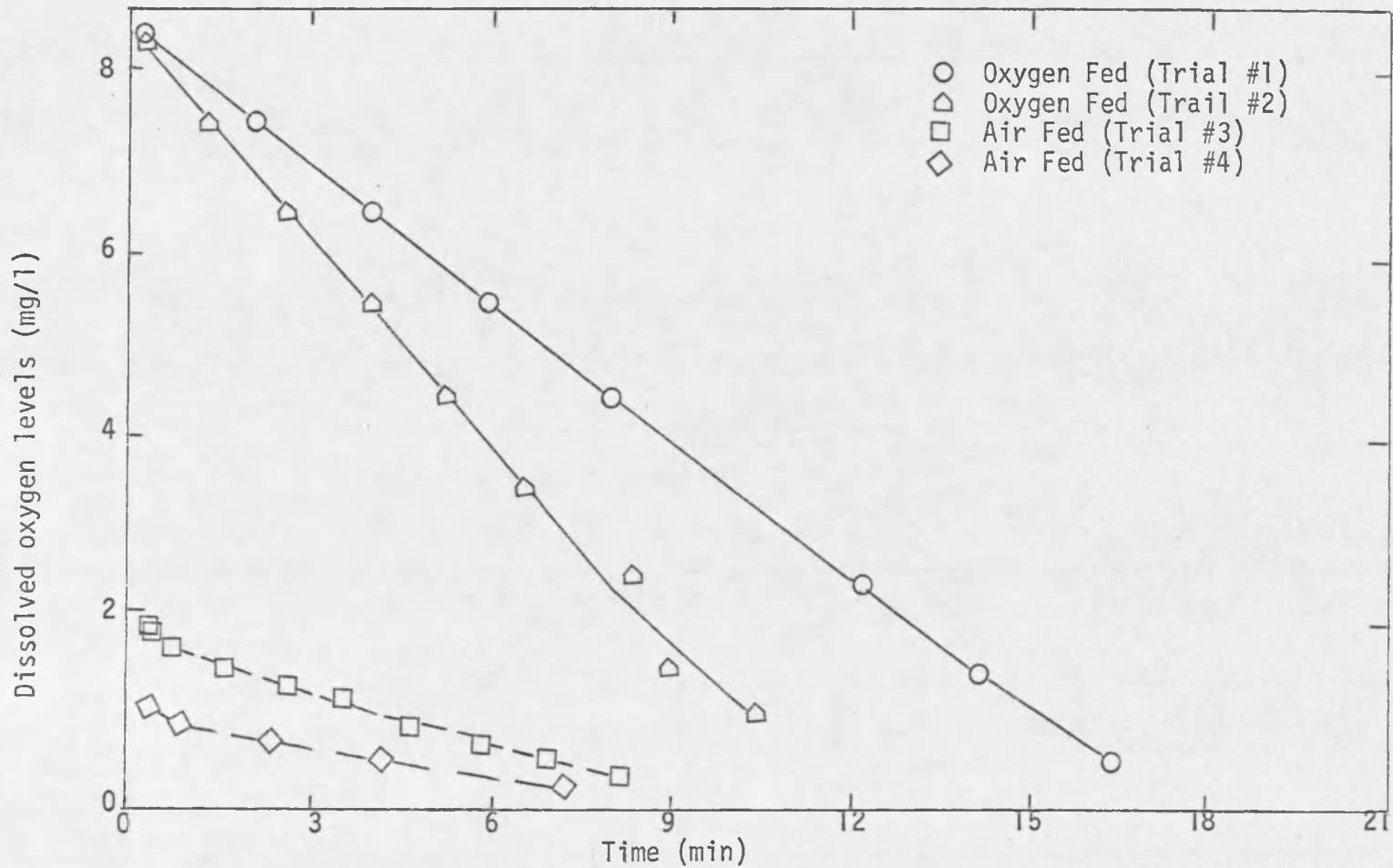


Figure 5.16 Changes in Dissolved Oxygen Levels in Sludge Samples From Oxygen and Air Fed Column Reactors

CHAPTER VI

CONCLUSION

An analysis of the results of this study of column reactors supplied with pure oxygen gas as compared to air is as follows:

(1) No differences in the maximum effluent COD reductions from the oxygen and air fed column reactors were ascertained.

(2) The same species of protozoa were found in each of the column reactors.

(3) The ultimate level of carbon dioxide production was the same for the oxygen and air fed column reactors.

(4) A more dense, healthier sludge growth, as indicated by visual observations and volatile solids profiles was maintained in the oxygen fed column reactors.

(5) The operating pH of the oxygen fed column reactors was 6.75 to 7.0 while it was 7.35 to 7.60 for the air fed column reactor.

