BIOLOGICAL NUTRIENT (NITROGEN AND PHOSPHORUS) REMOVAL FROM MUNICIPAL WASTEWATER USING DIFFERENT VARIATIONS OF THE ACTIVATED SLUDGE PROCESS

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LIST OF ABBREVIATIONS AND SYMBOLS

BOD_5	biochemical oxygen demand
COD	chemical oxygen demand
DO	dissolved oxygen concentration
F	flow rate
F/M	food over microorganisms ratio, FSi/XV
KB	substrate loading at which the substrate utilization is half of the maximum rate
MLSS	mixed liquor suspended solids
SRT	sludge retention time
SVI	sludge volume index
TKN	total kjeldal nitrogen
TSS	total suspended solids
U_{max}	specific substrate utilization rate
VSS	volatile suspended solids
ZSV	zone settling velocity

CHAPTER I

INTRODUCTION

Municipal wastewater effluents provide a valuable resource that for the most part goes untapped. Municipalities spend a tremendous amount of money in treating their municipal wastewaters to an acceptable level of treatment for discharge only to be released back into the environment. Control of nutrients discharged in wastewater plant effluents is an important consideration in protecting water bodies from excessive algae and aquatic vegetation growth. The negative aspects of algae growth such as taste and odor problems in water supplies, variation in water dissolved oxygen content during day and night, effect on the ability of certain fish species to grow, and impact on the recreational use of water are well documented. Strict effluent standards for nitrogen and phosphorous have been established to minimize eutrophication of streams and impounded waters, as well as contamination of ground water supplies.

One of the primary reasons that the treated effluents are not reused or recycled is due to the expense and difficulty in removing the nutrients (nitrogen and phosphorous) from municipal wastewaters. Local authorities in these sensitive areas may in the future be faced with problems of nutrient removal even if they do not plan on reusing their treated effluents.

There are a number of alternatives available for the control of effluent nutrients including both physical/chemical and biological treatment processes. The physical/chemical processes are very expensive due to the increased sludge production, continual chemical cost, chemical storage requirements, chemical handling requirements, and chemical feed control requirements. However, the biological nutrient (nitrogen and phosphorus) removal processes offer great promise for accomplishing economical, effective, and reliable nutrient removal. Results of research and full-scale application of nutrient removal activated sludge processes, such as the Bardenpho and Phoredox processes, are sufficiently promising that design engineers should seriously consider them for nutrient removal applications. These processes have been utilized more extensively in South Africa and the majority of the treatment plants being built there today consists of these types of nutrient removal facilities.

However, the research into biological nutrient removal is by no means complete. Even though the kinetics of nutrient removal are unknown and the reliability of operations presents problems, virtually every plant being built in South Africa today is designed for nutrient removal due to their water shortage and water reuse requirements. There is a definite requirement for research into the kinetics and mechanisms of biological nutrient removal processes along with process control and optimization research to provide more efficient and economical nutrient removal processes. Due to strict effluent standards for nitrogen and phosphorus in the United States, there is a definite need for research in these areas to accomplish economical, effective, and reliable nutrient removal.

The experimental research reported herein was undertaken in order to obtain operation and design information necessary for the successful functioning of wastewater treatment plants to accomplish nitrogen and phosphorus removal. Municipal wastewater was used as the substrate. Investigations were carried out on continuous flow bench-scale pilot systems. The continuous flow studies involved a one-stage nitrifying system, a three-stage nitrifying-denitrifying system, and a combined biological nitrogen-phosphorus removal system. The first two systems were operated simultaneously. These systems were operated under different sludge retention times and food-to-microorganism ratios. From these studies, necessary biological kinetic constants were calculated for carbonaceous and nitrogen removal based on BOD/COD to ammonia-nitrogen ratio. From the results, necessary operating conditions, process control, and optimization for organics, nitrogen, and phosphorus removal can be established.

CHAPTER II

LITERATURE REVIEW

Nitrogen and phosphorus in wastewater treatment plant effluents have been associated with undesirable effects on receiving waters and the environment. As early as 1969, researchers were developing activated sludge nitrification-denitrification processes with chemical addition to remove nitrogen and phosphorus from wastewater. The first commonly accepted activated sludge nutrient removal system was a three-stage system for separating carbonaceous removal, nitrification, and denitrification in an attempt to optimize process control (1). Phosphorus was typically removed from the wastewater through the addition of a metal salt such as sodium aluminate, aluminum sulfate, or ferric chloride. Because the denitrification process was situated after the carbonaceous removal stage, methanol addition was required as an energy source for the denitrifying bacteria. During the early 1970s, other investigators (2, 3) were applying a two-stage nitrification-denitrification process utilizing a combined carbon oxidation-nitrification system. This two-stage system relied on the same chemicals for nutrient removal as the three-stage process.

To meet wastewater effluent nutrient removal limitations for surface discharge, numerous municipalities resorted to construction of these energy-intensive treatment plants and incurred relatively high operating and maintenance expenses. Recently, there has been some resistance by the U.S. Environmental Protection Agency (EPA) to funding and accepting nitrogen and phosphorus removal wastewater treatment plant designs. It is apparent that a system with minimal capital and operational costs along with fewer operating problems is required before nutrient removal will be considered a reasonable treatment objective by the regulatory agencies.

An innovative treatment approach for accomplishing nutrient removal in a modified activated sludge system without requiring chemical addition, costly equipment, and complex operating procedures was developed in 1972 by James Barnard (4, 5). This approach, commonly known as the "Bardenpho System," proved to be the most cost-effective, with the economics significantly affected by the chemical cost savings for nitrogen and phosphorus removal (6).

In this chapter the literature is reviewed under three major topics, which are nitrification, denitrification, and phosphorus removal.

Nitrification

In 1877, Schloesing and Muntz (7) first demonstrated the association of living microorganisms with ammonia oxidation reaction. Winogradsky, in 1888, was the first person to isolate an unmistakable nitrifying organism in pure culture. The first American investigators to report the isolation of nitrifying bacteria were Jordan and Richards (8). Many researchers have studied autotrophic nitrifying bacteria (9, 10, 11, 12, 13, 14, 15). It is said that nitrification may be performed by either heterotrophic or autotrophic bacteria (9, 16, 17, 18, 19, 20, 21). In spite of the fact that over 100 species have been cited as forming nitrite (NO_2^-) from ammonia (22), it is doubtful that significant quantities of nitrate are generated heterotrophically in natural systems (23). Consequently, most research into nitrification in wastewater treatment systems has concentrated on the autotrophic organisms, Nitrosomonas and Nitrobacter. But recently Lan (21) found that heterotrophic nitrification could be the predominant mode, when nitrogen is in excess of assimilatory needs in biological nitrification systems.

Nitrification in Activated Sludge System

The oxidation of ammonia to nitrite, and nitrite to nitrate, is performed by nitrifying bacteria. The kinetics of ammonia oxidation in the activated sludge process have been investigated in detail by Downing, Painter, and Knowles (24). They showed that the rate of growth of nitrifying bacteria is lower than that of the bacteria responsible for carbonaceous oxidation. The shortest generation time reported (24) for Nitrosomonas in activated sludge is 2 days at 20°C, whereas the generation time for heterotrophic bacteria can be as short as 15 minutes. An activated sludge plant producing a nitrified effluent usually contains little nitrite, the ammonia oxidized being converted almost completely to nitrate. Downing, Painter, and Knowles (24) showed that the mass of Nitrosomonas in the whole sludge mass will tend to approach an equilibrium value such that complete nitrification will be obtained; or if the fractional rate of wastage of sludge is greater than the rate of growth of Nitrosomonas, washout will occur and nitrification will be absent. Downing and Knowles (25) came up with equations for the concentration of Nitrosomonas and Nitrobacter. When conditions are adequate for nitrification, then at equilibrium the concentration of Nitrosomonas, C_{ME}, in the mixed liquor will be given approximately by

$$E_M\ X_s/(1+p)\ C_{ME} = \Delta s/s \tag{2.1}$$

and that of Nitrobacter, C_{BE}, by

$$E_B\ fX_s/(1+p)\ C_{BE} = \Delta s/s \tag{2.2}$$

Under these equilibrium conditions, a small concentration of ammonia will "leak" through to the effluent defined by

$$X_E = X\Delta S/(K_M\ t_M S - \Delta S) \tag{2.3}$$

where

C_{ME}, C_{BE} = equilibrium concentrations, resply of Nitrosomonas and Nitrobacter;

E_M, E_B = "economic coefficient" for resply of Nitrosomonas and Nitrobacter. The economic coefficient is the mass of bacteria formed by the utilization of unit mass of substrate (ammonia-N and nitrite-N resply for these two bacteria);

X_s = concentration of ammonia-N in a waste, before treatment;

p = ratio of flow of returned sludge to that of sewage;

S = concentration of suspended solids in an activated sludge treatment plant;

ΔS = increase in S (in a given time) as a result of treatment of wastes (for a "plug-flow" activated-sludge treatment, the appropriate period is the mixed-liquor retention time);

f = number of units by weight of nitrite produced by bacterial oxidation of one unit by weight of ammonia, both measured in terms of weight of nitrogen;

X_E = equilibrium concentration of ammonia-N;

X = concentration of ammonia-N;

K_M = "maximum first-order" growth rate constant for Nitrosomonas; and

t_M = "mixed liquor" retention time in an activated sludge treatment plant.

Poduska and Andrews (26) and Stankewich (27) have summarized observed yields from the literature and have reported them to vary from 0.03 to 0.13 mg cells/mg NH_4^+-N oxidized for Nitrosomonas and from 0.02 to 0.07 mg cells/mg NO_2^--N oxidized for Nitrobacter. Johnson and Schroepfer (28) have found that nitrification depends primarily on the balance between loading and detention time, and when proper adjustments are made the process will proceed. They recommend load factors of less than 0.25 to 0.32 lbs BOD/day/lb sludge in the activated sludge process (28). The efficiency of the activated sludge process does not appear to be affected with NO_3-N concentration up to 4800 mg/ℓ (29). However, the same investigation showed undesirable effects at NH_4-N concentrations of 480 mg/ℓ and a BOD:N ratio of 0.2 to 1.0. Balakrishnan and Eckenfelder (30) were able to obtain complete nitrification on a domestic waste with about 30 mg/ℓ of TKN using loadings less than 0.4 lbs BOD/day/lb sludge, provided that all other conditions were optimum. Jansen and Behrens (31) estimated the maximum ammonia removal rate as 1.0 mg NH_4^+-N/g VSS hour or relating to an estimate of the amount of nitrifiers, as 210 mg NH_4^+-N/g VSS nitrifiers hour. Arueste (32) and Downing and Knowles (25) reported around

0.8 mg/ℓ of ammonia-nitrogen in the effluent during complete nitrification.

Nitrification with cell-recycle can be achieved in two ways: in combination with carbon oxidation or in a separate system following carbon oxidation. What are the relative merits of combined versus separate carbon-oxidation-nitrification? The question has been considered by Stall and Sherrad (33, 34) through a mathematical model based on the parameter SRT and the Continuous Culture theory (35). It has been shown experimentally by Stover and Kincannon (33) that one-stage combined carbonaceous-nitrification systems could achieve degrees of nitrification comparable to two-stage separated systems when designed and operated properly. Stover (36) from his investigations on the removal of nitrogenous oxygen demand in wastewaters has concluded that at 20°C, nitrification ceases in biological processes at a SRT of approximately 3 days or less; hence a 6-day or greater SRT is required for a two-stage system. For a one-stage system, it was suggested that a 10-day or greater SRT is necessary due to the effect of COD:NH_3-N ratio. Based on bench-scale studies, Sutton et al. (37) reported that the minimum aerobic SRT required to nitrify Dupont wastewater was 25 to 30 days at 20°C and 55 to 60 days at 10°C.

Nitrification in Attached-Growth System

The effect of bacteriological competition for space between the organic carbon oxidizing and nitrifying bacteria in a biological tower has been observed by Stover and Kincannon (38). They observed that when a wastewater containing both organic matter and NH_4^+-N is applied to a packed tower, only a fraction of the tower height will be available for nitrification; and the magnitude of that fraction will depend upon both the absolute and relative concentration of the two substrates, organic carbon and ammonia-nitrogen. Hence by varying the COD:NH_3-N ratio, the depth for nitrification to take place could be controlled. In other words, nitrification could be controlled at any depth by controlling the COD:NH_3-N ratio in the incoming waste as has also been observed by Little (39). Stover and Kincannon (40) treated a synthetic waste with a COD:NH_3-N ratio of 250:27.6 and found a 90 percent COD and almost complete ammonia-nitrogen removal in a rotating disc system (RBC). In their study, a six-stage system with five 23.25-in.-diameter polystyrene disks in each stage was employed. Results of their study show that COD removal is virtually completed in the first stage, whereas ammonium oxidation is completed only after the fifth stage.

Heterotrophic Nitrogen Oxidation

The physiological or biochemical characteristics associated with nitrogen oxidation by heterotrophs are unknown. Lan (21) reported from her research that the organism isolated from a nitrifying activated sludge system is capable of metabolizing organic carbon as a carbon and energy source and nitrifying after depletion of the organic carbon. The verified the fact that the organism is incapable of growing in an inorganic medium and nitrapyrin has no effect on its nitrifying activity, which indicates that nitrification by this organism is heterotrophic in nature. She also reported that under appropriate conditions of carbon and nitrogen supply, especially when nitrogen is in excess of assimilatory needs, heterotrophic nitrification could be the predominant mode of nitrification in biological nitrification systems.

Factors Affecting Nitrification

The main factors which affect nitrification are DO, pH, presence of inhibitors, temperature, and substrate and product inhibition.

Dissolved Oxygen Concentration. Downing, Painter, and Knowles (24) and Downing and Scragg (41) reported that the rate of nitrification was independent of DO concentration above 0.5 mg/ℓ. On the other hand, Nagel and Haworth (42) found that increasing the DO concentration above 1.0 mg/ℓ would increase the ammonium oxidation rate. Parker et al. (43) have summarized the effects of DO observed by a number of workers and reported that a treatment plant operated continuously at a DO near 1.0 mg/ℓ gave lower degrees of nitrification than plants held at 4.0 and 7.0 mg/ℓ. When small scale activated sludge plants were held at 1, 2, 4, and 8 mg/ℓ, the nitrification rates at 2.0 mg/ℓ were about 10 percent lower than at higher levels of DO, although nitrification was complete. The influence of DO on nitrification rates has been somewhat controversial, as examples of plants can be found with completely nitrified effluents with operating DO levels of 0.5 mg/ℓ. However, this type of evidence does not indicate that the nitrification rate was unaffected; merely that nitrification could be completed in the presence of a low DO level. Low nitrification rates, depressed by low DO levels, can still be sufficient to cause complete nitrification if the aeration tank detention time is large enough.

pH Value. Meyerhoff (44) found that the optimum range of pH value for nitrification was between 8 and 9, and Hofman and Lees (45) found that the optimum range was between pH 7.5 and 9.0, with about 50 percent of the maximum nitrification being obtained at pH 7.0. Engel and Alexander (46) found that the optimum range was between pH 7 and 9, within which maximum nitrification was obtained. The maximum respiration rate due to nitrification has been shown to occur between pH values of 7.5 and 8.5 (47).

The oxidation of ammonia produces hydrogen ions, with a consequent reduction in pH of the mixed liquor unless buffering occurs. However, unless there is an unusually high concentration of ammonia in the sewage being treated, the pH of the mixed liquor will not usually fall to a level which would affect the nitrification.

Temperature. Downing, Painter, and Knowles (24) found that the maximum specific growth rate of Nitrosomonas approximately doubled for each 10°C rise in temperature in the range of 6 to 25°C. Using works of others (24), Marais (48) formulated an expression to predict the sludge age at various temperatures as follows:

$$SA_{min} = 3.05 \times (1.127)^{(T-20)} \tag{2.4}$$

where SA_{min} is the minimum sludge age at temperature T. The predictive model developed by Knowles et al. (49) for the maximum growth rate of nitrifying bacteria based on temperature is of the following form:

$$\mu_m = 0.47\ e^{0.098\ (T-15)} \tag{2.5}$$

where μ_m is the maximum growth rate of nitrifying bacteria at day^{-1}, and T is the temperature at °C. The effect of temperature is therefore very pronounced.

Inhibition of Nitrification. Downing, Painter, and Knowles (24) reported that the maximum specific growth rate of Nitrosomonas in activated sludge grown on purely domestic sewage was 0.33 d^{-1}, at 20°C. This value is much lower than that reported by Skinner and Walker (50), i.e., 2.2 c^{-1}, at 29°C, for growth in pure culture, presumably due to the presence in sewage of compounds which are inhibitory to Nitrosomonas, even though the temperature is also a factor. Jenkins et al. (51) reported a lower growth rate of 0.063 d^{-1} at 15°C. The reduction was assumed to be caused by the presence of toxic industrial wastes.

Nitrifying bacteria are subject to both substrate and product inhibition, i.e., if the concentration of either their substrates or their products is too high, there will be a decrease in the rates of activity of the microorganisms (23, 26, 43). Studies with pure cultures have shown that free ammonia and undissociated nitrous acid are more inhibitory than NH_4^+ or NO_2^- (52, 53, 54), and studies with mixed cultures have suggested the same thing (55, 56). Rozich and Castens (57) did some research on a two-stage continuous culture system using synthetic ammonia waste devoid of organic carbon to assess the nature, inhibitory or noninhibitory, of ammonia-limited nitrification. The results of their studies indicated that nitrifier growth kinetics are best represented with a substrate inhibition function such as the Haldene equation. They also suggested that nitrifier growth followed an inhibitory pattern which means that the use of the Monod equation for representing nitrification is mechanistically inappropriate.

Stover (36) reported that inhibition of nitrification was observed at high organic carbon loading to the nitrification reactor. He explained the possibility of the production of metabolic byproducts by carbon oxidizing microorganisms which were inhibitory to the nitrification process. Another reasonable explanation given by him was the competition between the carbon oxidizing and nitrifying bacteria for the ammonia-nitrogen present in the wastewater. Esfandi (58) and Esfandi and Kincannon (59), from their study on nitrification inhibition, concluded that rapid growth of carbon oxidizing bacteria in one-stage systems and shock loads of organic carbon source would inhibit the nitrification process, but such an inhibition is only temporary and nitrification is restored when the system recovers from the consequences. Their conclusions agree with results presented by Stover (36). These effects have also been observed in biological towers (60, 39).

Nitrification processes have been found to be sensitive to the presence of toxic compounds, including some heavy metals and organic compounds (9, 20, 61, 62, 63). Beg et al. (64) found that the inorganic compounds of Cr, As, and F inhibit ammonia oxidation rates; and the inhibited reaction follows a zero-order reaction. The inhibitor coefficients were estimated as 1218 mg/ℓ for fluoride, 292 mg/ℓ for arsenic, and 50 mg/ℓ for chromium.

All nitrifying organisms are not obligately autotrophic (65) and in the presence of sufficient substrate will use organic carbon compounds as electron donors rather than reducted nitrogen (66).

Denitrification

After Comly (67) showed that infantile cyanosis caused by the oxidation of haemoglobin to methaemoglobin was associated with the presence of nitrate in well water, much attention has been given to this subject, and this led the World Health Organization (WHO) to set limits for the concentration of nitrate in drinking water (68). This awareness of health hazards associated with the presence of nitrates in water has led to the monitoring of nitrates in potable supplies as standard procedure.

Actually nitrification only converts the ammonia-nitrogen into nitrate-nitrogen, and ultimate removal of nitrate-nitrogen (NO_3-N) into nitrogen gas is carried out by the denitrification process. There are two distinct pathways for the reduction of nitrates or nitrites by bacteria (69):

1. Assimilative reduction, i.e., the formation of ammonia from nitrates and nitrites which is then transferred to the anabolic cell-metabolism. This is of no consequence to large-scale denitrification plants.

2. Respiratory reduction or denitrification, in which nitrates or nitrites replace oxygen as the final electron acceptors in the respiration chain. In doing so they are reduced to nitrogen gas, which is preferably produced as N_2O, which is also a gas, and other minor forms of nitrogen gas. The process holds great promise for the economical removal of nitrogen from wastewaters.

Biological denitrification is brought about by a group of facultative heterotrophic bacteria, including those from the species of Micrococous, Pseudomonas, Denitrobacillus, Spirillus, Bacillus, and Achromobacter (9), which are capable of modifying their metabolism so as to utilize nitrate as a source of oxygen in the absence of DO. Blaszczyk et al. (70) reported that the selection of denitrification species depended on the nitrogen (N) and carbon (C) sources to which they were exposed. Thus Alcaligenes faecalis, pseudomonas fluorescens, and pseudomonas mendocina were enriched in the presence of glucose, methyl alcohol, and ethyl alcohol, respectively. When acetic acid was used as the carbon source, denitrification of nitrite-enriched pseudomonas fluorescens and pseudomonas aeruginosa occurred. Waki et al. (71) studied the characteristics of paracoccus denitrificans exposed to aerobic followed by anaerobic conditions and vice versa. The growth yield was lower in the anaerobic conditions than under the aerobic conditions (0.59 versus 0.41 g/g of glucose utilized). Smith and Tiedje (72) reported that the relative growth rates of denitrifiers in soil were unrelated to those of pure cultures.