(6) Nitrification progressed more rapidly in the oxygen fed column reactors.

(7) The reductions in TOC were greater for the oxygen fed than the air fed column reactors. For instance, at detention times from 30 to 120 min 15 per cent more TOC reduction was noted, however, the differences were only 5 per cent at detention times greater than 125 min.

Although no definite improvement in the ultimate level of treatment with respect to COD reductions was attained, these results indicated

that the use of pure oxygen would significantly improve the capacity at which column reactor biological treatment plants could operate efficiently. This was explained by the fact that the DO levels were ten times greater in the oxygen fed column reactors.

Pure oxygen treatment systems can be used to upgrade existing over loaded treatment plants as well as in new plant design. The use of pure oxygen would provide more effective odor control and higher DO content in the plant effluent.

CHAPTER VII

SUGGESTIONS FOR FURTHER STUDIES

More experimental work needs to be done to establish the advantages and disadvantages of using the submerged packing oxygen fed biological reactor. Some of the design parameters which need further study are:

- 1) Establishing optimum oxygen feed rates for the column reactor.
- 2) Recycling sewage and gas to improve efficiency.
- 3) Optimizing the geometry of the packing.
- 4) Mixing gas and sewage either in the reactor or prior to its entering the reactor.
- 5) More completely analyzing chemical and biological parameters to establish if the use of pure oxygen is advantageous under varied operating conditions.
- 6) Comparing oxygen and air fed systems to establish if the use of pure oxygen is economically justifiable.
- 7) Constructing a pilot scale pure oxygen column reactor treatment system.

Bonner, Busch and Caster (23) have recently discussed some of the design factors that should be evaluated on a pilot scale operational basis. These include comparing BOD and COD loadings, SS removals, clarifier solids loadings, and nitrification. Oxygen requirements per pound

of BOD or COD removed, odor control, specialized equipment required, and on-site generation of oxygen vs. purchased tonnage oxygen with alternative treatment systems were also listed as needing evaluation.

APPENDIX A
ANALYTICAL DATA

ANALYTICAL DATA

The average value is given where more than one analysis was run on the same day.

Collection Point samples were collected from the column reactor effluent tubes and the primary sewage storage tank.

Gas Fed Rate column reactors #1, #2, and #3 were oxygen fed, and column reactor #4 was air fed.

CO₂ 0.18 ppt CO₂ has been subtracted from the values obtained from air fed column reactor #4 in order to account for the CO₂ in the influent gas.

1971	Sample Collection Point	Hydraulic Detention Time (min)	Gas Fed Rate (ml/min)	pH	COD (mg/l)	TC (ppm)	IC (ppm)	TOC (ppm)	NH ₃ -N (mg/l)	Organic-N (mg/l)	NO ₂ -N (mg/l)	NO ₃ -N (mg/l)	PO ₄ -3 (mc/l)	CO ₂ (ppt)	Temperature (°C)
4/2	Primary 1				410										
4/3	Primary 1				425										
	2				70										
	3				100										
	4				140										
	4				55										
4/6	Primary 1				---										
	2				110										
	3				50										
	4				130										
	4				10										
4/10	Primary 1				506										
	3				243										
	4				121.7										
	4				234										
4/11	Primary 1				890										
	2				244										
	3				365										
	4				683										
	4				318										

1971	Sample Collection Point**	Hydraulic Detention Time (min)	Gas Fed Rate (ml/min)***	pH	COD (mg/l)	TC (ppm)	IC (ppm)	TOC (ppm)	NH ₃ -N (mg/l)	Organic-N (mg/l)	NO ₂ -N (mg/l)	NO ₃ -N (mg/l)	PO ₄ -3 (mc/l)	CO ₂ (ppt)****	Temperature (°C)
4/14	1	100	80												
	2	92	80												
	3	129	80												
	4	83	215												
4/15	Primary			7.90											
	1	100	80												
	2	96	80												
	3	137	80												
4/16	Primary			7.70	376										11.0
	1	102	80	7.35	115										25.8
	2	94	80	7.30	84										25.8
	3	133	80	7.40	94										25.8
4/19	Primary			7.50	1425										8
	1	109	70	7.35	61										25.5
	2	107	62	7.20	41										25.5
	3	126	62	7.35	51										25.5
4/20	Primary			7.55	428										9
	1	109	80	7.40	51.0										
	2	96	80	7.35	61.2										
	3	137	80	7.45	61.2										
4/21	Primary			7.65	286										
	(Filtered-0.45 μ Milipore Filter)				143										
	1	99	80	7.40	61.2										
	(Filtered)														
4/21	2	96	70	7.30	81.5										
	(Filtered)														
	3	134	80	7.40	71.3										
	(Filtered)														
4/21	4	82	356	7.55	50.9										
	(Filtered)				50.9										