Christianson, Rex, Webster, and Virgil (73) were perhaps the first to add a chemical electron donor for denitrification of a high-nitrate industrial waste. Both sugar and methanol were tried and methanol was found to be the most satisfactory when 2.6 parts were added for each part of nitrate-nitrogen. After examining several different materials, Finsen and Sampson (74) selected molasses as a cheap source of carbon. Satisfactory results were obtained using 6.5 parts of molasses per part of nitrate-nitrogen, although its use resulted in a significant increase in residual COD. A more detailed study of several sources of carbon was made by McCarty et al. (75). Acetate, ethanol, acetone, and sugar were each examined but methanol was finally selected as being the cheapest, and most convenient to use. The quantity of methanol required to denitrify a given concentration of nitrate is also influenced by the nitrite content and the concentration of DO (which must first be removed). Based on experimental work, McCarty et al. (75) established a formula for calculating the quantity of methanol required for denitrification, i.e.:

$$C_m = 2.47\ N_o + 1.53\ N_i + 0.87\ DO \tag{2.6}$$

where

C_m = required methanol concentration (mg/ℓ);

N_o = initial nitrate concentration (mg N/ℓ);

N_i = initial nitrite concentration (mg N/ℓ); and

DO = initial DO concentration (mg/ℓ).

The quantity of biomass produced (C_b mg/ℓ) could also be calculated from

$$C_b = 0.53\ N_o + 0.32\ N_i + 0.19\ DO \tag{2.7}$$

The quantity of methanol actually used exceeds the theoretical amount by a ratio of about 1.3 (the "consumptive" ratio) and allowance is made for this in the McCarty equation. Barth, Brenner, and Lewis (76) also used methanol for denitrification and reported a required methanol/nitrate ratio of 4:1 involving a consumptive ratio of 2.1:1.0. Barth et al. (76) also drew attention to a relevant observation by placak and Ruchhoft (77) that lower alcohols tend to be oxidized rather than synthesized into cells: a further point supporting the selection of methanol.

Denitrification in Activated Sludge System

Bailey and Thomas (78) reported around 98 percent removal of NO_3-N for the influent concentration of 35 to 55 mg/ℓ as NO_3-N. Neytzell de wilde (79) and Francis (80) have published work on the denitrification of solutions containing high concentrations of nitrates by activated sludge using methanol as the carbon source. The authors have made mention of the fact that it is possible to denitrify solutions of 2800 mg/ℓ NO_3-N and according to Francis (80) up to 6000 mg/ℓ NO_3-N provided that certain precautions are taken to prevent inhibition by NH_3, HNO_2, H_2S, and CH_3OH. Vossoughi et al. (81) reported the NO_3-N removal rate of 560 mg/ℓ·h of empty reactor volume with a retention time of less than 3 minutes for synthetic wastewater using methanol as the carbon source. Jansen and Behrens (31) reported the maximum nitrate removal rate of 7.8 mg NO_3^--N/g VSS hour. Lewandowski (82) presented data to show that the denitrification rate of a wastewater depends on the type of hydrogen donor used. The denitrification rate was linear with acetic acid, methanol, acetone, and endogenous hydrogen donors within the temperature range of 5 to 35°C. Acetic acid was the most effective because it exhibited the highest denitrification rate of the four hydrogen donors tested. Kone and Behrens (83) reported that denitrification in activated sludge mixed cultures was increased when NH_4^+-N was present as an N source with acetic acid as a hydrogen donor because NO_3-N was exclusively available as an electron acceptor. Musselwhite (84) came up with a method to calculate the residual methanol concentration in the denitrified effluents using a Technicon Auto Analyzer.

Wuhrmann (85) carried out research into the nitrification-denitrification of effluents using a single-stage activated-sludge system; in this scheme denitrification is achieved by endogenous respiration of the sludge. In 1961, Ludzach and Ettinger (86) suggested using the carbon present in the untreated influent to achieve denitrification by exogenous respiration and this idea was subsequently adopted by Barnard (4).

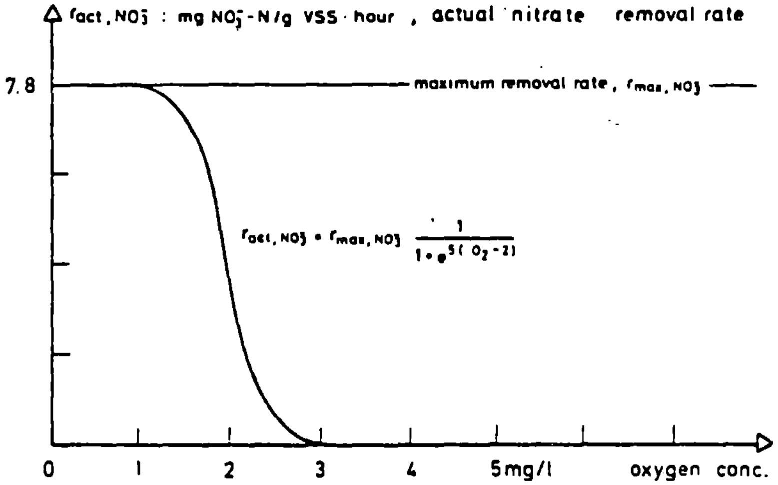
Factors Affecting Denitrification

The factors affecting denitrification include the carbonaceous energy source, temperature, pH, DO, and SRT.

Kim and Chung (87) reported on the use of pseudomonas denitrificans for achieving denitrification of a wastewater in a tapered fluidized activated carbon bed reactor. They reported that a pH of 7.0 to 8.5 and a temperature of 25 to 35°C were optimal. Steinmueller and Kutzner (88) obtained optimum denitrification at a pH of 8.0 and a temperature of 30°C for an inorganic industrial wastewater. The rate was reported as 34.43 NO_3-N/L·h for the suspended growth system. Dawson and Murphy (89) found a Q_{10} value of approximately 3 for pseudomonas denitrificans between 5 and 27°C, and Mulbarger (90) reached a similar conclusion. The Q_{10} value is defined as follows:

$$Q_{10} = \frac{\text{Rate at } (t+10)^\circ\text{C}}{\text{Rate at } t^\circ\text{C}} \tag{2.8}$$

Bailey et al. (91) reported very satisfactory reduction in the concentration of nitrate, even at temperatures as low as 7°C for an activated-sludge process. Focht and Chang (23) reported that temperature exerts a greater effect below 15°C than above it. According to Delwiche (92) the optimum pH of denitrification lies between 7.0 and 8.2. Grady and Lim (93) reported the optimum pH range of 7.0 to 7.5 for highest rates of denitrification. They also reported that denitrification rates depressed below pH 6.0 and above pH 8.0. At a sludge age <1 day, Johnson and Schroepfer (28) obtained an effluent containing less than 2 mg/ℓ nitrate-N. Stern and Marais (94) developed an equation showing that the denitrification rate was inversely proportional to the sludge age. Sutton et al. (95) showed that a sludge age of 6 days is required at 5°C temperature, while at higher temperatures only 3 days are required. In a more recent study, Sutton and Jank (96) indicated that the temperature sensitivity of the denitrification process is essentially independent of sludge age over a range of 3 to 9 days. Jansen and Behrens (31) reported the nitrate removal up to an oxygen tension of 3 mg O_2/ℓ. Figure 1 shows the actual rate of nitrate removal as a function of the oxygen concentration.



Note: There are other limiting factors for the nitrate removal rate than oxygen.

Figure 1. Nitrate Removal Rate as a Function of Oxygen Concentration (31)

Their preliminary experiment showed denitrification throughout the reactor and not only in limited anoxic zones. The phenomenon is assumed to occur due to a formation of anoxic conditions within the single sludge particle even at substantial oxygen concentrations in the water.

Inhibition of Denitrification

McElhannon (97) reported on the inhibition of denitrification by 2-chloro-6-(trichloro methyl) pyridine, whereas Tresidder and Corke (98) developed an S-triazine biocide for inhibiting the denitrification of compounds containing nitrite that were used to prevent corrosion of cooling water systems. Francis and Hancher (99) reported that radiation doses greater than 10^5 Rads decreased denitrification rates. Solutions made with ammonium nitrate at a concentration of NO_3-N greater than 2.5 g/ℓ denitrified better than those made with $Ca(NO_3)_2$ or $NaNO_3$. Nickel and NH_4-N inhibited denitrification at a concentration of 0.5 g/m^3 and 5.0 Kg/m^3, respectively. The authors also reported that denitrification was inhibited severely, depending on the nature of the organic carbon source used. Thus, calcium acetate, when used as a carbon source, was inhibitory at carbon concentrations greater than 6.5 kg/m^3, whereas methanol was not inhibitory even at a carbon concentration of 15 kg/m^3. Ammonia-nitrogen inhibits the assimilation of oxidized nitrogen compounds into cell material (92).

Biological Phosphorus Removal

Barnard (4) first reported on a four-stage system without an initial fermentation zone to achieve over 90 percent nitrogen removal in the early 1970s. In the course of evaluating the performance of the system, he found that phosphorus removal was also occurring. He believed this phenomenon was related to the occurrence of an anaerobic stress condition on the biological sludge in the system (100). Thus, by contacting the recycled sludge with the influent wastewater under anaerobic conditions, high levels of biological phosphorus removal could be expected in the activated sludge systems. Nicholls and Osborn (101) stated that an anaerobic stress condition causes the bacteria to release stored phosphorus and then assimilate and store greater than normal quantities of phosphorus under subsequent aerobic conditions. Nicholls (102) further verified that the biological phosphorus removal mechanism is stimulated by anaerobic stress conditions when he created an anerobic zone in front of the full-scale Johannesburg, Alexandria, extended aeration facility in South Africa. Venter et al. (103) reported that olifantsvlei extended aeration plant in Johannesburg was modified to create an anaerobic zone ahead of the aeration. Results reported showed that 50 to 80 percent phosphorus removal could occur. Menar and Jenkins (104) reported on laboratory and pilot plant work wherein reasons for phosphorus removals greater than the 2 to 3 mg/ℓ metabolic uptake were examined. Their conclusion was that pH increases, arising from the sweeping out of metabolically produced CO_2 by the air added in activated sludge, led to the precipitation of certain metal-phosphates.

The effects of the COD:P ratio on laboratory activated sludge systems was studied by Bates and Torabian (105) and Torabian (106). Their study showed that the cellular phosphorus content increased with an increasing phosphorus content in the feed. The percentage of cellular phosphorus was relatively constant from COD:P ratio of 100:3.5 to 100:5.

The cellular phosphorus content reached a maximum value of 1.3 percent at the COD:P ratio of 100:5. They also reported that alkaline phosphatase activity was at a minimum when the cellular phosphorus content reached its maximum value. In addition, in the units where alkaline phosphatase activity was high, it was observed that the sludge was characterized by poor settling and the COD removals were somewhat lower than those achieved in the units at minimum alkaline phosphatase activity.

Excess phosphate uptake by bacteria in an activated sludge plant was observed for the first time by Vacker, Connel, and Wells (107). A certain bacterium belonging to the Acinetobacter-Morazella group was thought to be responsible. Several workers (108, 109, 110) subsequently found high numbers of these bacteria in phosphate-removing sludges. Davelaar (111), however, showed that bacteria isolated from both phosphate-removing and nonphosphate-removing sludges could accumulate phosphate when grown in the liquid culture medium proposed by Fuhs and Chen (110) for the enrichment of Acinetobacter species. Phosphate uptake has been reported for other microorganisms as well, such as the bacteria Escherichia coli (112) and Azotobacter vinelandii (113), and the fungus Neurospora Crassa (114, 115).

Brodisch and Joyner (116) did extensive research on the bacteria responsible for the phosphorus uptake. They reported that Acinetobacter is probably not the only organism capable of enhanced phosphate uptake. Aeromonas and pseudomonas species most likely contribute to biological phosphate removal. Filamentous organisms, presumably members of the species Microthrix and Nocardia, were also reported. These organisms are known to accumulate polyphosphate granules in their cells (117). Brodisch and Joyner (116) also reported that different recycle modes had no effect on the population dynamics, but different anaerobic retention times did. The number of Acinetobacter-Morazella species was also reported to be influenced by the length of the anaerobic retention time, because of its strictly aerobic, nonspore-forming nature, which would not be able to withstand extended anaerobic conditions. Buchan (108) reported on findings at the Goudkoppies sewage works, Johannesburg, where 40 percent of the organisms observed were Acinetobacter, while the plant was removing phosphate to less than 0.5 mg/ℓ as P in the effluent. This plant, however, has an actual anaerobic retention time of only half an hour. Fuhs and Chen (110) reported the optimum growth temperature for the Acinetobacter lwoffi isolate as 20 to 24°C, and maximum phosphate uptake at these temperatures. At 10°C and 37°C, phosphate uptake was reported to be inhibited significantly (110).

Barnard (5, 118, 119) from pilot scale studies on the Bardenpho process reported that excess biological P removal is induced if at some point in the process configuration the organism mass is stressed by subjecting it to an "anaerobic" state (i.e., a state in which neither oxygen nor nitrate is present) such that phosphorus is released by the sludge mass to the bulk liquid. He proposed to produce this stage efficiently by including an anaerobic reactor ahead of the primary anoxic reactor in the Bardenpho process, this reactor receiving the influent flow and the underflow recycle from the secondary settling tank. To explain the excess removal phenomenon, Barnard (119) hypothesized that it is not the release that stimulates the excess uptake mechanism, but that release indicates a certain low redox potential has been established, i.e., that the low redox potential triggers off the release and thereby stimulates excess P uptake. In terms of this hypothesis, nitrate-nitrogen recycled via the underflow to the anaerobic reactor will restrain, in some degree, the level to which the redox potential can be lowered and consequently, nitrate-N can be expected to influence excess P uptake adversely. No data on redox potential were reported. In any event he considered that nitrate entering the anaerobic reactor could be countered by increasing the retention time of this reactor.

Rabinowitz and Marais (120) reported from their investigations that when the nitrate concentration in the effluent (and underflow recycle) was low, usually P release and excess uptake were observed. They also reported that with different batches of wastewater having the same nitrate concentration in recycle, one batch may give high P release and excess removal, whereas the next may give no (or little) release and little excess removal. No apparent reason for this behavior was reported. Ekama et al. (121, 122) reported that readily biodegradable COD in the anaerobic reactor surrounding the organisms is the key parameter determin- whether or not P release and excess P uptake take place. They also reported that the degree of P release appears to increase as soluble COD increases and the larger the mass of sludge recycled through the anaerobic reactor, the higher the P removal. Ekama et al. (121) reported that high hydrogen sulphide concentration in the feed to a process can have adverse effects on the process response.

Simpkins and McLaren (123) reported that 90 percent phosphorus removal could be achieved only after obtaining high levels of nitrate removal. With an effluent nitrate-nitrogen concentration of 6.7 mg/ℓ, only around 55 percent phosphorus removal was obtained. Burdick et al. (6) reported 3.0 mg/ℓ of phosphorus in the effluent (65% P removal) from the Palmetto Bardenpho plant.

The effect of the anoxic zones on the nitrifying organisms has not been established, but it was said that the aerobic zone must be larger than the combination of the anoxic and the fermentation zones (124). Existing plants are usually operated at mixed liquor suspended solids concentration between 4000 and 5000 mg/ℓ with SRT's varying between 15 and 20 days (124).

CHAPTER III

MATERIALS AND METHODS

Municipal wastewater was collected from Oklahoma State University's Environmental Engineering pilot plant building on McElroy Street and was used in all experiments. The wastewater was settled for one to two hours to remove the settable solids. The wastewater was then carefully characterized for BOD, COD, suspended solids, etc. along with nitrogen and phosphorus. It was found that the soluble BOD of the wastewater was very low. Therefore, soluble BOD was added in the wastewater by the addition of isopropyl alcohol. This wastewater was then subjected to biological treatment investigations in three different types of activated sludge systems. The first bench scale system was a nitrifying one-stage activated sludge system with an internal clarifier. The second system consisted of three reactors with internal clarifiers; the first reactor was used to remove carbon, the second one to convert the ammonia-nitrogen (NH_3-N) into nitrate-nitrogen (NO_3-N), and the third one to reduce the NO_3-N into nitrogen gas (denitrification). These two systems were operated simultaneously from March, 1983, through April, 1984. The third, combined carbon-nitrogen-phosphorus removal system consisted of three reactors in series. The first reactor (anaerobic) was used to achieve partial removal of carbon and to release the phosphorus and condition the sludge for uptake or removal of phosphorus in the third reactor (aerobic). The second anoxic (denitrification) reactor was primarily used for conversion of NO_3-N into nitrogen gas. This third combined nitrogen-phosphorus removal system was operated from May, 1984, through July, 1985.

One-Stage Nitrifying Activated Sludge System

The one-stage system is designed to accomplish both carbonaceous removal and nitrification in the same reactor. The experimental bench-scale pilot plant used in this investigation is diagrammed in Figure 2. This was a plexiglass reactor with internal recycle of biological solids. The aeration and settling chambers were contained in the same reactor and separated by an adjustable plexiglass baffle. Compressed air, which had been filtered and saturated with water, was supplied to the reactor through porous diffusers. The compressed air provided oxygen supply to the biological solids, mixing and "suction" to recycle the settled biological solids from the settling compartment into the aeration chamber.

This system was seeded with heterotrophic and autotrophic microorganisms brought from the Tulsa activated sludge wastewater treatment plant. Operation under continuous flow conditions was accomplished by pumping the feed solution to the aeration chamber of the reactor. The total volume of the reactor was four liters (approximately three liters aeration chamber and one liter settling chamber). A finger pump from Sigma-motors provided a continuous flow of wastewater to the system at a pumping rate of 10.0 mℓ/min (14.4 lit/day). This feed rate provided an overall hydraulic detention time of 6.6 hours with 5.0 hours of aeration tank hydraulic detention time. The temperature of the reactor varied between 21 and 30°C. The feed line was disinfected by pumping a 1 percent solution of clorox and distilled water to prevent the growth in the feed

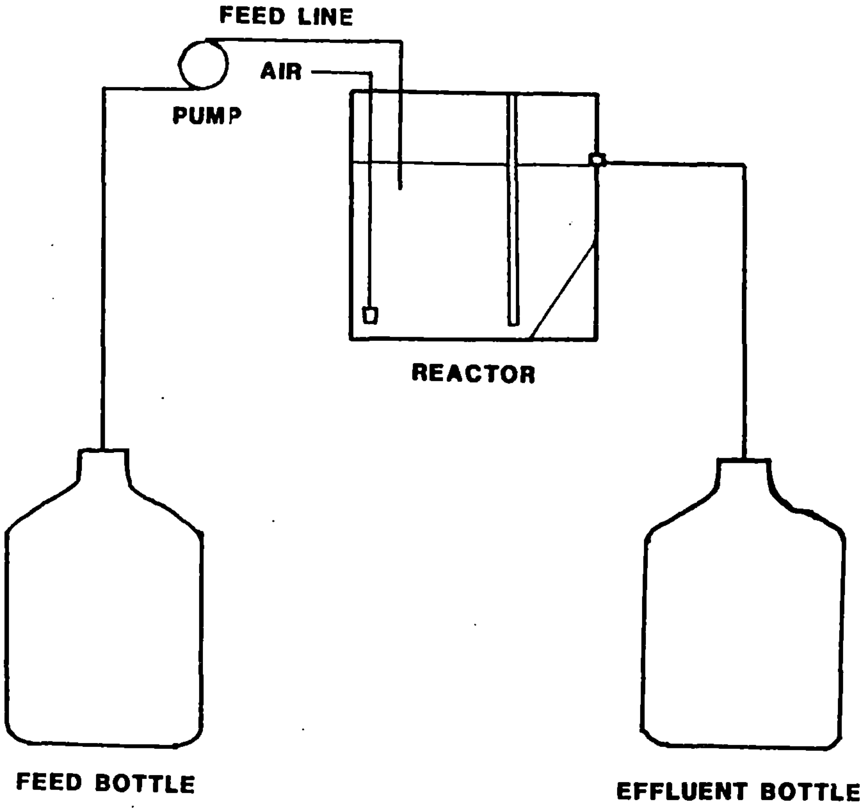


Figure 2. Diagram of Experimental One-Stage Nitrifying System

line. The effluent flowed by gravity from the settling compartment to the holding tank where it was collected.

Prior to sampling, the settling chamber outlet was closed, the feed flow stopped, and the plexiglass baffle separating the aeration and settling chambers was pulled out, allowing the biological solids in both compartments to mix thoroughly. A sample of mixed liquor was then removed from the reactor for biological solids determination. Also, while the baffle was pulled out, a predetermined amount of biological solids was wasted from the system. The baffle was immediately replaced, the settling tank outlet opened, and feeding resumed. Samples were also taken from the feed solution for analysis of BOD, COD, ammonia-nitrogen, nitrate-nitrogen, and ortho-phosphorus. Portions of the effluent from the system were collected for biological solids analysis, measurement of BOD, COD, ammonia-nitrogen, nitrate-nitrogen, and ortho-phosphorus. The pH was monitored constantly with a pH meter. The BOD/COD:NH_3-N ratios of the feed were closely monitored throughout the study.

Three-Stage Nitrifying-Denitrifying System

This three-stage system is designed to accomplish both carbonaceous removal and nitrogen removal in three separate reactors in series with internal clarifiers in each reactor. The experimental bench-scale pilot plants used in this investigation are diagrammed in Figure 3. The reactors were essentially the same as the one described in the one-stage nitrifying system.