1971	Sample Collection Point**	Hydraulic Detention Time (min)	Gas Fed Rate (ml/min)***	pH	COD (mg/l)	TC (pmm)	IC (pmm)	TOC (pmm)	NH ₃ -N (mg/l)	Organic-N (mg/l)	NO ₂ -N (mg/l)	NO ₃ -N (mg/l)	PO ₄ -3 (mc/l)	CO ₂ (ppt)****	Temperature (°C)
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(All Subsequent Samples were Filtered through a 0.45 Millipore Filter Before Analyses)

4/23	Primary			7.70	141.5									7.83	
	1	81	90	7.40	81.1										
	2	98	90	7.40	81.1										
	3	176	90	7.40	60.8									2.50	
4/26	4	80	356	7.65	70.9										
	1	82													
	2	108													
	3	129													
4/27	4	80													
	Primary			7.55											
	1	83		7.30											
	2	112		7.30											
4/28	3	123		7.05											
	4	83		7.50											
	Primary				115.3										
	1				48.2										
4/29	2				57.8										
	3				48.2										
	4				57.8										
	Primary			7.65	116.7										
5/1	1	84		7.20	58.3										
	2	102		7.05	48.6										
	3	122		6.95	48.6										
	4	80		7.65	58.3										
5/1	Primary			7.35	136.0	105									
	1	79	80	7.00	48.6	55									
	2	115	80	6.85	48.6	39									
	3	135	80	6.85	38.8	34									
5/1	4	82	370	7.65	38.8	67									

1971	Sample Collection Point**	Hydraulic Detention Time (min)	Gas Fed Rate (ml/min)***	pH	COD (mg/l)	TC (pmm)	IC (pmm)	TOC (pmm)	NH ₃ -N (mg/l)	Organic-N (mg/l)	NO ₂ -N (mg/l)	NO ₃ -N (mg/l)	PO ₄ -3 (mc/l)	CO ₂ (ppt)****	Temperature (°C)
5/2	Primary			7.35							0.14	0.65	40.5		
	1	82	80	6.95							2.10	3.12	42.5		
	2	114	80	6.75							3.35		45.5		
	3	140	80	6.75							2.55		46.0		
	4	83	370	7.55							0.27	0.65	44.5		
5/3	Primary				196				31.0	4.2	0.1	0.265	45.0		
	1	82			39.2				17.1	2.8	2.70	3.15	46.0		
	2	113			39.2				5.6	2.2	3.40	12.1	48.0		
	3	133			39.2				0.4	2.0	2.40	16.4	48.7		
	4	82			39.2				24.4	2.8	0.45	0.840	47.0		
5/5	Primary													2.97	
	1	82												4.17	
	2	111												4.88	
	3	138												1.667	
	4	83													
5/6	1	43.3													
	2	66.3													
	3	51													
	4	39.6													
5/9	Primary			7.3	88.4				30.4	3.60	0	0.225	28.5		
	1	44.7	80	6.90	53				24.5	2.38	1.45	0.917	30.0	1.399	
	2	64.9	80	6.75	44.2				15.25	1.96	2.65	4.50	29.0	1.876	
	3	51.8	80	6.70	35.3				11.75	2.10	2.60	6.49	28.0	4.38	
	4	39.2	370	7.55	35.3				30.5	2.52	0.06	0.282	30.0	0.849	
5/10	Primary			7.35	88.4										8
	1	44.0		7.00	53									1.757	23.5
	2	64.3		6.85	35.3									2.62	24
	3	53.1		6.80	53									4.98	24
	4	39.2		7.65	53									1.042	23

1971	Sample Collection Point**	Hydraulic Detention Time (min)	Gas Fed Rate (ml/min)***	pH	COD (mg/l)	TC (pmm)	IC (pmm)	TOC (pmm)	NH ₃ -N (mg/l)	Organic-N (mg/l)	NO ₂ -N (mg/l)	NO ₃ -N (mg/l)	PO ₄ -3 (mc/l)	CO ₂ (ppt)****	Temperature (°C)
5/11	Primary					101									
	1					70									
	2					62									
	3					58									
	4					77									
5/12	Primary				131	102			30.8	3.30					
	1	44.7	80		56.1	73			16.52	2.10	0.75	0.50	36.5		
	2	67.8	80		42.0	64			9.11	1.68	1.40	3.08	36.5		
	3	58.0	80		46.7	58			7.14	1.82	1.45	3.44	37.5		
	4	40.5	370		79.5	92			19.45	2.24	0	0.304	35.0		
5/21	Primary														
	1	27	80												
	2	131	80												
	3	114	80												
	4	149	370												
5/22															
	1	25													
	2	112													
	3	96.5													
	4	133													
5/24	Primary			7.50	137.7	98	57	41							11
	1	27	80	7.05	82.6	90	67.5	22.5							23
	2	121	80	6.70	41.3	33	22.5	10.5							25
	3	101	80	6.75	64.3	36	20.5	15.5							25
	4	193	370	7.25	27.5	27	16.5	10.5							25
5/25	Primary				165.3	95	56.5	38.5	30.2	4.2	0.002	0.283	40.5		
	1	27.9	80		92.0	87	62	25	30.0	3.64	0	0.032	44.5		
	2	123	80		57.4	35	26	9	0.56	2.52	187	13.80	43.5		
	3	99.3	80		71.2	36	21	15	2.8	2.52	3.75	13.20	42.5		
	4	204	370		45.9	36	23.5	12.5	0	1.4	1.25	14.80	42.0		