The total volume of each of the three reactors used in this system was essentially the same as the reactor used in the one-stage nitrifying system. The feed pump was common for both the three-stage nitrifying-

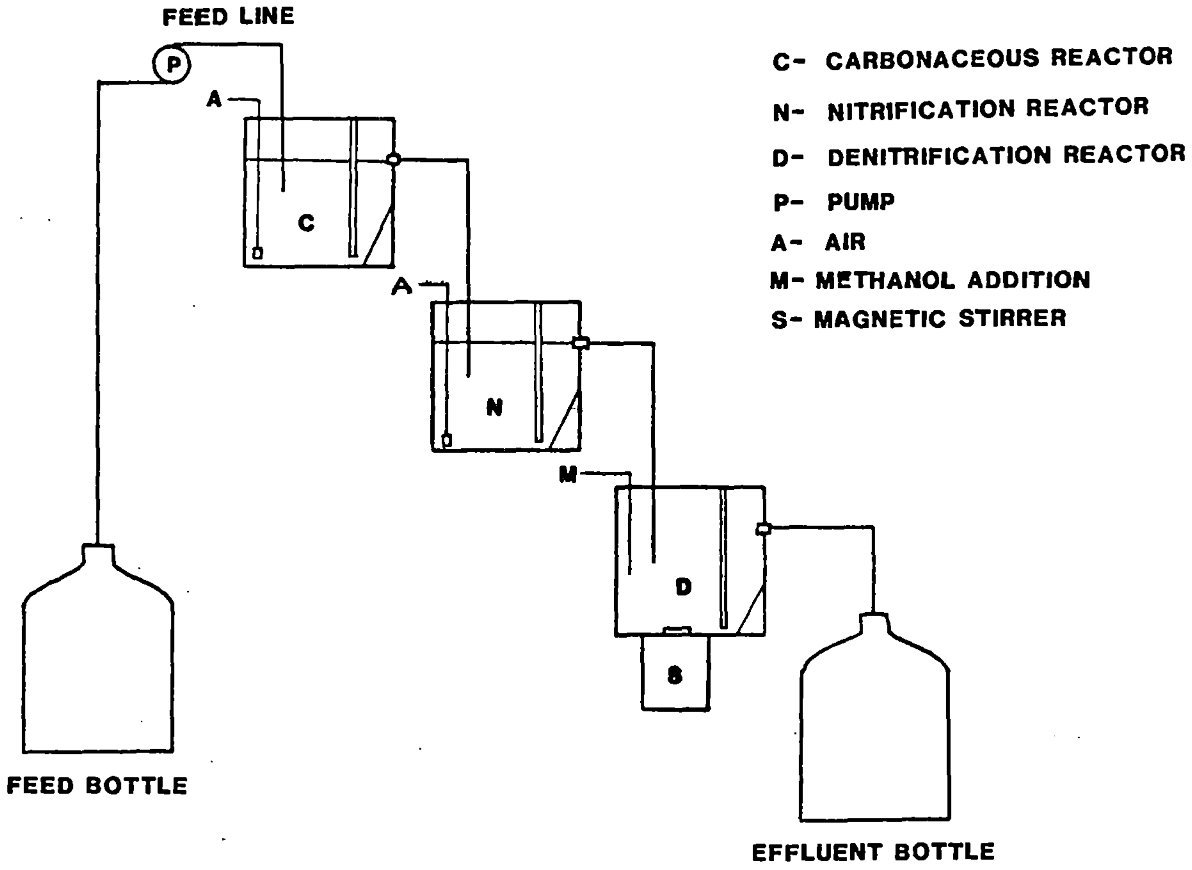


Figure 3. Diagram of Experimental Three-Stage Nitrifying-Denitrifying System

denitrifying system and the one-stage nitrifying system by using two feed lines from the same pump. The flow rate for the three-stage system was maintained at 10 mℓ/min (14.4 ℓ/day).

The feed was pumped into the first carbonaceous removal reactor. This reactor was designed to remove only organics. Air was supplied to this reactor through diffusers. The effluent flowed by gravity from the settling compartment of this first reactor to the aeration chamber of the second reactor. This second reactor was the nitrification system which biologically converted (oxidized) the ammonia-nitrogen to nitrate-nitrogen. The volume of the second reactor was the same as the first reactor and was also provided with diffused aeration. The ammonia-nitrogen remaining in the effluent served as the energy source for the microorganisms contained in the second reactor. The feed rate provided approximately the same hydraulic detention time as the first reactor. Effluent from the settling compartment of the second reactor flowed by gravity to the mixing chamber of the third reactor. This third reactor was the denitrification system (anoxic), which biologically converts nitrate-nitrogen into nitrogen gas. Mixing of solids for this reactor was provided by using a magnetic stirrer. This reactor was also divided into a mixing chamber and a settling chamber like the other two reactors. Diluted methanol was continuously pumped by a finger pump into the mixing chamber of the third reactor as an external carbon source (external electron donor) for denitrification to occur. The volume of third reactor was also the same as the other two reactors, with approximately the same hydraulic detention time. Effluent from this system flowed by gravity from the settling chamber to a holding tank where it was collected.

The operational procedure for the three-stage nitrifying-denitrifying system again involved wasting of biological solids from each reactor in order to maintain the desired sludge retention times. The same procedure for solids wasting as described for the one-stage system was again used, except the settled effluent from sludge wasting was added back to the respective reactors in order to maintain approximately the same hydraulic detention times. This was never a problem, because of the good settling characteristics of the sludge in all three reactors. The samples were collected from each reactor for analyses such as biological solids, BOD, COD, ammonia-nitrogen, nitrite-nitrogen, nitrate-nitrogen, and ortho-phosphorus.

The first reactor was operated at a fairly high food-to-microorganism ratio and low sludge retention time, in order to not allow this reactor to nitrify. This condition was maintained in the first reactor during the entire operation of the three-stage system. The other two nitrification and denitrification reactors were operated at different sludge retention times in order to determine the effect of SRT or food to microorganisms ratios upon the degree of nitrification and denitrification achievable by the system. The pH and temperature were monitored closely in each reactor throughout the study.

Combined Biological Carbon-Nitrogen-Phosphorus Removal System

This system is designed to accomplish carbonaceous removal, nitrogen removal, and phosphorus removal by employing three reactors in series. The experimental bench-scale pilot plant used in this investigation is diagrammed in Figure 4. These reactors were made of plexiglass with

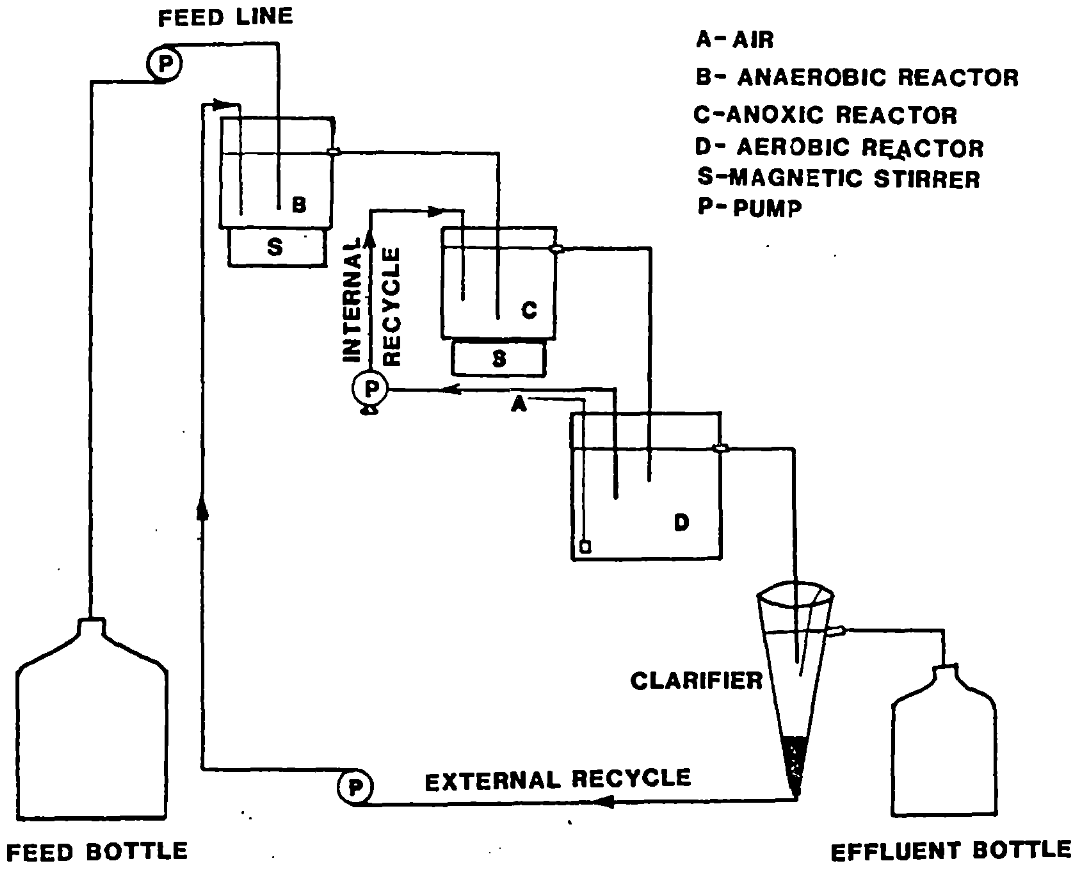


Figure 4. Diagram of Experimental Combined Biological Nitrogen-Phosphorus Removal System

only mixing chambers. Operation under continuous flow conditions was accomplished by pumping the feed solution to the first anaerobic reactor. The volume of this reactor was 1.38 liters. The mixing of solids for this anaerobic reactor was provided by a magnetic stirrer. A finger pump from Sigma-motors provided a continuous flow of wastewater to the system at a pumping rate of 12 mℓ/min (17.28 lit/day). This feed rate provided a hydraulic detention time of approximately 1.9 hours, based on forward flow, to the first anaerobic reactor. This anaerobic reactor was tightly closed in order to prevent the entry of air. The mixed liquor suspended solids flowed by gravity from the first (anaerobic) reactor to the second (anoxic) reactor.

The second anoxic reactor was also closed tightly and used for denitrification. The volume of this reactor was 2.21 liters. The feed rate provided a hydraulic detention time of approximately 3.0 hours, based on forward flow, for the second anoxic (denitrification) reactor. For this reactor mixing of solids was also provided by a magnetic stirrer. To achieve denitrification the nitrified sludge was recycled from the third (aerobic) reactor back to the second (anoxic) reactor at internal recycle ratios of 5:1 to 6:1 based on the forward flow of 12 mℓ/min. The remaining organic matter from the effluent of the first reactor served as an electron donor for denitrification in the anoxic reactor. Therefore, addition of external carbon source was not required for this system. The mixed liquor suspended solids flowed by gravity from the second (anoxic) reactor to the third (aerobic) reactor.

The third aerobic reactor was used for three purposes: (1) to remove any remaining biodegradable organic matter from the second (anoxic) reactor, (2) to convert the ammonia-nitrogen in the nitrate-nitrogen, and (3) to remove phosphorus by Luxury uptake mechanism under aerobic conditions. Since nitrification (NH_3-N removal) is the controlling design factor in this combined biological carbon-nitrogen-phosphorus removal system, the third (aerobic) reactor was designed with a higher detention time. The volume of the third reactor was 4.33 liters. The feed rate provided a hydraulic detention time of approximately 6.0 hours, based on forward flow, for the third reactor. The compressed air through porous diffusers provided oxygen supply and mixing to the biological solids. Finally, the sludge or mixed liquor flowed by gravity from the third (aerobic) reactor to the final circular clarifier.

The settled biological solids were recycled from the clarifier back to the anaerobic reactor in order to maintain the required SRT (or food-to-microorganism ratio) and to create a proper environment for the microorganisms to release the phosphorus from the cells into the liquid. The external recycle rate of settled sludge varied for different SRTs in order to maintain a certain minimum sludge blanket level in the clarifier. The clarified effluent flowed by gravity to a holding tank where it was collected.

Prior to sampling the feed flow was stopped. A sample of mixed liquor was removed from each of the three reactors for biological solids determination. A predetermined amount of biological solids was wasted from the third (aerobic) reactor in order to maintain the required SRT based on the total volume of all three reactors. This sludge wastage can be done from the clarifier also. Samples were also taken from the feed solution for analysis of BOD, COD, NH_3-N, TKN, ortho-phosphorus, and total phosphorus. Samples were collected from the anaerobic and anoxic reactors for analysis such as BOD, COD, NH_3-N, NO_3-N, and ortho-phosphorus. In order to collect samples from the first two reactors, the magnetic stirrers were turned off. Sufficient time was allowed for the sludge to settle in these reactors. Then the required quantity of clear liquid was syphoned out from these first two reactors. Normally this was done within five to ten minutes. Portions of the final effluent from the system was collected for biological solids analysis, measurement of BOD, COD, NH_3-N, NO_3-N, TKN, ortho-P, and total-P. Samples were also collected from the third (aerobic) reactor for the analysis of ortho-phosphorus. This was done in order to compare the ortho-phosphorus concentration in the aerobic reactor and in the final effluent. This comparison was basically a check for the release of phosphorus in the clarifier if dissolved oxygen reduces to near zero. The pH and temperatures were monitored closely in all three reactors throughout the study. This combined biological nitrogen-phosphorus removal system was operated at different sludge retention times based on total volume of all the reactors. The organics/nitrogen/phosphorus ratios were monitored very closely throughout the entire experimental program.

Method of Data Analysis

All of the three systems discussed earlier were operated at different sludge retention times or different growth rates. The growth rate was controlled by the daily wasting of sludge. The growth rate is defined as

$$\mu_n = \frac{1}{SRT} = \frac{F_w X_r + (F - F_w) X_e}{VX} \tag{3.1}$$

and the sludge waste flow rate is

$$F_w = \frac{\mu_n VX - FX_e}{X_r - X_e} \qquad (3.2)$$

where

F_w = waste sludge flow rate;

μ_n = observed growth rate;

V = volume of reactor;

F = influent flow rate;

X_e = effluent suspended solids;

X_r = waste solids concentration; and

X = aeration tank solids.

For the combined biological nitrogen-phosphorus removal system, the sludge retention time was controlled based on total volume of the system. Removal efficiency or treatment purification was calculated according to the following expression:

$$E = \frac{100\ (S_i - S_e)}{S_i} \qquad (3.3)$$

where

E = removal efficiency, percent;

S_i = influent substrate concentration, mg/ℓ; and

S_e = effluent substrate concentration, mg/ℓ.

The biokinetic constants U_{max} and K_B were calculated using the Kincannon and Stover model for BOD, COD, NH_3-N, and NO_3-N removal for all three systems.

Analytical Procedures

The analytical methods and techniques employed during this research were the same for all three continuous flow reactor systems and are described below.

Biological Solids

Suspended solids were determined by filtering the sample through a preweighed glass microfiber filter (Whatman 934-AH, 4.25 cm diameter), drying it in an oven at 103°C for at least one hour, and reweighing. Following suspended solids determinations, the filter was combusted in a muffle furnace at 550°C for 20 minutes and then reweighed in order to obtain volatile solids.

pH

The pH determinations were done by using an Orion Research Model 601A/digital ionalyzer pH meter with an Orion Combination pH 91-05 electrode.

Dissolved Oxygen Concentration

The dissolved oxygen concentration was monitored using an Orion Research Model 98-08-00 probe.

Biochemical Oxygen Demand (BOD)

A standard methods technique with an Orion Research DO probe was used for the measurement of BOD (125).

Chemical Oxygen Demand (COD)

The COD of samples was determined by using Hach Chemicals (Hach Chemical Company, Ames, Iowa) (126). The Hach Reactor Digestion COD

Method used is a semimicro adaptation of the Standard Methods (125) test. A 2 mℓ sample size, rather than a 20 mℓ sample, allows digestion in screw-cap test tubes instead of Erlenmeyer flasks and condensers. Samples and blanks are digested at 150°C in a dry bath heater, the COD reactor. Digestion reagents--sulfuric acid, potassium dichromate, silver sulfate catalyst, and mercuric sulfate to inhibit chloride--remain the same as the standard test, although quantities are reduced.

Ammonia-Nitrogen, Nitrate-Nitrogen, and TKN

All of the nitrogen analyses were determined by using Hach chemicals (Hach Chemical Company, Ames, Iowa) (126). The Nessler method was used for ammonia-nitrogen. The method of analysis used for the nitrate-nitrogen in the high range test is a modification of the cadmium reduction method using gentisic acid in place of 1-naphthylamine. All necessary reagents for this test have been combined into a single stable powder called NitraVer® 5 Nitrate Reagent. The digestion and modification of the Nessler method was used for the analysis of TKN.

Ortho-Phosphorus and Total Phosphorus

Hach chemicals (Hach Chemical Company, Ames, Iowa) were used for the analysis of phosphorus (126). The amino acid method was used for the ortho-phosphorus analysis. In a highly acidic solution, ammonium molybdate reacts to form a heteropoly acid, molybdophosphroic acid. This is reduced by the amino acid reagent to the intensely colored complex, molybdenum blue. The sulfuric and digestion followed by the amino acid method was used for the total phosphorus analysis.

Phosphorus Content of Sludge

Hach chemicals (Hach Chemical Company, Ames, Iowa) were used for the analysis of sludge phosphorus content (126). The acid digestion followed by the amino acid method was used for the phosphorus content of sludge.

Settling Test

The settling tests were performed by transferring one liter of mixed liquor from the reactor to a 1000 mℓ graduated cylinder and reading the sludge blanket height at time intervals for one hour.

CHAPTER IV

RESULTS

The bench-scale pilot studies were conducted in two phases for the removal of carbon, nitrogen, and phosphorus. The first phase included the operation of a continuous flow one-stage nitrifying system and a three-stage nitrifying-denitrifying system. These systems were started on March 20, 1983, and operated side by side with the same flow rate for different sludge retention times. The second phase was started on May 25, 1984, which included the combined biological nitrogen-phosphorus removal system. In this system phosphorus removal was optimized in addition to carbon and nitrogen removal. This bench-scale pilot study ended July 15, 1985.

The experimental results are presented in three major sections dealing with (1) a one-stage nitrifying system, (2) a three-stage nitrifying-denitrifying system, and (3) a combined biological nitrogen-phosphorus removal system. The operational performance of each system is presented for such parameters as (1) the influent characteristics, which include concentrations of feed BOD_5, COD, NH_3-N, and ortho-P; (2) biological solids concentration in mg/ℓ; and (3) effluent characteristics which include effluent BOD_5, COD, NH_3-N, NO_3-N, phosphorus, and suspended solids concentrations. All of these data were collected under steady state operating conditions for different sludge retention times (SRT's).

One-Stage Nitrifying System

The one-stage nitrifying system was operated at different sludge retention times (10, 5, 3, 2, and 1 days) or in other words different food-to-microorganisms ratios (F/M). The results are shown in a tabular form in Tables I through V. Food-to-microorganism ratios (F/M) were calculated based on both soluble BOD_5 and soluble COD to mixed liquor volatile suspended solids in the reactor. For each parameter, the operating range and average values are given in order to have a better understanding of the treatment performance of the system. The biokinetic constants were obtained using the Kincannon and Stover model for BOD, COD, and NH_3-N removal based on the total volatile suspended solids (carbonaceous solids and nitrifying solids). In general, the system was operated at 10, 5, 3, 2, and 1 day SRT's with the average mixed liquor volatile suspended solids concentrations of 1625, 1243, 1030, 768, and 496 mg/ℓ, respectively. The effluent suspended solids concentration varied from 0 to 6 mg/ℓ with the average being 4 mg/ℓ for all SRT's except for 1 day when it averaged 6 mg/ℓ. The pH of the influent (feed) varied between 6.5 and 7.1 throughout the study. The reactor pH varied from 7.4 to 7.6 for all conditions except a 1 day SRT when it varied from 6.9 to 7.3. The reactor temperature varied between 21 and 30°C throughout the study. The performance of this system for BOD, COD, and NH_3-N removal (conversion of NH_3-N into NO_3-N) are presented individually as follows.

BOD Removal

The influent soluble BOD_5 concentration varied from 87 to 130 mg/ℓ for all operating conditions. The average influent soluble BOD_5 concen-

TABLE I

SUMMARY OF OPERATIONAL CHARACTERISTICS OF ONE-STAGE NITRIFYING ACTIVATED SLUDGE SYSTEM AT 10-DAY SRT

Description	No. of Data Points	Influent		Reactor		Effluent	
		Range	Avg.	Range	Avg.	Range	Avg.
TSS*	14	45-70	55	1740-1950	1877	1.0-6.0	2.5
VSS*	14	20-35	26	1500-1650	1625	0-5.0	2.0
BOD_5^*	14	95-120	107	---	---	1.0-5.0	2.5
COD*	8	200-290	275	---	---	8-32	23.0
NH_3-N*	14	22-36	28	---	---	0.2-0.7	0.4
NO_3-N*	14	0	0	---	---	15-28	21.0
Ortho-P*	5	4-8	7.0	---	---	5-8	7.0
pH	14	6.5-7.0		7.4-7.6		---	---
Temp. °C	14	23-28		24-29		---	---
BOD_5/NH_3-N	14	2.9-4.8	3.8	---	---	---	---
COD/NH_3-N	7	8.0-13.0	9.5	---	---	---	---
F/M (MLVSS) Sol. BOD_5	14			0.20-0.34	0.29		
F/M (MLVSS) Sol. COD				0.60-1.00	0.79		
Sol. NH_3-N				0.06-0.10	0.08		

*Expressed in mg/ℓ.

Volume of the reactor = 3.0 ℓ.

Inflow = 14.4 ℓ/d.

DO range = 2.0-3.0 mg/ℓ.