1971	Sample Collection Point**	Hydraulic Detention Time (min)	Gas Fed Rate (ml/min)***	pH	COD (mg/l)	TC (ppm)	IC (ppm)	TOC (ppm)	NH ₃ -N (mg/l)	Organic-N (mg/l)	NO ₂ -N (mg/l)	NO ₃ -N (mg/l)	PO ₄ -3 (mc/l)	CO ₂ (ppt)****	Temperature (°C)
5/26	1	25.8													
	2	129.5													
	3	104.2													
	4	118.8													
5/27	1	24.5												3.87	
	2	122												3.04	
	3	102.8												3.58	
	4	120												0.953	
5/29	Primary								26.8	3.64	0	--	24.5		
	1	26.6	80						26.6	2.52	0	0.032	23.5		
	2	133	80						0	1.68		16.20	30.0		
	3	107.8	80						5.88	1.12		16.90	27.0		
5/30	4	127	370						0	1.12		9.70	28.0		
	1	27.9												1.965	
	2	142												3.27	
	3	106.9												4.64	
6/8	4	128												2.13	
	Primary				145.2	122	62	60							
	1	61.4	80		56.1	94	77	17							
	2	138.8	80		39.4	49	34.5	14.5							
6/8	3	(Column Reactor Operation was Terminated in Order to Perform an Analysis of the Sludge on the Packing)													
	4	84.6	370		47.7	75	62	13							1.453
6/12	Primary			7.05					21.8	3.92	0	0.200	46.5		
	1	50.3	80	6.95											
	2	135.5	80	6.80											
	4	119.5	370	7.40					9.56	1.68	0.47	3.00	47.0		
6/15	1	50.3													
	2	135.2													
	4	95.6													

1971	Sample Collection Point**	Hydraulic Detention Time (min)	Gas Fed Rate (ml/min)***	pH	COD (mg/l)	TC (pmm)	IC (pmm)	TOC (pmm)	NH ₃ -N (mg/l)	Organic-N (mg/l)	NO ₂ -N (mg/l)	NO ₃ -N (mg/l)	PO ₄ -3 (mc/l)	CO ₂ (ppt)****	Temperature (°C)
6/17	Primary			7.25	149.8	83	41	42	24.4	3.64	0	0	47.0		
	1	51.7		7.10	83.2	57	33.9	23.1			0.025	6.00			
	2	159.2		6.80	33.3	31	21	10	0	2.38	0	17.80			
6/22	4	7.13		7.55	60.4	65	44	21	17.35	2.24	0.05	6.80	48.5	0.395	
	1	84.5													
	2	107													
6/24	4	147													
	Primary			7.35	114.2				22.4	3.92	0	0.225	42.5		
	1	88.8	80	7.10	44.8				11.05	2.52	0.70	1.10	46.0		
6/25	2	139.0	80	6.90	28.5						0	9.62			
	4	182	370	7.45	32.6				0	1.68	0.22	13.80	46.0		
	Primary					74	27	47							
6/26	1	88.5				32	13.5	18.5							
	2	140				25	14	11							
	4	165				30	13.5	16.5						2.20	
7/13	Primary				111.2				27.7	3.92	0	0.195	40.5		
	1	88	80		---				11.2	1.96	2.90	1.20	43.0		
	2	160	80		30.6				0	1.68	0	17.00			
7/13	4	164.7	370		27.8				0	1.40	0.65	4.80	4.30	1.05	
	Primary				113	113	63	50							
	1	46.0	80		50.6	87	53	34							
7/13	2	16.0	80		22.7	38	23.9	14.1							
	4	44.7	370		35.0	98	57	41						2.62	

(All Column Reactor Operation was Terminated in Order to Perform Analyses of the Sludge on the Packing)

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