TABLE II

SUMMARY OF OPERATIONAL CHARACTERISTICS OF ONE-STAGE NITRIFYING ACTIVATED SLUDGE SYSTEM AT 5-DAY SRT

Description	No. of Data Points	Influent Range	Influent Avg.	Reactor Range	Reactor Avg.	Effluent Range	Effluent Avg.
TSS*	14	28-50	45.0	1250-1515	1344	1.0-5.0	3.0
VSS*	14	15-20	18.0	1200-1300	1243	1.0-5.0	3.0
BOD_5^*	14	87-130	102.0	---	---	2.5-5.0	3.0
COD*	11	240-340	273.0	---	---	8.0-29.0	20.0
NH_3-N*	14	24-36	30.0	---	---	0.3-0.9	0.5
NO_3-N*	14	0	0	---	---	18-25	21.7
Ortho-P*	8	6-9	7.3	---	---	5.5-9.0	7.3
pH	14	6.6-7.1		7.3-7.5		---	---
Temp. °C	14	25-29	---	27.0-30.0		---	---
BOD_5/NH_3-N	14	2.7-4.6	3.4				
COD/NH_3-N	11	7.6-11.6	9.2				
F/M (MLVSS) Sol. BOD_5	14			0.32-0.45	0.40		
Sol. COD	11			0.95-1.20	1.04		
Sol. NH_3-N	14			0.09-0.14	0.12		

*Expressed in mg/ℓ.

Volume of the reactor = 3.0 ℓ.

Inflow = 14.4 ℓ/d.

DO range = 2.5-3.5 mg/ℓ.

TABLE III

SUMMARY OF OPERATIONAL CHARACTERISTICS OF ONE-STAGE NITRIFYING ACTIVATED SLUDGE SYSTEM AT 3-DAY SRT

Description		No. of Data Points	Influent		Reactor		Effluent	
			Range	Avg.	Range	Avg.	Range	Avg.
TSS*		11	25-55	40.0	1020-1112	1063	1.0-6.0	5.0
VSS*		11	15-40	30.0	988-1080	1030	1.0-6.0	5.0
BOD_5^*		11	93-116	107	---	---	2.0-4.5	3.2
COD*		7	220-297	255	---	---	18-46	29.0
NH_3-N*		11	24.6-34.5	29.7	---	---	1.0-2.5	1.7
NO_3-N*		11	0	0	---	---	18-24	20.6
Ortho-P*		4	9.0-12.0	11.0	---	---	9-11	10.5
pH		11	6.9-7.2		7.4-7.6			
Temp. °C		11	21-24		23-25			
BOD_5/NH_3-N		11	2.7-4.2	3.7				
COD/NH_3-N		7	7.5-10.9	8.3				
F/M (MLVSS)	Sol. BOD_5	11			0.43-0.55	0.49		
	Sol. COD	7			1.00-1.40	1.17		
	Sol. NH_3-N	11			0.11-0.19	0.14		

*Expressed in mg/ℓ.

Volume of the reactor = 3.0 ℓ.

Inflow = 14.4 ℓ/d.

DO range = 2.5-3.5 mg/ℓ.

TABLE IV

SUMMARY OF OPERATIONAL CHARACTERISTICS OF ONE-STAGE NITRIFYING ACTIVATED SLUDGE SYSTEM AT 2-DAY SRT

Description		No. of Data Points	Influent		Reactor		Effluent	
			Range	Avg.	Range	Avg.	Range	Avg.
TSS*		12	35-57	38.0	742-898	800	2.0-6.0	5.0
VSS*		12	23-35	27.0	720-862	768	1.5-6.0	5.0
BOD_5^*		12	99-121	111	---	---	4.0-7.0	5.5
COD*		6	236-296	259	---	---	38-44	40.0
NH_3-N*		12	27.5-36.0	30.9	---	---	3.2-5.8	4.5
NO_3-N*		12	0	0	---	---	14.6-20.6	17
Ortho-P*		4	9.2-12.0	10.5	---	---	7.5-11.2	9.2
pH		12	6.5-6.9		7.4-7.6		---	---
Temp. °C		12	18-21		21-24			
BOD_5/NH_3-N		12	3.1-4.3	3.6				
COD/NH_3-N		6	6.6-10.3	8.7				
F/M (MLVSS)	Sol. BOD_5	11			0.63-0.81	0.69		
	Sol. COD	6			1.36-1.97	1.61		
	Sol. NH_3-N				0.16-0.22	0.19		

*Expressed in mg/ℓ.

Volume of the reactor = 3.0 ℓ.

Inflow = 14.4 ℓ/d.

DO range = 3.0-4.0 mg/ℓ.

TABLE V

SUMMARY OF OPERATIONAL CHARACTERISTICS OF ONE-STAGE NITRIFYING ACTIVATED SLUDGE SYSTEM AT 1-DAY SRT

Description		No. of Data Points	Influent		Reactor		Effluent	
			Range	Avg.	Range	Avg.	Range	Avg.
TSS*		14	25-50	36.0	520-578	545	3-11	7.0
VSS*		14	20-40	29.0	480-530	496	2-10	6.0
BOD$_5^*$		14	94-177	110	---	---	8-16	10.5
COD*		14	220-380	270	---	---	40-82	52.0
NH_3-N*		14	22-36	28.0	---	---	16-27	22.0
NO_3-N*		14	0	0	---	---	0	0
Ortho-P*		5	4-8	7.0	---	---	---	---
pH		14	6.5-7.0	---	6.9-7.3	---	---	---
Temp. °C		14	23-28	---	24-29	---	---	---
BOD_5/NH_3-N		14	2.9-4.8	3.8	---	---	---	---
COD/NH_3-N		7	8-13	9.5	---	---	---	---
F/M (MLVSS)	Sol. BOD_5	14			0.90-1.57	1.04		
	Sol. COD	7			2.20-3.10	2.75		
	Sol. NH_3-N	14			0.23-0.32	0.27		

*Expressed in mg/ℓ.

Volume of the reactor = 3.0 ℓ.

Inflow = 14.4 ℓ/d.

DO range = 3.0-4.0 mg/ℓ.

trations for 10, 5, 3, 2, and 1 day SRT's were 107, 102, 107, 111, and 110 mg/ℓ, respectively. The average effluent soluble BOD_5 concentrations for the above mentioned SRT's were 2.5, 3.0, 3.0, 5.5, and 10.5 mg/ℓ, respectively. These values are tabulated in Tables I through V. The reactor was operated at different F/M ratios in terms of soluble BOD_5. The average values of F/M at the different operational conditions were 0.286 (10 day SRT), 0.388 (5 day SRT), 0.490 (3 day SRT), 0.690 (2 day SRT), and 1.040 (1 day SRT). For all of these conditions, the BOD_5 to NH_3-N ratio varied from 3.40 to 3.75. This small variation was mainly due to the variation of soluble BOD_5 and NH_3-N in the municipal wastewater.

Figures 5 and 6 represent the soluble BOD_5 removal efficiency of the system with respect to F/M and SRT. More than 96.5 percent BOD removal was achieved up to the F/M value of 0.49 (3 day SRT). BOD removal declined for the F/M value of 0.69 (2 day SRT) and 1.04 (1 day SRT), as shown in Figures 5 and 6. In general, BOD removal was more than 90 percent throughout the entire operation of the one-stage nitrifying system. The BOD removal biokinetic constants were calculated using the Kincannon and Stover model for the particular BOD_5 to NH_3-N ratio ($\simeq$3.6). Figure 7 shows the substrate utilization (U) as a function of mass substrate loading (F/M) in terms of soluble BOD_5. The biokinetic constants U_{max} and K_B were obtained from the reciprocal plot of F/M and U (Figure 8). For BOD_5 to NH_3-N ratio of 3.6, U_{max} and K_B are 13.90 and 13.90, respectively, with the correlation coefficient of 0.999. Figure 9 shows the graphical determination of yield (Y_t) for the one-stage nitrifying system. From Figure 9, Y_t (yield coefficient) and K_d (decay coefficient) are

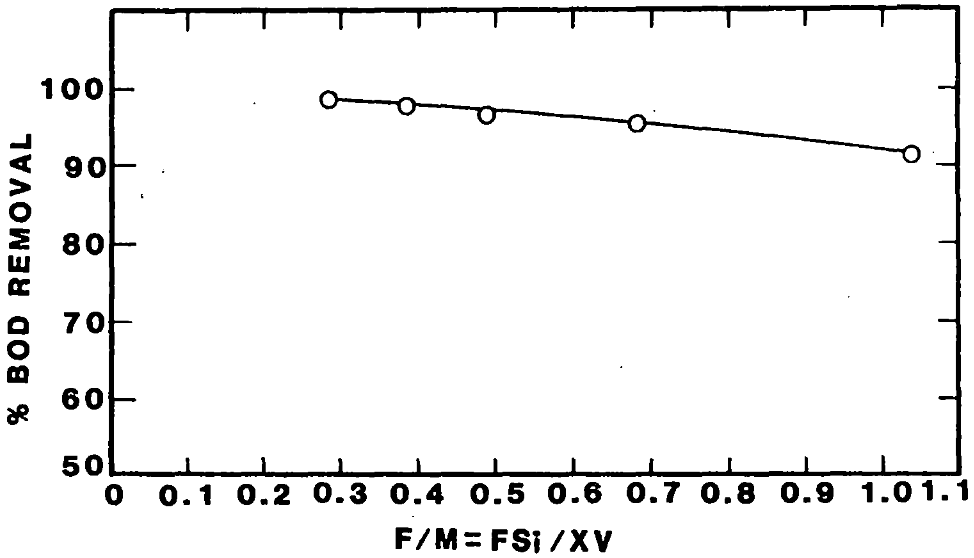


Figure 5. Percent BOD Removal as a Function of F/M for Nitrifying One-Stage System

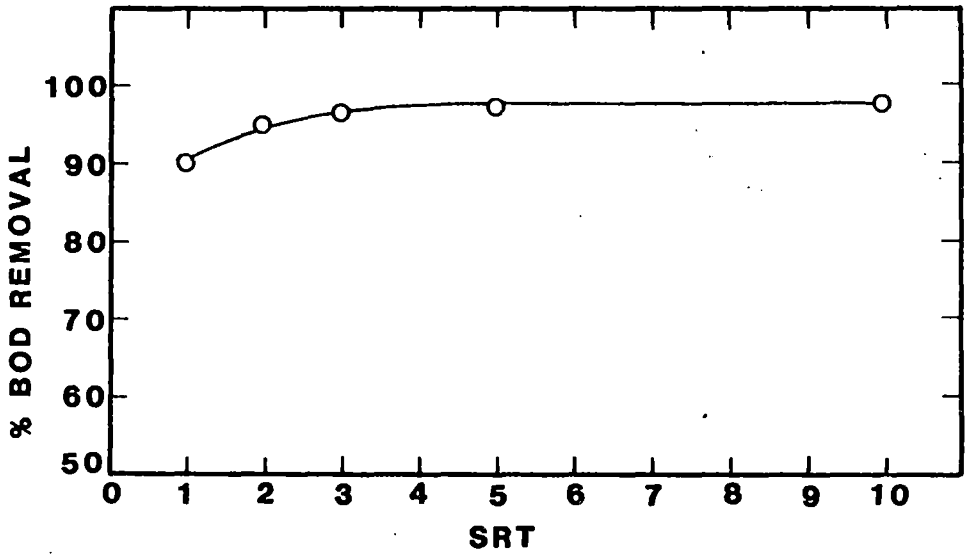


Figure 6. Percent BOD Removal as a Function of SRT for Nitrifying One-Stage System

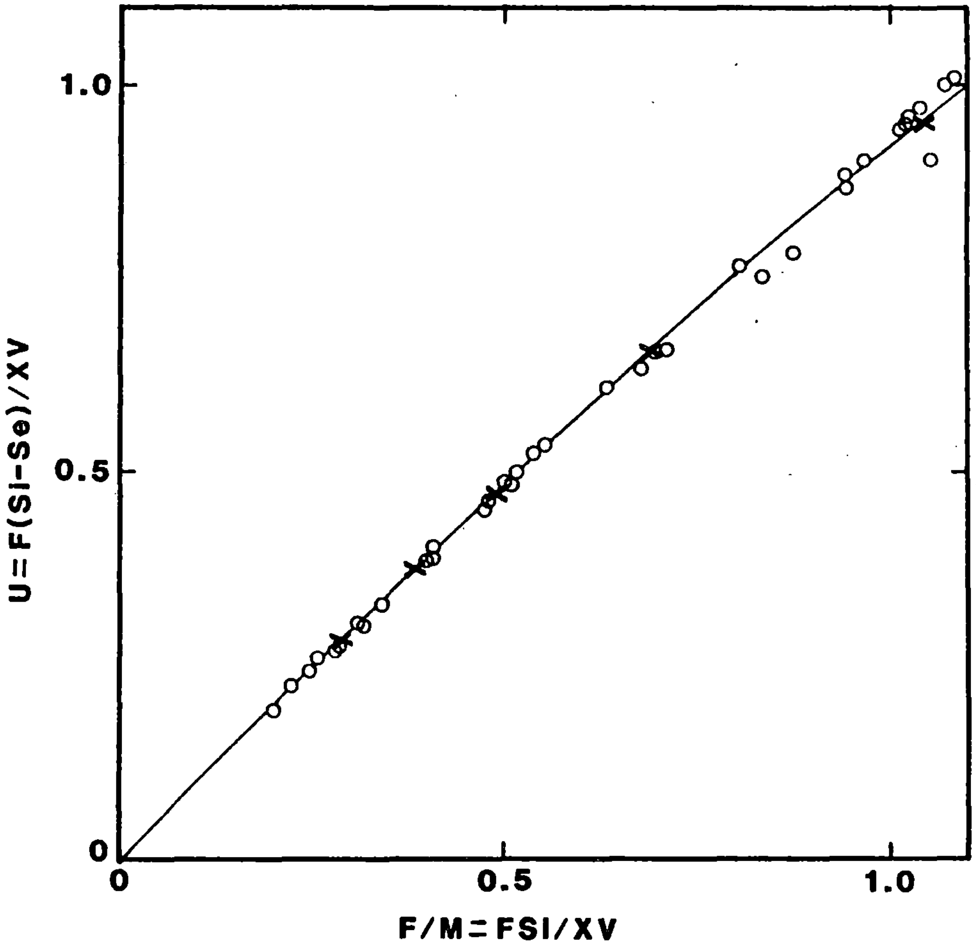


Figure 7. Substrate Utilization as a Function of Mass Substrate Loading in Terms of BOD_5 for Nitrifying One-Stage System

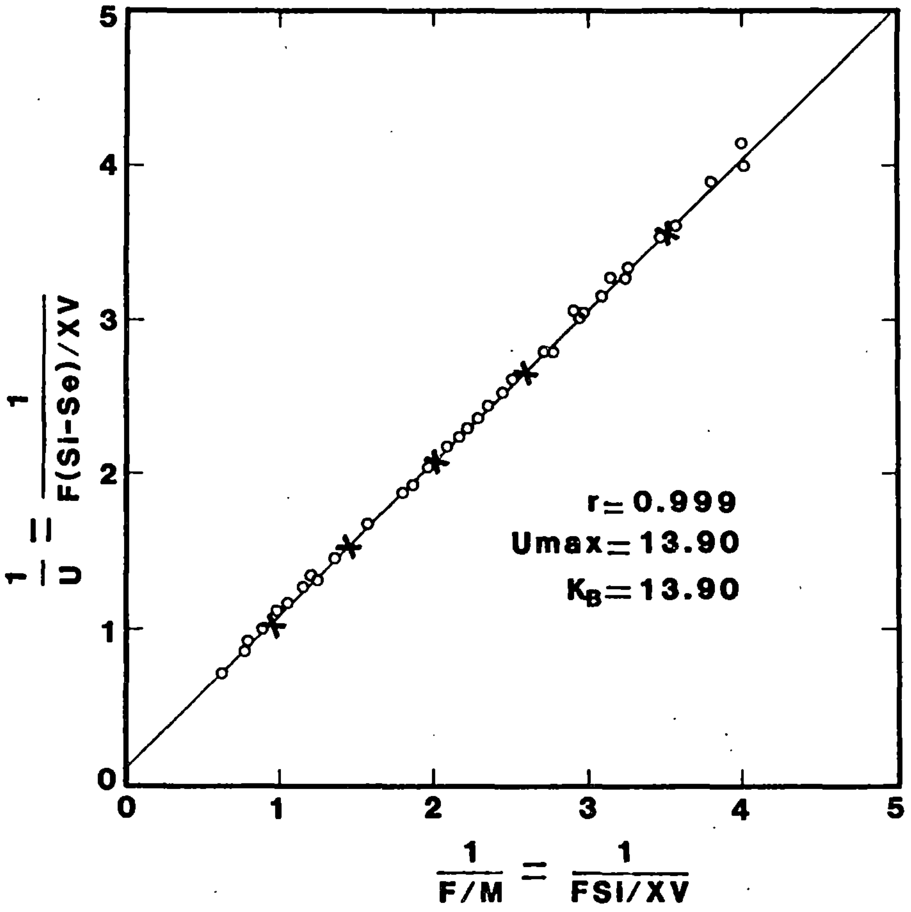


Figure 8. Graphical Determination of U_{max} and K_B in Terms of BOD_5, for Nitrifying One-Stage System

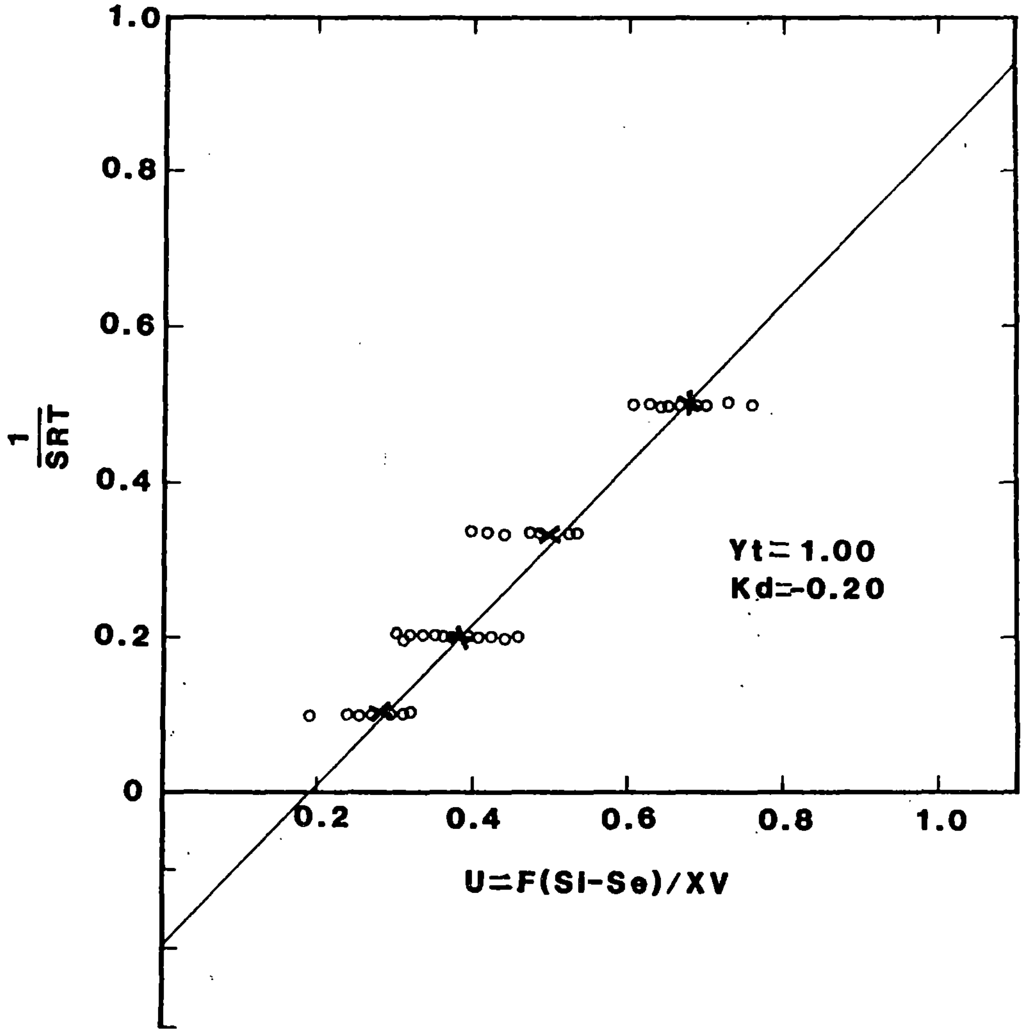


Figure 9. Graphical Determination of Y_t and K_d in Terms of BOD_5, for Nitrifying One-Stage System

1.00 and -0.20, respectively. These BOD removal kinetics are summarized in Table VI.

COD Removal

The influent soluble COD concentration for all operating conditions varied from 200 to 340 mg/ℓ. The average COD concentrations for 10, 5, 3, 2, and 1 day SRT's were 275, 273, 255, 259, and 270 mg/ℓ, respectively. The average effluent COD concentrations for these SRT's were 23, 20, 29, 40, and 52 mg/ℓ, respectively. All of these data are tabulated in Tables I through V. The average F/M values for the reactor in terms of COD, corresponding to the operated SRT's of 10, 5, 3, 2, and 1 day, are 0.787, 1.042, 1.170, 1.610, and 2.750, respectively. The COD to NH_3-N ratio averaged around 9.0 for all of these operating conditions.

COD removal of more than 90 percent was achieved for the F/M values below 1.0. For the F/M values of 1.2 and above, the removal started declining and reached 80 percent for the value of 2.75 (1 day SRT). These percent COD removals with respect to F/M and SRT's are shown in Figures 10 and 11, respectively. Figure 12 represents the F/M versus U (substrate utilization) in terms of COD. The COD removal biokinetic constants U_{max} and K_B were determined from Figure 13 by plotting 1/U versus 1/F/M. The values of U_{max} and K_B are 20.00 and 20.60, respectively. The yield coefficient (Y_t) and decay coefficient (K_d) were also calculated in terms of COD from Figure 14. The values of Y_t and K_d are 0.52 and -0.25, respectively. These biokinetic constants are presented in Table VI.

TABLE VI

SUMMARY OF BIOKINETIC CONSTANTS FOR NITRIFYING ONE-STAGE SYSTEM

Description	U_{max}	K_B	Y_t	$-K_d$
BOD	13.90	13.90	1.00	0.20
COD	20.00	20.60	0.52	0.25
NH_3-N	0.89	0.83	4.41	0.24

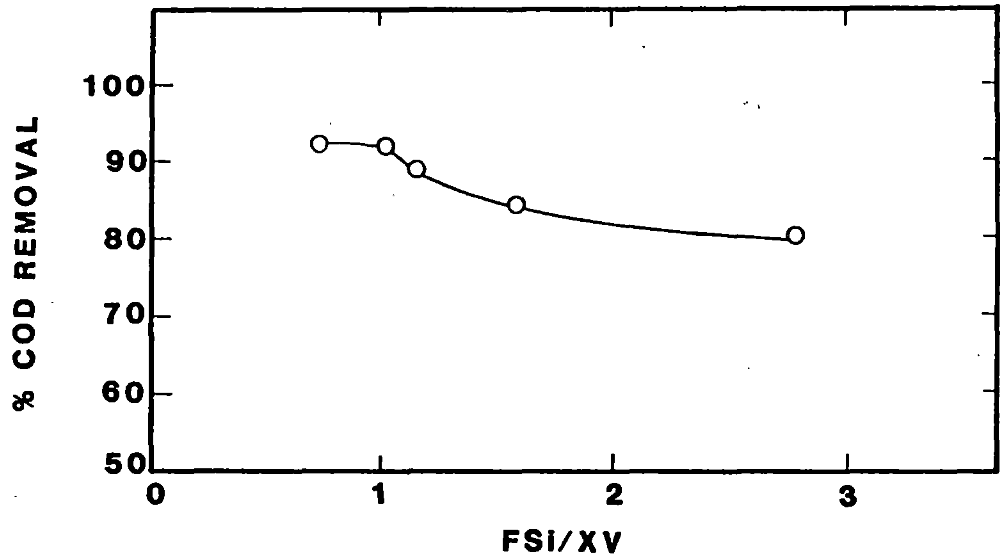


Figure 10. Percent COD Removal as a Function of F/M for Nitrifying One-Stage System

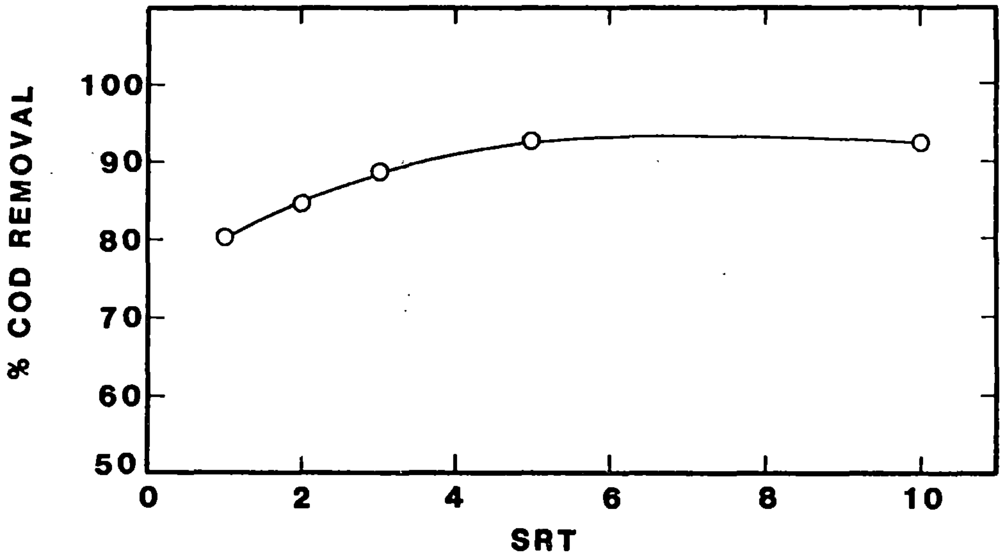


Figure 11. Percent COD Removal as a Function of SRT for Nitrifying One-Stage System

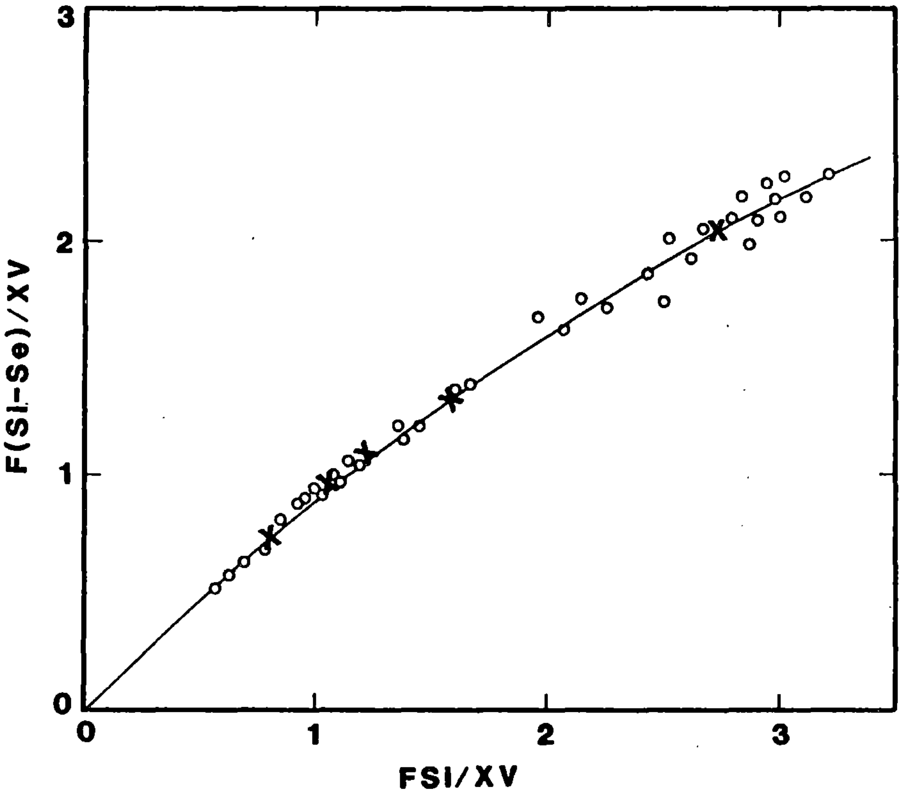


Figure 12. Substrate Utilization as a Function of Mass Substrate Loading in Terms of COD for Nitrifying One-Stage System

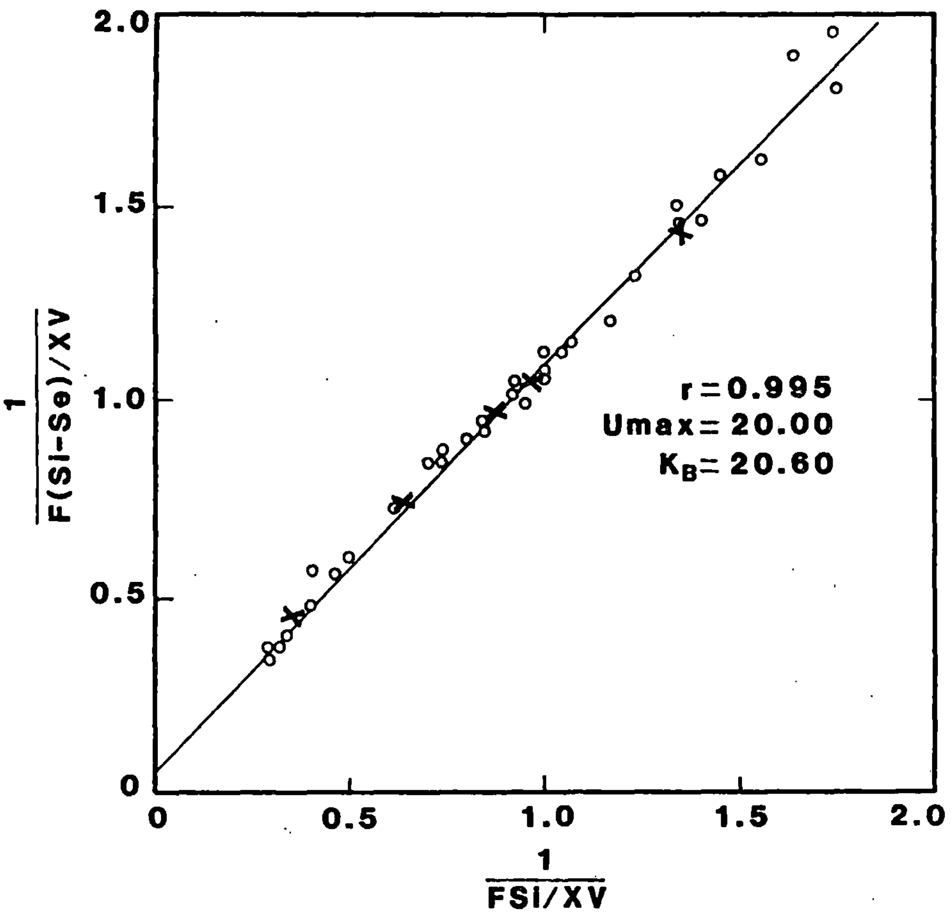


Figure 13. Graphical Determination of U_{max} and K_B in Terms of COD, for Nitrifying One-Stage System

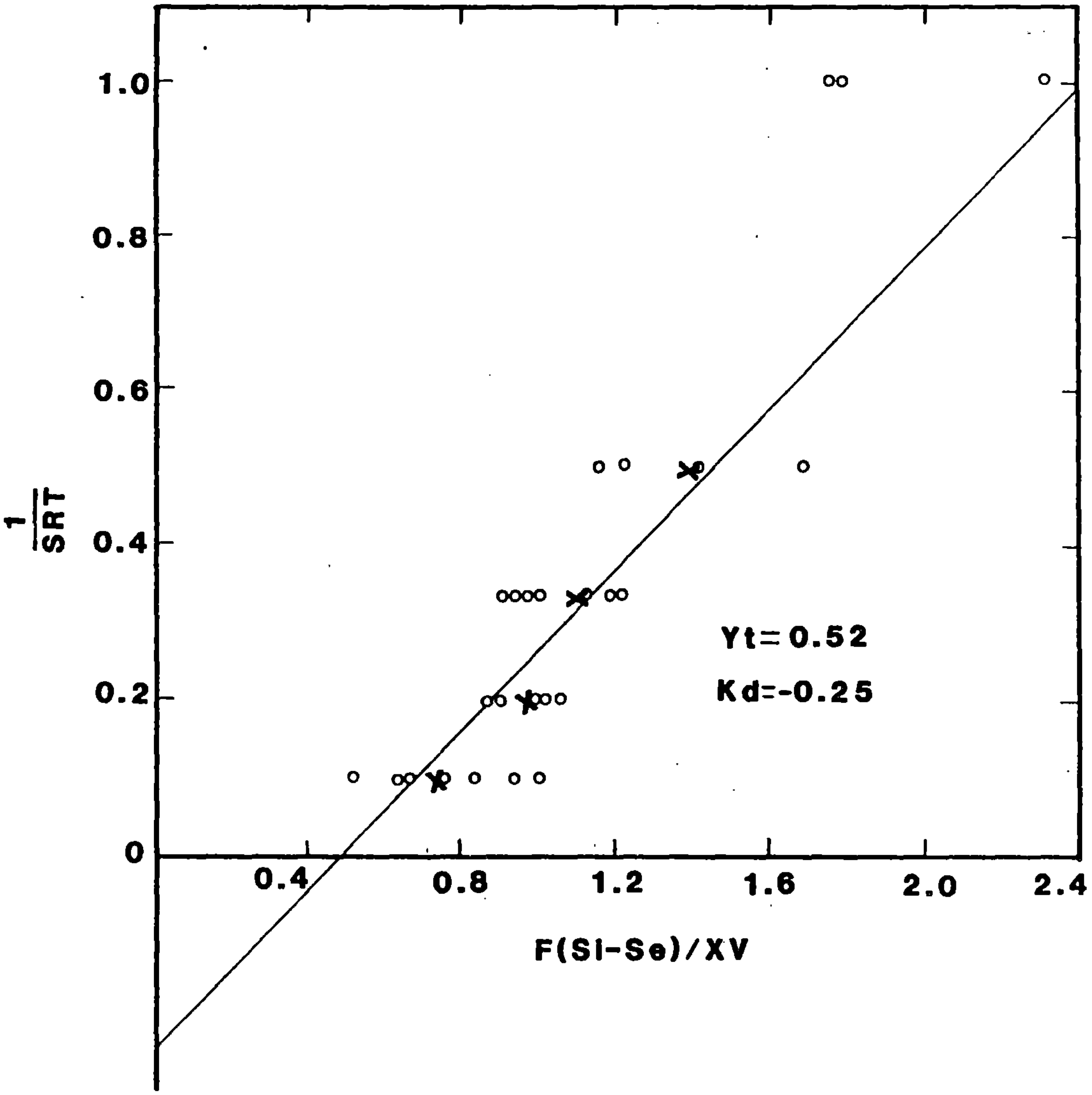


Figure 14. Graphical Determination of Y_t and K_d in Terms of COD, for Nitrifying One-Stage System

NH_3-N Removal (Nitrification)

The NH_3-N concentration in the influent (municipal wastewater) varied from 22.0 to 36.0 mg/ℓ. The average NH_3-N concentrations were 28.0, 30.0, 29.7, and 30.9 mg/ℓ for the operated conditions of 10, 5, 3, and 2 day SRT's. The average F/M values in terms of NH_3-N for the 10 day, 5 day, 3 day, and 2 day SRT's were 0.078, 0.115, 0.137, and 0.192, respectively. Almost complete nitrification was achieved for the F/M values of 0.078 (10 day SRT) and 0.115 (5 day SRT). For these two conditions, the average effluent NH_3-N concentrations were 0.4 and 0.5 mg/ℓ, respectively. For the F/M value of 0.137 (3 day SRT), the average effluent NH_3-N concentration was 1.73 mg/ℓ, whereas 4.5 mg/ℓ was observed for the F/M value of 0.192 (2 day SRT). This indicates that there is a decline in nitrification from the F/M values of 0.137 (3 day SRT) and above for the particular soluble BOD_5 to NH_3-N ratio of 3.70 or soluble COD to NH_3-N ratio of 9.00. The nitrification in the one-stage system completely stopped for the F/M value of 0.27 (1 day SRT). There was no NO_3-N observed in the influent. The effluent NO_3-N concentration varied based on the influent NH_3-N concentration, and the reactor operational conditions. The average effluent NO_3-N concentrations were 21.0, 21.7, 20.6, and 17.2 mg/ℓ for the F/M values of 0.078 (10 day SRT), 0.115 (5 day SRT), 0.137 (3 day SRT), and 0.192 (2 day SRT), respectively. All of these data are summarized in Tables I through V.

Figures 15 and 16 represent the percent NH_3-N removal with respect to F/M and SRT. It can be seen from these figures that for the F/M values of 0.078 (10 day SRT) and 0.115 (5 day SRT), NH_3-N removal was 99 percent. Then the removal started declining to 85 percent when the F/M

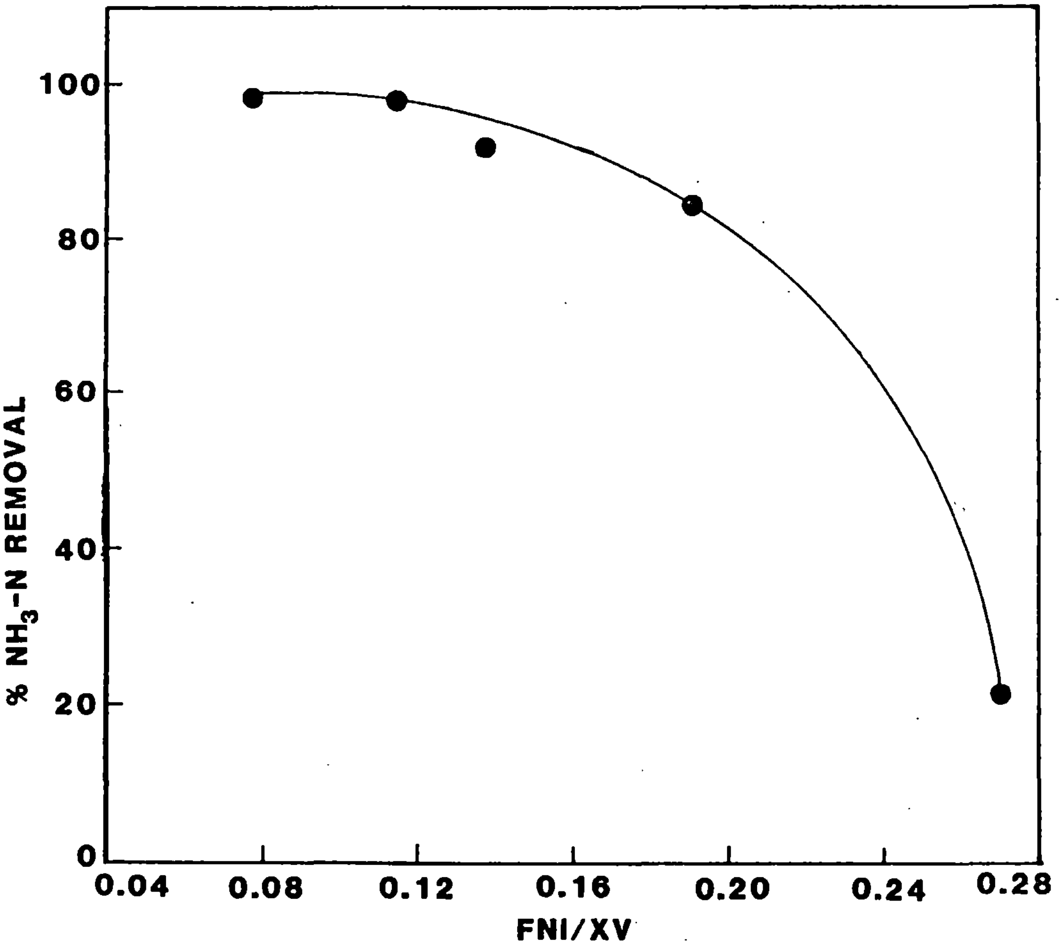


Figure 15. Percent NH_3-N Removal as a Function of F/M for Nitrifying One-Stage System

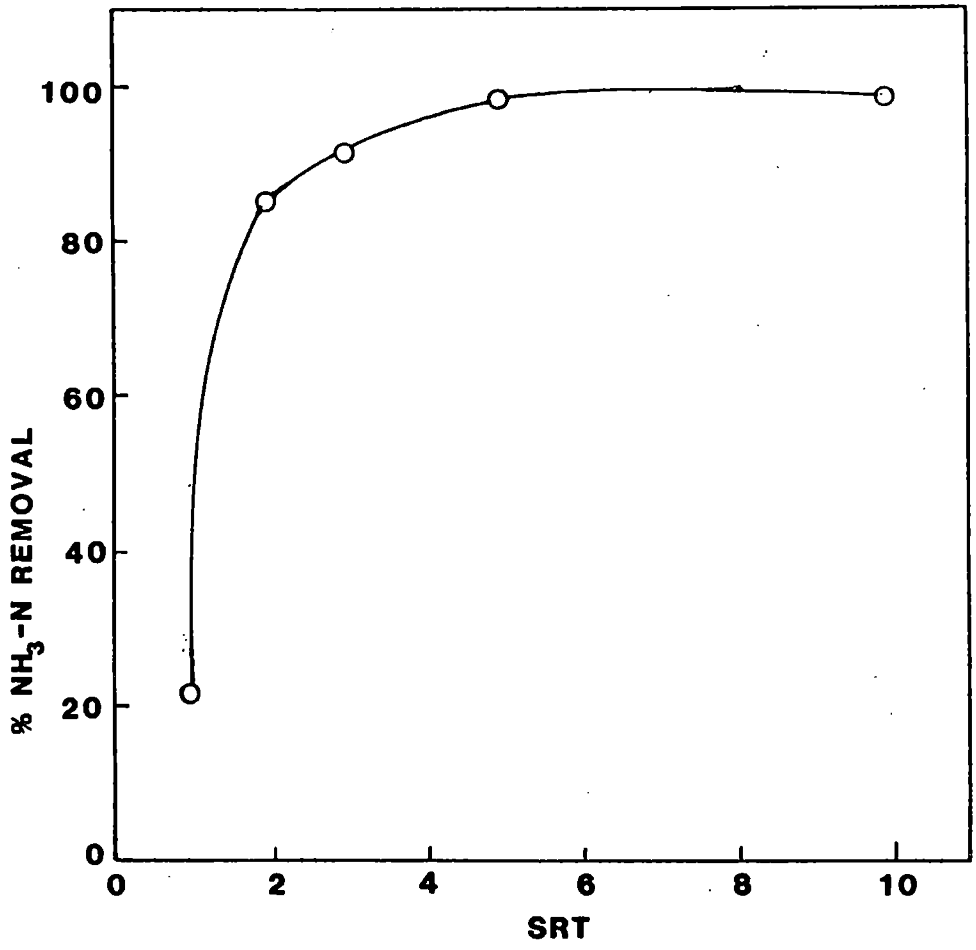


Figure 16. Percent NH_3-N Removal as a Function of SRT for Nitrifying One-Stage System

value reached 0.192 (2 day SRT), for the BOD to NH_3-N ratio of 3.70 or COD to NH_3-N ratio of 9.0. Figure 17 shows the mass substrate loading versus substrate utilization in terms of NH_3-N for the one-stage nitrifying system. The NH_3-N removal kinetic constants can be obtained from Figure 18 for the BOD to NH_3-N ratio of 3.7 or COD to NH_3-N ratio of 9.0, by plotting the reciprocal of the mass NH_3-N removed in the reactor versus the reciprocal of the mass NH_3-N applied. The values of the constants, U_{max} and K_B, are 0.89 and 0.83, respectively. The yield coefficient Y_t and decay coefficient K_d can be calculated based on total volatile suspended solids from Figure 19. The values of Y_t and K_d are 4.41 and -0.24, respectively. These NH_3-N removal kinetic constants are summarized in Table VI.

Phosphorus Removal

Phosphorus concentrations in the influent and effluent were monitored at regular time intervals. There was no removal of phosphorus observed in the one-stage nitrifying system.

Three-Stage Nitrifying-Denitrifying System

Three bench-scale reactors with internal clarifiers were operated in series at different conditions in order to optimize the design condition for nitrification and denitrification. In this three-reactor system, the first reactor was used primarily for the removal of organic carbon, the second reactor for the conversion of NH_3-N into NO_3-N (nitrification), and the third reactor for the conversion of NO_3-N into nitrogen gas (denitrification). The first carbonaceous removal reactor was operated at a constant F/M value of around 1.0 (1 day SRT) in terms of BOD in order

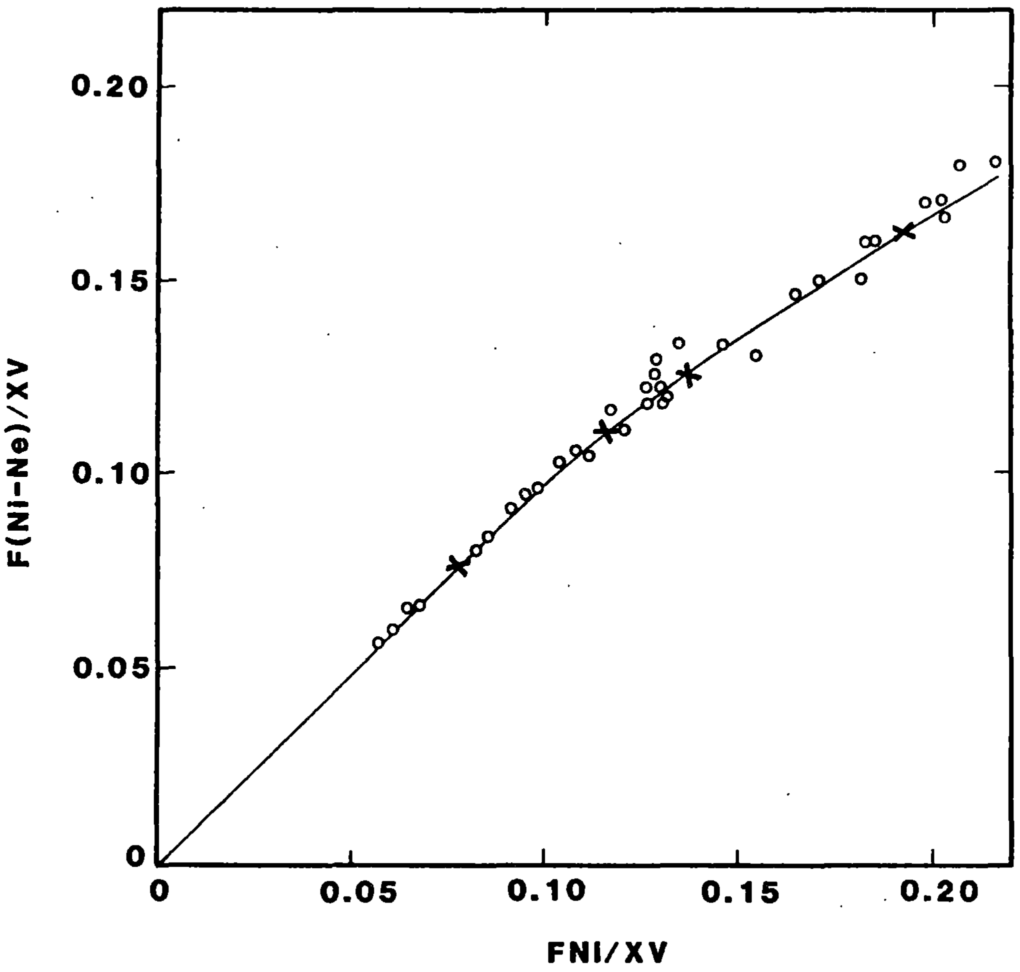


Figure 17. Substrate Utilization as a Function of Mass Substrate Loading in Terms of NH_3-N for Nitrifying One-Stage System

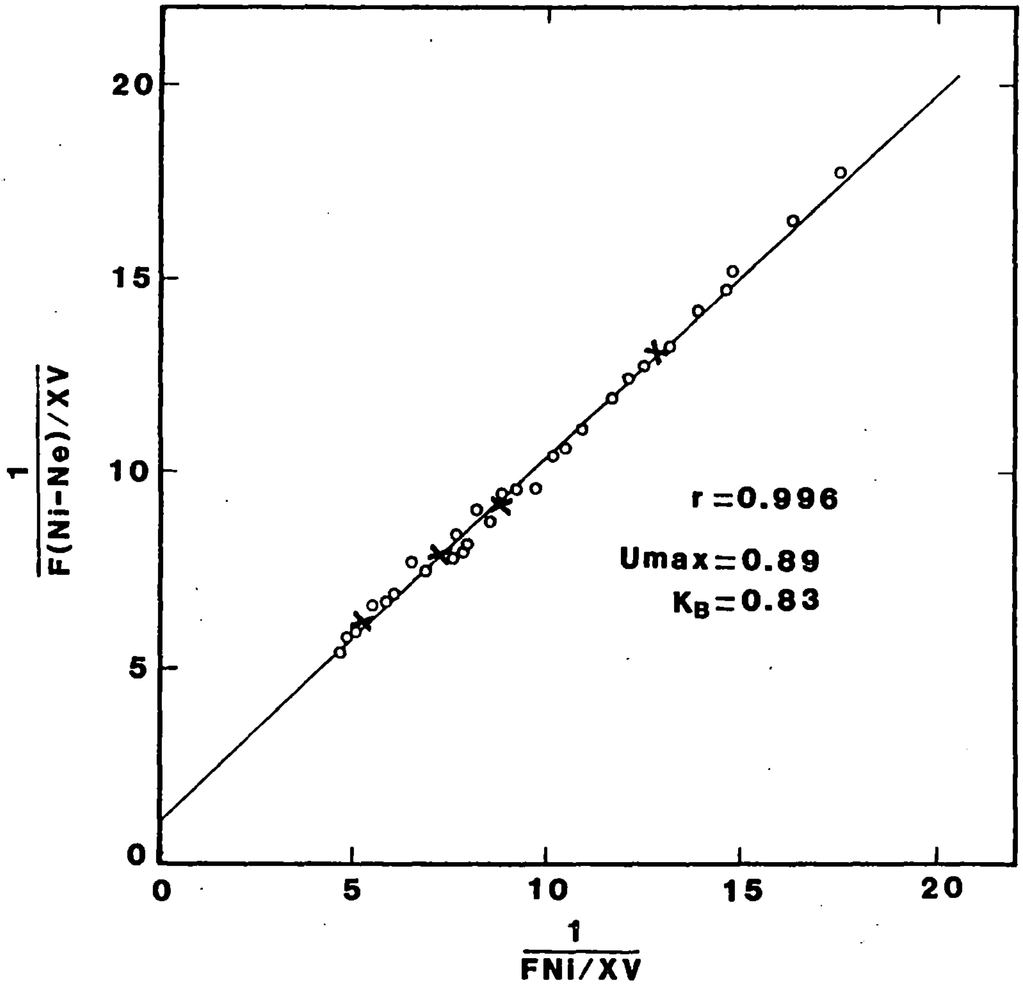


Figure 18. Graphical Determination of U_{max} and K_B in Terms of NH_3-N, for Nitrifying One-Stage System

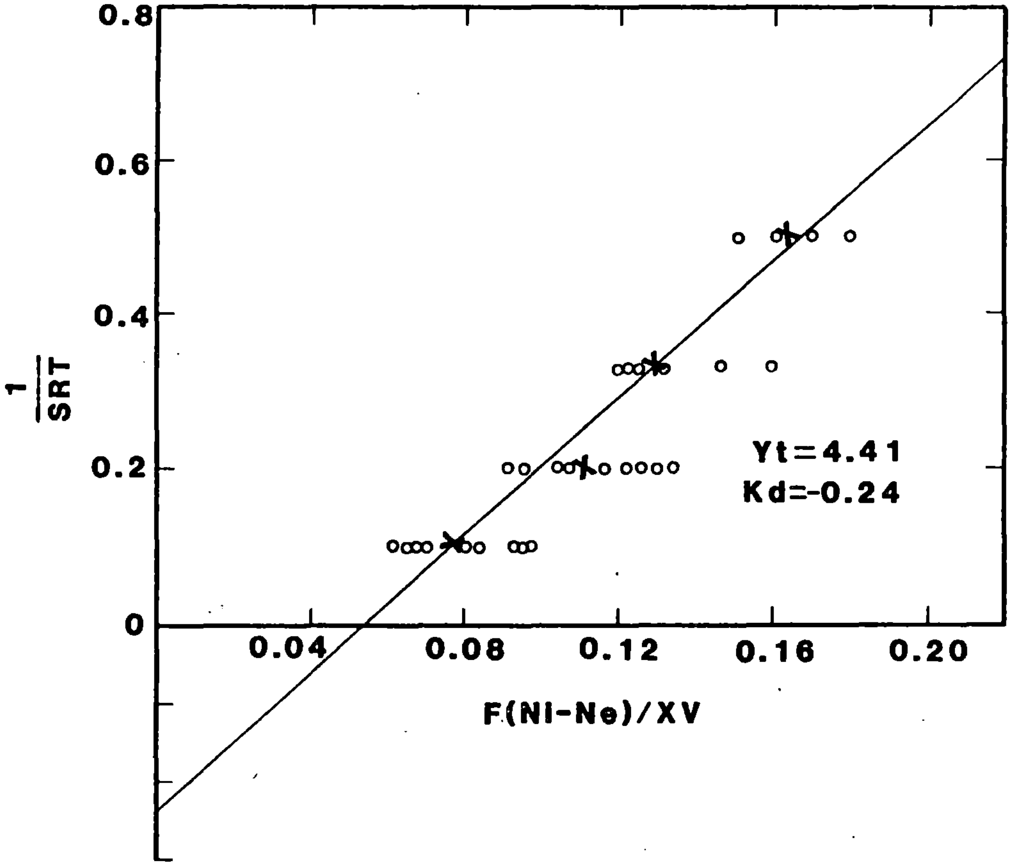


Figure 19. Graphical Determination of Y_t and K_d in Terms of NH_3-N for Nitrifying One-Stage System

to achieve maximum removal of organic matter, but at the same time not allowing the reactor to nitrify. The data were collected at steady state for each operating condition. The average influent volatile suspended solids concentration was around 28.0 mg/ℓ during the entire study. The influent pH varied between 6.5 and 7.0. The BOD_5:NH_3-N ratio of the influent was around 3.7 and the COD:NH_3-N ratio was around 9.0. The operational characteristics of the three-stage nitrifying-denitrifying system are summarized in Tables VII through XIII. The treatment performance of the system will be presented separately for each reactor.

Carbonaceous Removal

The carbonaceous removal reactor, which is the first reactor in the series to receive the influent (raw wastewater) was operated at constant SRT of 1 day, in order to prevent the reactor from nitrification. The average influent soluble BOD_5 and COD concentrations were around 110.0 and 275.0 mg/ℓ, respectively. The average effluent soluble BOD_5 and COD concentrations out of the first reactor were around 12.0 and 55.0 mg/ℓ, respectively. The average mixed liquor volatile suspended solids concentration in the reactor was around 510.0 mg/ℓ during the entire operation of the system. There was good settling in the carbonaceous removal reactor. So the effluent average suspended solids concentration was only around 4.0 mg/ℓ throughout the operation, even though the reactor was operated at a very low SRT. This good settling prevented the carbonaceous solids from being carried into the nitrification (second) reactor. The F/M values in terms of soluble BOD_5 and soluble COD were around 1.0 and 2.5, respectively. The reactor pH varied from 7.0 to 7.5 throughout

TABLE VII

SUMMARY OF OPERATIONAL CHARACTERISTICS OF THREE-STAGE 15-DAY NITRIFYING AND 15-DAY DENITRIFYING SYSTEM

Description	No. of Data Points	Influent		SRT, 1 Day First Stage		SRT, 15 Days Second Stage		SRT, 15 Days Third Stage		Effluent	
		Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
TSS*	14	45-70	55.0	520-578	545	465-521	472	527-689	585		
Eff. TSS*	14	---	---	0-6	3.5	0	0			1.0-3.0	1.5
VSS*	14	20-35	26.0	480-530	495	410-490	447	460-590	566		
Eff. VSS*	14	---	---	0-6	3.5	0	0			0-2.0	1.0
BOD_5*	14	95-120	107.0	8.0-16.0	11.0	1.5-2.5	2.0	2.0-6.0	4.0	2.0-6.0	4.0
COD*	8	200-290	275	45.0-82.0	53	10-22	16	18.0-60.0	35.0	18.0-60.0	35.0
NH_3-N*	14	22-36	28	16-27	20.8	0.2-0.5	0.3	0.2-0.5	0.3	0.2-0.5	0.3
NO_3-N*	14	0	0	0	0	12.0-20.5	16.4	0	0	0	0
Ortho-P*	5	4-8	7	---	---	---	---	---	---	4.7	6.5
pH		6.5-7.0		7.2-7.4		7.4-7.5		7.4-7.6	---	---	---
Temp. °C		23-28	---	24-28	---	24-28	---	24-28	---	---	---
BOD_5/NH_3-N		2.8-4.8	3.7			0.30-0.97	0.6	---	---	---	---
COD/NH_3-N		8.0-13.0	9.5			2.8-3.0	2.5	---	---	---	---
F/M BOD				0.9-1.5	1.0						
F/M COD				2.2-3.1	2.8						
NH_3-N						0.16-0.28	0.2				
NO_3-N								0.11-0.16	0.14		

*Expressed in mg/ℓ.

Inflow = 14.4 ℓ/d.

First Reactor
Volume = 3.0 ℓ
DO range = 3.0-4.0 mg/ℓ

Second Reactor
Volume = 3.0 ℓ
DO range = 3.0-4.0 mg/ℓ

Third Reactor
Volume = 3.0 ℓ
BOD_5 due to external methanol addition } = 75 mg/ℓ

TABLE VIII

SUMMARY OF OPERATIONAL CHARACTERISTICS OF THREE-STAGE 8-DAY NITRIFYING AND 8-DAY DENITRIFYING SYSTEM

Description	No. of Data Points	Influent		SRT, 1 Day First Stage		SRT, 8 Days Second Stage		SRT, 8 Days Third Stage		Effluent	
		Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
TSS*	16	30-46	33.0	500-596	565	348-472	390	351-463	405	2.5-6.0	4.0
Eff. TSS*		---	---	2.0-7.0	4.5	0	0				
VSS*	16	22-36	27.0	440-530	490	290-400	332	325-437	361	2.0-5.0	3.5
Eff. VSS*		---	---	2.0-7.0	4.0	0	0				
BOD_5*	16	87-131	109.0	9.5-15.0	11.6	1.0-2.5	2.0	1.5-8.5	5.0	1.5-8.5	5.0
COD*	14	240-329	284.0	41-56	49.0	8-22	15.0	22.0-55.0	39.0	22.0-55.0	39.0
NH_3-N*	16	24-36	30.0	19-30	24.2	0.1-0.5	0.3	0.1-0.5	0.3	0.1-0.5	0.3
NO_3-N*	16	0	0	0	0	15-26	19.0	0	0	0	0
Ortho-P*	11	5.3-13.0	10.3	---	---	---	---	---	---	7.0-11.3	8.5
pH		6.5-7.0		7.3-7.4		7.4-7.8		7.4-7.7			
Temp. °C		24-28		26-28		26-28		28-30			
BOD_5/NH_3-N		2.7-4.6	3.4			0.40-0.84	0.6				
COD/NH_3-N		7.6-11.5	9.2			2.05-2.30	2.3				
F/M BOD				0.84-1.31	1.07						
F/M COD				2.36-3.41	2.78						
NH_3-N						0.26-0.42	0.35				
NO_3-N								0.19-0.30	0.25		

*Expressed in mg/ℓ.

Inflow = 14.4 ℓ/d.

First Reactor

Volume = 3.0 ℓ

DO range = 3.0-4.0 mg/ℓ

Second Reactor

Volume = 3.0 ℓ

DO range = 3.0-4.0 mg/ℓ

Third Reactor

Volume = 3.0 ℓ

BOD_5 due to external methanol addition } = 75 mg/ℓ

TABLE IX

SUMMARY OF OPERATIONAL CHARACTERISTICS OF THREE-STAGE 5-DAY NITRIFYING AND 5-DAY DENITRIFYING SYSTEM

Description	No. of Data Points	Influent		SRT, 1 Day First Stage		SRT, 5 Days Second Stage		SRT, 5 Days Third Stage		Effluent	
		Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
TSS*	10	28-49	33.0	480-620	564	238-323	292	271-395	320	3.0-5.0	4.5
Eff. TSS*		---	---	3.0-5.5	4.0	0	0				
VSS*	10	20-35	25.0	400-570	500	200-280	252	214-321	275	2.5-4.5	4.0
Eff. VSS*		---	---	3.0-5.5	4.0	0	0				
BOD_5*	10	93-116	106	10-15	12	1.5-2.5	2.0	1.5-11.0	5.0	1.5-11.0	5.0
COD*	6	250-326	285	42-72	58	8.0-15.0	12	13-40	36	13-40	36.0
NH_3-N*	10	22.8-35.5	30.8	17-27	24.5	0.15-0.30	0.3	0.1-0.2	0.15	0.1-0.2	0.15
NO_3-N*		0	0	0	0	14.0-22.0	18	0	0	0	0
Ortho-P*	5	9.7-11.3	10.5	---	---	---	---	8.0-9.5	9.0	8.0-9.5	9.0
pH		6.6-7.0		7.3-7.5		7.4-7.6		7.3-7.4			
Temp. °C		21-25		23-27		23-27		27-30			
BOD_5/NH_3-N		2.7-4.2	3.6			0.45-0.64	0.5				
COD/NH_3-N		7.5-10.9	8.3			2.3-2.7	2.4				
F/M BOD				0.96-1.24	1.02						
F/M COD				2.40-3.27	2.74						
NH_3-N						0.35-0.53	0.45				
NO_3-N								0.23-0.41	0.32		

*Expressed in mg/ℓ.

Inflow = 14.4 ℓ/d.

First Reactor
Volume = 3.0 ℓ
DO range = 3.0-4.0 mg/ℓ

Second Reactor
Volume = 3.0 ℓ
DO range = 3.0-4.0 mg/ℓ

Third Reactor
Volume = 3.0 ℓ
BOD_5 due to external methanol addition } = 75 mg/ℓ

TABLE X

SUMMARY OF OPERATIONAL CHARACTERISTICS OF THREE-STAGE 5-DAY NITRIFYING AND 3-DAY DENITRIFYING SYSTEM

Description	No. of Data Points	Influent		SRT, 1 Day First Stage		SRT, 5 Days Second Stage		SRT, 3 Days Third Stage		Effluent	
		Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
TSS*	12	34-50	37.0	517-650	610	245-290	270	140-192	165	3.0-8.5	5.5
Eff. TSS*		---	---	3.0-7.0	5.0	0	0	---	---		
VSS*	12	25-35	28.0	480-566	525	230-270	248	130-170	147	2.0-7.0	4.5
Eff. VSS*		---	---	3.0-6.0	4.0	0	0	---	---		
BOD_5*	12	99-121	111.0	9.0-14.5	12.5	1.0-2.5	1.8	2.5-16.0	5.5	2.5-16.0	5.5
COD*	6	236-296	259	36-58	52.0	8-15	10.0	16-80	40	16-80	40.0
NH_3-N*	12	27.5-36.0	30.9	20.5-30.0	24.0	0.15-0.35	0.3	0.15-0.25	0.20	0.15-0.25	0.2
NO_3-N*		0	0	0	0	16.0-23.0	19.5	0.10-0.35	0.20	0.10-0.35	0.2
Ortho-P*	6	9.2-12.0	10.5	---	---	---	---	---	---	9.0-12.0	9.8
pH		6.5-6.9		7.2-7.4		7.3-7.5		7.4-7.6			
Temp. °C		18-23		21-23		21-23		25-28			
BOD_5/NH_3-N		3.1-4.3	3.6			0.40-0.76	0.6				
COD/NH_3-N		6.6-10.3	8.7			2.2-2.6	2.4				
F/M BOD				0.95-1.30	1.01						
F/M COD				2.0-2.8	2.34						
NH_3-N						0.39-0.55	0.47				
NO_3-N								0.47-0.85	0.62		

*Expressed in mg/ℓ.
Inflow = 14.4 ℓ/d.

First Reactor
Volume = 3.0 ℓ
DO range = 3.0-4.0 mg/ℓ

Second Reactor
Volume = 3.0 ℓ
DO range = 3.0-4.0 mg/ℓ

Third Reactor
Volume = 3.0 ℓ
BOD_5 due to external metnanol addition } = 75 mg/ℓ

TABLE XI

SUMMARY OF OPERATIONAL CHARACTERISTICS OF THREE-STAGE 3-DAY NITRIFYING AND 2-DAY DENITRIFYING SYSTEM

Description	No. of Data Points	Influent		SRT, 1 Day First Stage		SRT, 3 Days Second Stage		SRT, 2 Days Third Stage		Effluent	
		Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
TSS*	12	28-52	38.0	585-686	620	148-201	169	84-110	97.0	4.0-7.0	6.0
Eff. TSS*		---	---	1.5-8.0	5.0	0	0	---	---		
VSS*	12	20-40	30.0	512-605	545	140-172	149	76-90	82.0	3.0-6.0	5.0
Eff. VSS*		---	---	1.5-7.0	4.5	0	0	---	---		
BOD$_5$*	12	102-130	116	10.5-18.0	13.5	2.0-4.0	3.5	6.0-34.0	19.0	6.0-34.0	19.0
COD*	6	248-296	273	34-60	54.0	12-22	16	35-98	73.0	35-98	73.0
NH$_3$-N*	12	25.0-34.8	30.5	16.5-27.0	23.0	1.10-2.25	1.5	0.3-0.6	0.5	0.3-0.6	0.5
NO$_3$-N*	12	0	0	0	0	12.0-21.0	17.1	1.0-1.7	1.4	1.0-1.7	1.4
Ortho-P*	4	9.0-12.0	10.3	---	---	---	---	---	---	8.0-12.0	10.0
pH		6.6-7.0		7.3-7.5		7.4-7.6		7.4-7.6			
Temp. °C		18-20		21-23		21-23		24-27			
BOD$_5$/NH$_3$-N		2.8-5.0	3.8			0.48-0.86	0.7				
COD/NH$_3$-N		7.3-11.0	9.0			2.3-2.7	2.5				
F/M BOD				0.86-1.26	1.02						
F/M COD				1.86-2.90	2.40						
NH$_3$-N						0.66-0.86	0.76				
NO$_3$-N								0.80-1.30	1.00		

*Expressed in mg/ℓ.

Inflow = 14.4 ℓ/d.

First Reactor

Volume = 3.0 ℓ

DO range = 3.0-4.0 mg/ℓ

Second Reactor

Volume = 3.0 ℓ

DO range = 3.0-4.0 mg/ℓ

Third Reactor

Volume = 3.0 ℓ

BOD$_5$ due to external methanol addition } = 75 mg/ℓ

TABLE XII

SUMMARY OF OPERATIONAL CHARACTERISTICS OF THREE-STAGE 3-DAY NITRIFYING AND 1-DAY DENITRIFYING SYSTEM

Description	No. of Data Points	Influent Range	Influent Avg.	SRT, 1 Day First Stage Range	SRT, 1 Day First Stage Avg.	SRT, 3 Days Second Stage Range	SRT, 3 Days Second Stage Avg.	SRT, 1 Days Third Stage Range	SRT, 1 Days Third Stage Avg.	Effluent Range	Effluent Avg.
TSS*	12	25-55	41	520-638	578	152-188	172	52-71	60	3.0-12.0	9.0
Eff. TSS*		---	---	2.0-6.5	4.0	0-1.5	1.0	---	---		
VSS*	12	15-40	30	460-570	520	138-162	150	40-60	50	2.0-10.0	7.5
Eff. VSS*		---	---	2.0-6.0	4.0	0-1.0	0.5	---	---		
BOD_5*	12	98-131	115	10.0-17.0	14.0	2.0-3.5	3.0	36-56	47	36-56	47
COD*	6	226-308	250	36-76	60.0	12-26	18.0	80-125	110	80-125	110
NH_3-N*	12	21-36	28.8	15.8-29.0	22.0	1.2-3.7	1.8	0.8-2.9	1.3	0.8-2.9	1.3
NO_3-N*	12	0	0	0	0	12.8-19.6	16.5	4.5-9.6	7.3	4.5-9.6	7.3
Ortho-P*	4	8.2-13.0	10.6	---	---	---	---	---	---	8.0-13.0	11.0
pH		6.6-6.9		7.2-7.3		7.4-7.6		7.4-7.5			
Temp. °C		19-22		22-24		22-24		24-27			
BOD_5/NH_3-N		3.4-4.8	4.0			0.45-0.85	0.62				
COD/NH_3-N		7.9-10.8	8.7			2.00-2.72	2.40				
F/M BOD				0.94-1.30	1.06						
F/M COD				1.90-2.65	2.31						
NH_3-N						0.54-0.88	0.72				
NO_3-N								1.3-2.2	1.58		

*Expressed in mg/ℓ.

Inflow = 14.4 ℓ/d.

First Reactor
Volume = 3.0 ℓ
DO range = 3.0-4.0 mg/ℓ

Second Reactor
Volume = 3.0 ℓ
DO range = 3.0-4.0 mg/ℓ

Third Reactor
Volume = 3.0 ℓ
BOD_5 due to external methanol addition } = 75 mg/ℓ

TABLE XIII

SUMMARY OF OPERATIONAL CHARACTERISTICS OF TWO-STAGE TWO-DAY NITRIFYING SYSTEM

Description	No. of Data Points	Influent		SRT, 1 Day First Stage		SRT, 2 Days Second Stage		Effluent	
		Range	Avg.	Range	Ave.	Range	Avg.	Range	Avg.
TSS*	12	30.0-65.0	45.0	550-640	595.0	90-130	102.0	0-3.0	1.0
Eff. TSS*		---	---	5.0-7.0	6.0				
VSS	12	17.0-54.0	36.0	480-575	510.0	78-102	89.0	0-2.5	1.0
Eff. VSS*		---	---	4.0-7.0	5.0				
BOD_5*	12	92-120	110.0	11.0-15.0	12.0	2.5-4.0	3.5	2.5-4.0	3.5
COD	6	210-302	246.0	39.0-74.0	56.0	12.0-28.0	20.0	12.0-28.0	20.0
NH_3-N*	12	27.5-35.0	29.6	18.8-26.6	22.6	1.9-4.1	3.3	1.9-4.1	3.3
NO_3-N*	12	0	0	0	0	14.0-20.0	16.7	14.0-20.0	16.7
Ortho-P*	4	7.0-9.6	8.8	---	---	---	---	7.0-9.0	8.5
pH		6.7-7.0		6.9-7.3	---	7.5-7.8			
Temp. °C		19.0-22.0		21.0-23.0		21.0-23.0			
BOD_5/NH_3-N		2.8-4.6	3.7			0.40-0.90	0.7		
COD/NH_3-N		7.5-11.6	8.3			2.0-2.8	2.5		
F/M BOD				0.90-1.30	1.04				
F/M COD				1.70-3.00	2.32				
NH_3-N						1.1-1.5	1.2		

*Expressed in mg/ℓ.

First reactor: volume = 3.0 ℓ; DO range = 3.0-4.0 mg/ℓ.

Second reactor: volume = 3.0 ℓ; DO range = 3.0-4.0 mg/ℓ.

the operating period. The liquid temperature of the reactor varied between 21 and 28°C.

The percent soluble BOD and soluble COD removal of this reactor was around 90 and 80 percent, respectively. So a considerable amount of organic matter removal was achieved in the first reactor. This reactor data were also used in obtaining the biokinetic constants of U_{max} and K_B for the one-stage nitrifying system in terms of soluble BOD_5 and soluble COD. These data were used because of the same BOD:NH_3-N ratio and COD: NH_3-N ratio as the one-stage nitrifying system (the same influent wastewater). The average influent NH_3-N concentration was around 30.0 mg/ℓ into the reactor. The average effluent NH_3-N concentration was around 23.0 mg/ℓ. There was no NO_2-N or NO_3-N in the effluent. So the difference of 7.0 mg/ℓ between influent and effluent concentration was basically used for the synthesis of new cells in the carbonaceous removal reactor. Complete data are shown in Tables VII through XIII. Settled or clarified effluent from the first reactor was continuously fed into the second (nitrification) reactor.

NH_3-N Removal (Nitrification) Reactor

In order to optimize the nitrification and to get the design biokinetic constants, the second (nitrification) reactor was operated at different SRT's or in other words at different F/M values using NH_3-N as influent substrate. The influent for this nitrification reactor was the clarified effluent from the carbonaceous removal (first) reactor. The flow was continuous for the entire system, with separate internal clarifiers for each reactor.

The average concentrations of soluble BOD_5 and soluble COD in the influent (effluent from the first-stage reactor) were 12.0 and 55.0 mg/ℓ, respectively. The average NH_3-N concentration in the influent was around 23.0 mg/ℓ. This nitrification reactor was operated at SRT's of 15, 8, 5, 3, and 2 days. The corresponding average mixed liquor volatile suspended solids were 447, 332, 250, 150, and 89 mg/ℓ. The average F/M values using NH_3-N as substrate for the SRT's of 15, 8, 5, 3, and 2 days were 0.22, 0.35, 0.46, 0.74, and 1.20, respectively. The average soluble BOD_5:NH_3-N ratios and COD:NH_3-N ratios of the influent into the nitrification reactor were around 0.60 and 2.40, respectively. The average nitrification reactor effluent concentrations of BOD_5 for the SRT's of 15, 8, 5, 3, and 2 days were 2.0, 2.0, 2.0, 3.0, and 3.5 mg/ℓ, respectively. The average COD concentrations of 16, 15, 11, 17, and 20 mg/ℓ were observed in the effluent for the SRT's of 15, 8, 5, 3, and 2 days. The clarified effluent suspended solids concentration was zero for all of the operating conditions except for the 2-day SRT which was 1.0 mg/ℓ. Thus, practically no suspended solids were carried into the third (denitrification) reactor. The pH of the nitrification reactor varied between 7.3 and 7.8, depending upon the pH of the raw wastewater. Almost complete nitrification was achieved for the F/M values of 0.22 (15 day SRT), 0.35 (8 day SRT), and 0.46 (5 day SRT). The effluent NH_3-N concentration for these conditions was only around 0.25 mg/ℓ. For the F/M values of 0.74 (3 day SRT) and 1.20 (2 day SRT), the average effluent NH_3-N concentrations were 1.65 and 3.30 mg/ℓ, respectively. The effluent average NO_3-N concentration varied based on the influent NH_3-N concentration and SRT. At 15 day SRT, the effluent average NO_3-N concentration was 16.4 mg/ℓ for the influent NH_3-N concentration of 20.7 mg/ℓ. At 8 and 5 day SRT, the average NO_3-N concentration was around 19.0 mg/ℓ for the influent NH_3-N concentration of around 24.2 mg/ℓ. At 3 and 2 day SRT's, the effluent average NO_3-N concentration was 16.8 and 16.7 mg/ℓ, respectively, for the influent NH_3-N concentration of 22.5 and 22.6 mg/ℓ, respectively. The dissolved oxygen concentration of the reactor was maintained in the range of 3.0 to 4.0 mg/ℓ for all of the conditions.

Figures 20 and 21 represent the percent NH_3-N removal as a function of F/M and SRT for the nitrification reactor. Maximum NH_3-N removal of 99 percent was achieved for the F/M values of 0.22 (15 day SRT), 0.35 (8 day SRT), and 0.46 (5 day SRT). Then the percent removal started declining and reached 86 percent for the F/M value of 1.20 (2 day SRT). Figure 22 shows the F/M versus U, using NH_3-N as the substrate for the nitrification reactor. A reciprocal plot of U versus F/M is shown in Figure 23. The NH_3-N removal kinetic constants, U_{max} and K_B, obtained from this plot are 13.10 and 13.10, respectively, for the influent BOD: NH_3-N ratio of 0.60 or COD:NH_3-N ratio of 2.40. From Figure 24, the yield coefficient Y_t and decay coefficient K_d are determined to be 0.52 and -0.05, respectively. The kinetic constants are summarized in Table XIV. Complete nitrification data are shown in Tables VII through XIII. The clarified effluent from the second (nitrification) reactor was continuously fed into the third (denitrification) reactor.

NO_3-N Removal (Denitrification) Reactor

Complete data for the denitrification reactor are summarized in Tables VII through XII. The average influent NO_3-N concentration for this reactor was around 16.4 to 19.5 mg/ℓ. The denitrification reactor was operated at the SRT's of 15, 8, 5, 3, 2, and 1 days. The corresponding

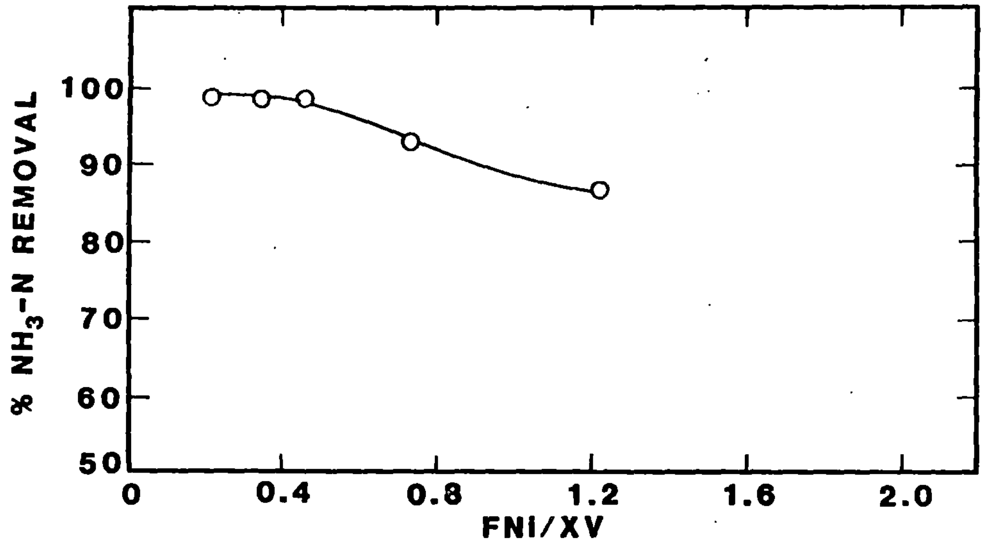


Figure 20. Percent NH_3-N Removal as a Function of F/M for Three-Stage Nitrification System

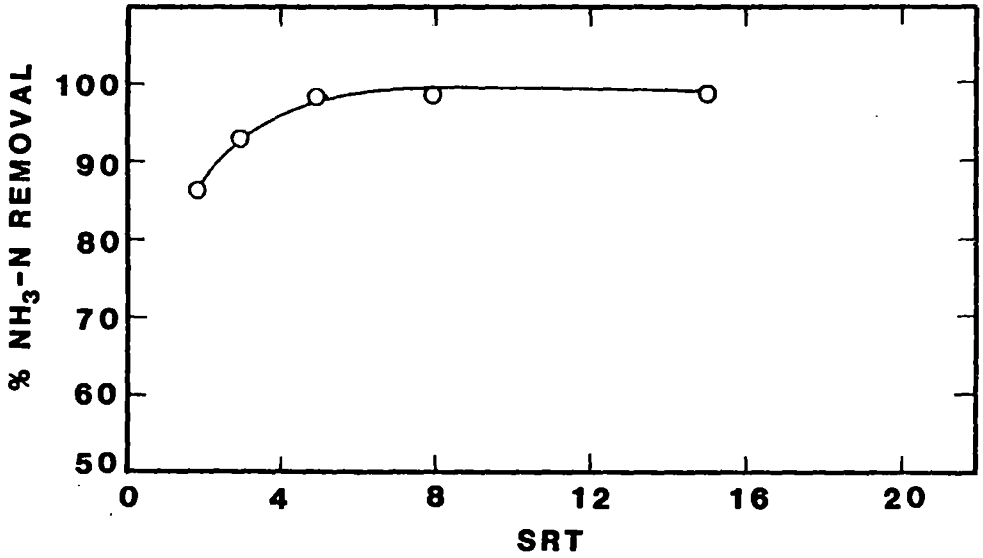


Figure 21. Percent NH_3-N Removal as a Function of SRT for Three-Stage Nitrification System

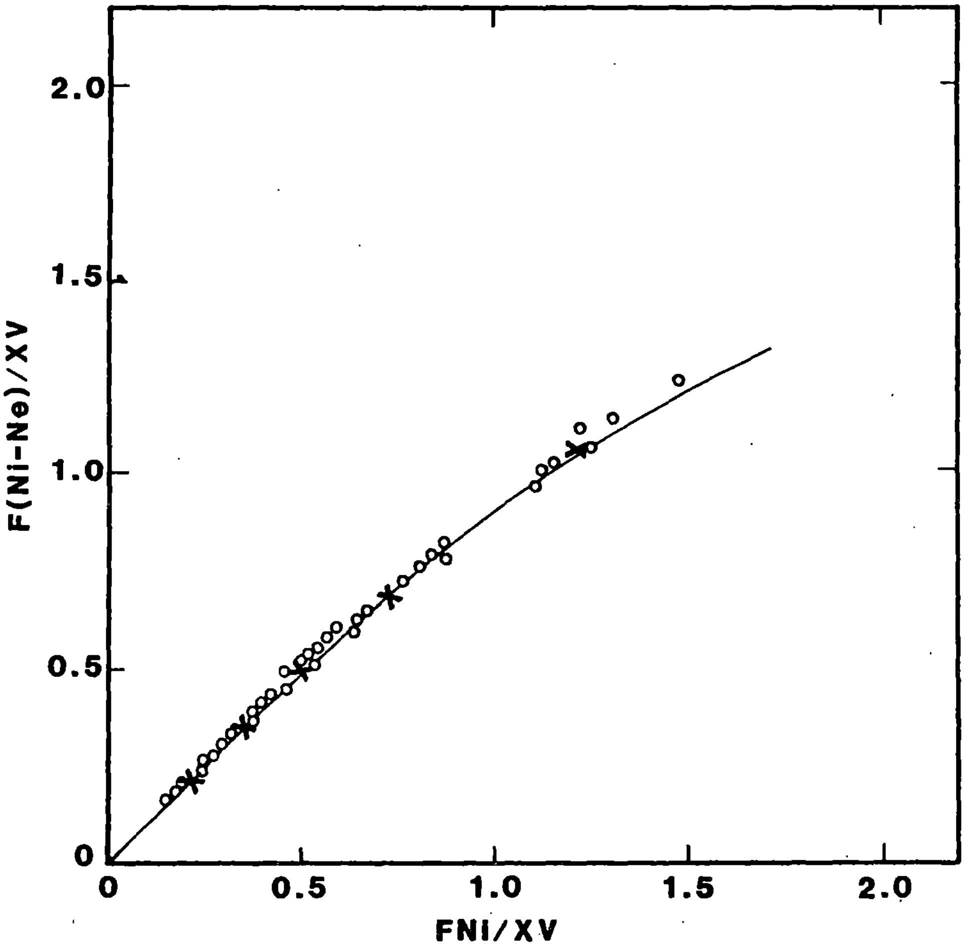


Figure 22. Substrate Utilization as a Function of Mass Substrate Loading in Terms of NH_3-N for Three-Stage Nitrification System

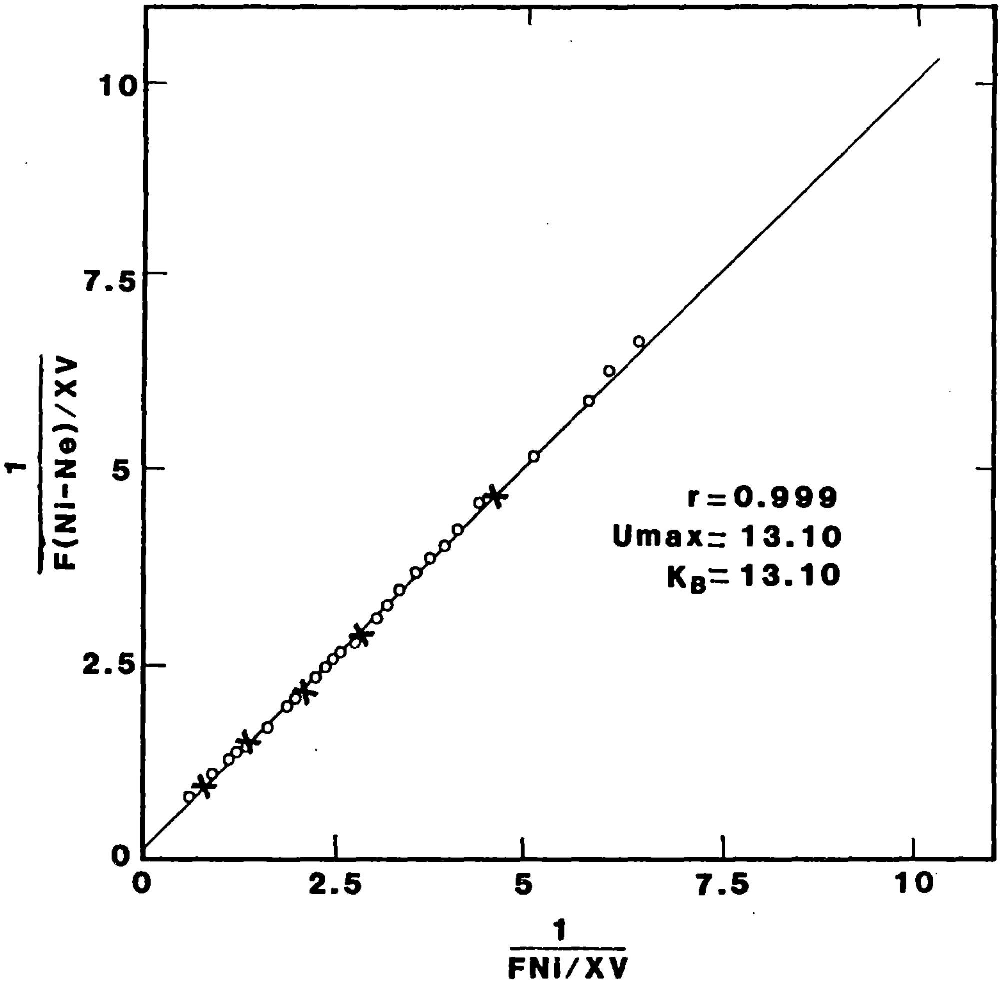


Figure 23. Graphical Determination of U_{max} and K_B in Terms of NH_3-N for Three-Stage Nitrification System

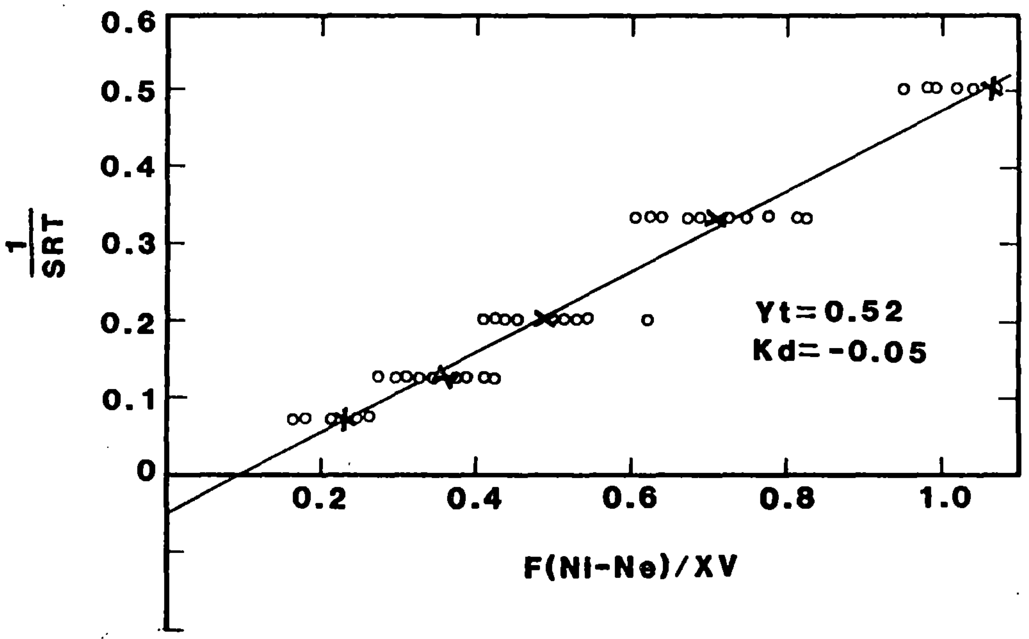


Figure 24. Graphical Determination of Y_t and K_d in Terms of NH_3-N for Three-Stage Nitrification System

TABLE XIV

SUMMARY OF BIOKINETIC CONSTANTS FOR THREE-STAGE NITRIFICATION-DENITRIFICATION SYSTEM

Description	First Stage				Second Stage				Third Stage			
	U_{max}	K_B	Y_t	$-K_d$	U_{max}	K_B	Y_t	$-K_d$	U_{max}	K_B	Y_t	$-K_d$
BOD	13.90	13.90	1.00	0.20	---	---	---	---	---	---	---	---
COD	20.00	20.60	0.52	0.25	---	---	---	---	---	---	---	---
NH_3-N	---	---	---	---	13.10	13.10	0.52	0.05	---	---	---	---
NO_3-N	---	---	---	---	---	---	---	---	10.00	9.70	0.60	0.03

average F/M values in terms of NO_3-N were 0.14, 0.25, 0.32, 0.62, 1.00, and 1.58. The average reactor mixed liquor volatile suspended solids for these conditions were 566, 361, 275, 147, 82, and 50 mg/ℓ, respectively. Since most of the raw wastewater organic carbon was removed in the first two stages, it was necessary to add an external electron donor (carbon source) for denitrification to occur in the third (denitrification) reactor. So the highly reduced single-carbon compound methanol was used as the external electron donor. The BOD_5 added to the reactor due to this addition of methanol was around 75 mg/ℓ for all of the conditions. The pH of the mixed liquor varied between 7.3 and 7.6. The temperature of the liquid varied from 24 to 30°C.

The average effluent suspended solid concentrations for the SRT's of 15, 8, 5, 3, 2, and 1 days were 1.0, 3.5, 4.0, 4.5, 5.0, and 7.5 mg/ℓ, respectively. The effluent BOD_5 and COD concentrations varied as shown in Tables VII through XII, based on influent NO_3-N concentrations and SRT's. External methanol BOD_5 of 75 mg/ℓ was constantly added to the reactor even for low SRT's, so that it was not a limiting factor for denitrification. That is the reason why there was high BOD and COD concentrations in the effluent for lower SRT's (higher F/M) conditions. The final effluent NH_3-N concentration for the 15, 8, 5, and 3 day SRT was around 0.3 mg/ℓ, whereas 0.5 and 1.30 mg/ℓ concentrations were observed for the SRT's of 2 and 1 days. Zero NO_3-N concentration was observed in the final effluent from the denitrification reactor for the 15, 8, and 5 day SRT's. Then 0.2 mg/ℓ NO_3-N concentration was observed for the SRT of 3 days (0.62 F/M). For the SRT's of 2 days (1.0 F/M) and 1 day (1.58 F/M), the average effluent NO_3-N concentrations were 1.40 and 7.30 mg/ℓ, respectively.

Figures 25 and 26 represent the percent NO_3-N removal as a function of F/M and SRT, respectively. One hundred percent removal of NO_3-N was achieved for the 15 day (0.14 F/M), 8 day (0.25 F/M), and 5 day (0.32 F/M) SRT's. For the SRT of 3 days (0.62 F/M) and 2 days (1.00 F/M), the NO_3-N removal was observed as 99 and 91 percent, respectively. Then the removal rapidly reduced to 55 percent for the F/M value of 1.58 (1 day SRT). Figure 27 shows the U versus F/M in terms of NO_3-N. From this figure it is clear that the denitrification was considerably reduced at higher F/M values (lower SRT's).

The biokinetic constants, U_{max} and K_B, for NO_3-N removal were obtained from Figure 28 as 10.00 and 9.70, respectively. The yield and decay coefficients, Y_t and K_d, were obtained from Figure 29 as 0.60 and -0.03. These biokinetic constants are summarized in Table XIV.

Phosphorus Removal

The influent and effluent phosphorus concentrations are given in Tables VII through XIII. There was some phosphorus removal of 0.5 to 1.5 mg/ℓ through the entire system.

Combined Biological Nitrogen-Phosphorus Removal System

This combined nitrogen-phosphorus removal system was operated using three reactors in series. The first anaerobic reactor was primarily used for the partial removal of organic matter and the release of phosphorus from the cells into the liquid. The second anoxic reactor was used for denitrification purposes using the remaining raw wastewater's carbon as an electron donor. The third reactor was used for the conversion of NH_3-N into NO_3-N in addition to the removal of carbon. The phosphorus

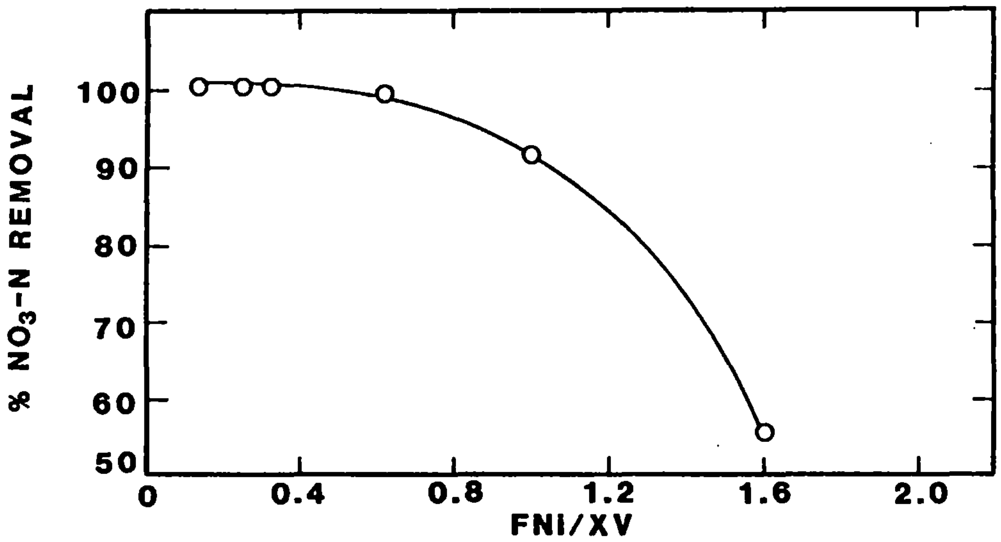


Figure 25. Percent NO_3-N Removal as a Function of F/M for Three-Stage Denitrification System

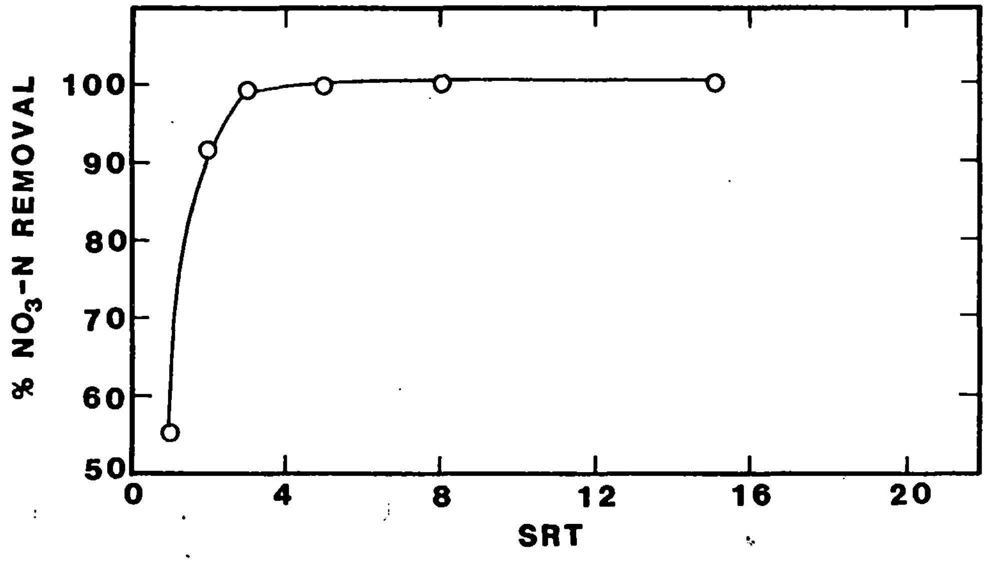


Figure 26. Percent NO_3-N Removal as a Function of SRT for Three-Stage Denitrification System

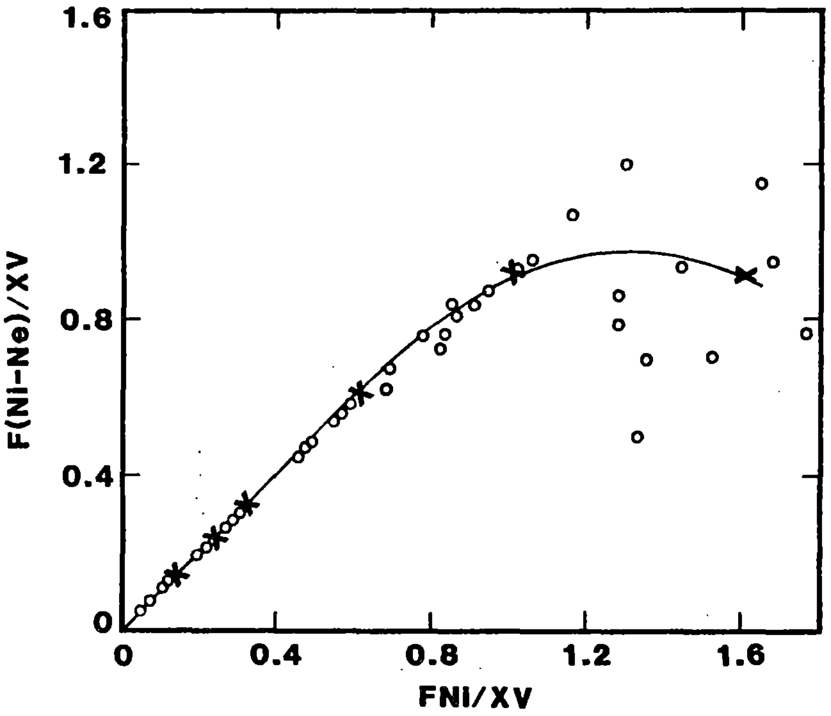


Figure 27. Substrate Utilization as a Function of Mass Substrate Loading in Terms of NO_3-N for Three-Stage Denitrification System

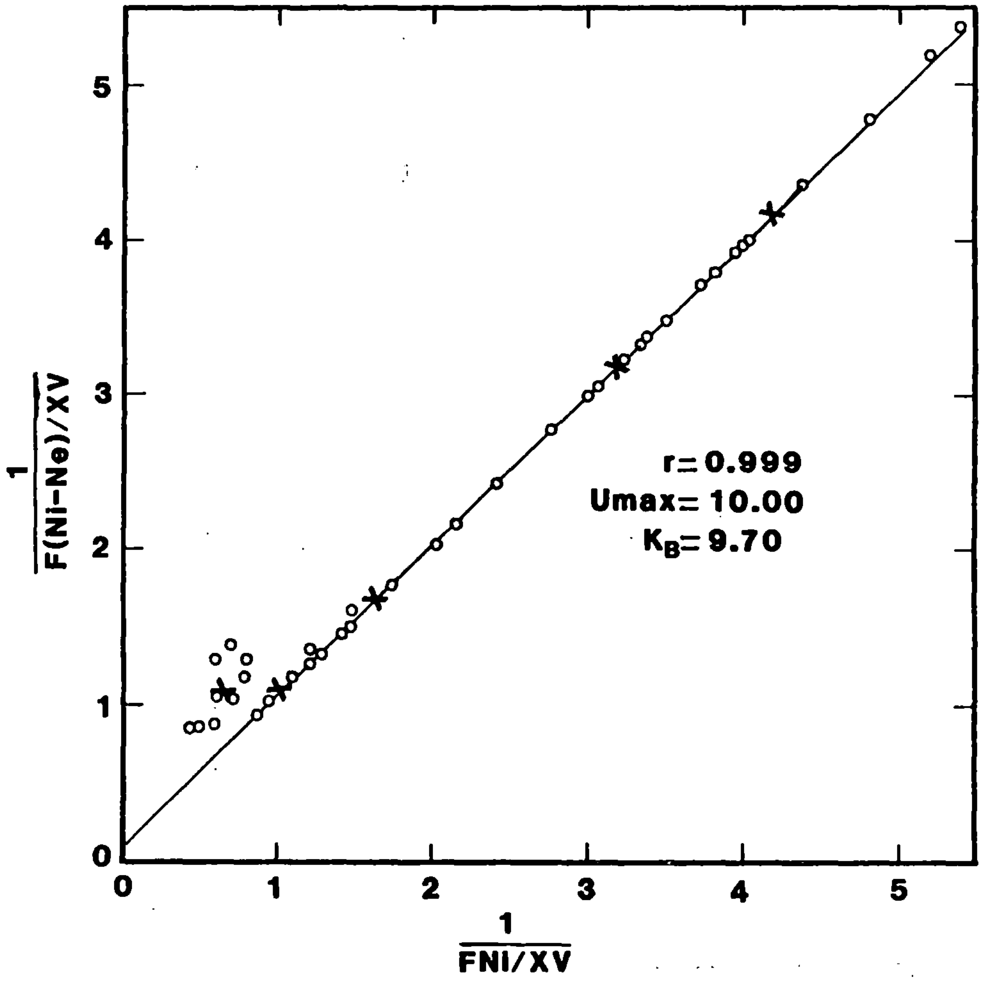


Figure 28. Graphical Determination of U_{max} and K_B in Terms of NO_3-N for Three-Stage Denitrification System

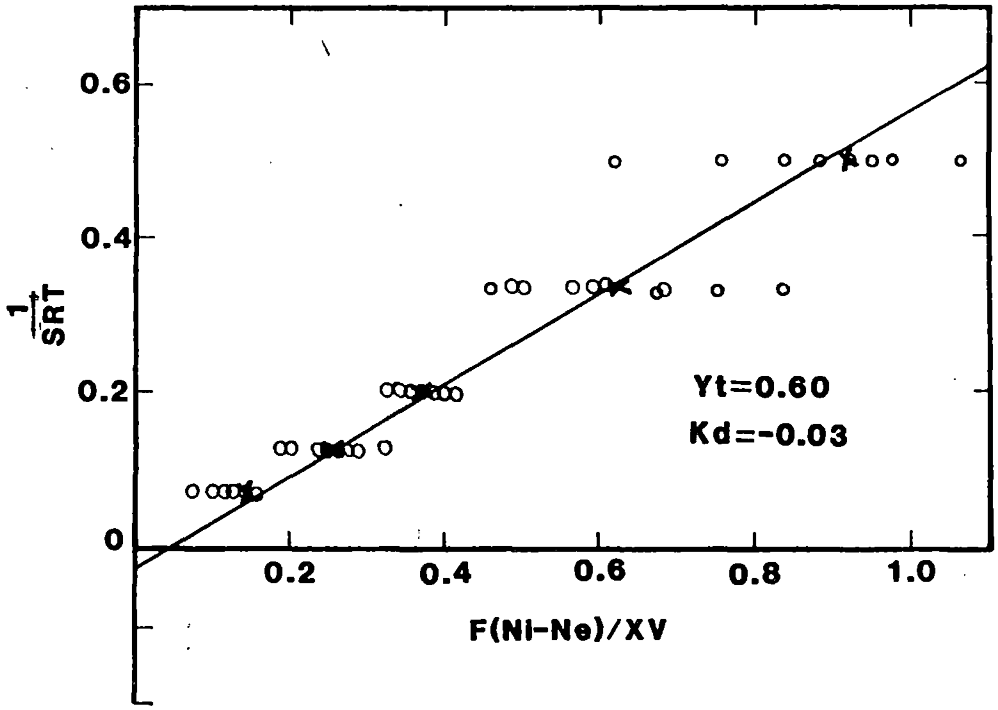


Figure 29. Graphical Determination of Y_t and K_d in Terms of NO_3-N for Three-Stage Denitrification System

Luxury uptake takes place only in this third aerobic reactor. To achieve the denitrification, the nitrified sludge was recycled from the third (aerobic/nitrification) reactor to the anoxic reactor at the ratio of 5:1 to 6:1 based on forward flow.

The SRT for this system is based on the total volume of all three reactors. The influent flow rate for this system was around 17.28 L/d throughout the operation. The external settled sludge was recycled at different rates for different SRT's in order to maintain a constant sludge blanket level in the clarifier. The complete operational performance data for this system were collected at steady state for each condition. These data are summarized in Tables XV through XIX.

The influent pH varied from 6.5 to 7.2. The alkalinity of the influent varied between 280 and 360 mg/ℓ as $CaCo_3$. The BOD:TKN:TP ratios are shown in Tables XV through XIX for all of the conditions. In general, the ratio was around 11:3:1. The COD:TKN:TP ratio was around 30:3:1. The system was operated at the total SRT's of 25, 15, 10, 7, and 3 days.

The average mixed liquor volatile suspended solids concentrations in the anaerobic reactor for the SRT's of 25, 15, 10, 7, and 3 days were 3615, 2700, 2000, 1268, and 500 mg/ℓ, respectively. The pH of this reactor varied from 6.7 to 7.4. The temperature of the reactor varied from 22 to 27°C, except for the 3 day SRT for which it varied between 27 and 34°C.

The average mixed liquor volatile suspended solids concentrations in the anoxic (denitrification) reactor for the SRT's of 25, 15, 10, 7, and 3 days were 4268, 3000, 2300, 1613, and 807 mg/ℓ, respectively. The pH of this reactor varied between 6.8 and 7.5. The temperature of this reactor was the same as the anaerobic reactor temperature.

TABLE XV

SUMMARY OF OPERATIONAL CHARACTERISTICS OF COMBINED NITROGEN-PHOSPHORUS REMOVAL SYSTEM AT 25-DAY SRT

Description	No. of Data Points	Influent		Anaerobic		Anoxic		Aerobic		Effluent	
		Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
TSS*	13	25-65	45.0	3560-4580	4050.0	4560-5140	4720.0	4660-5220	4820.0	0-5	2.50
VSS*	13	20-40	28.0	3120-4360	3615.0	4060-4680	4268.0	4180-4640	4340.0	0-5	2.50
BOD_5*	13	90-134	116.0	16-21	18.5	1.0-2.5	2.0	1.0-1.5	1.1	1.0-1.5	1.10
COD*	13	260-340	300.0	95-136	112.0	13-22	18.0	9.0-16.0	12.0	9-16	12.00
NH_3-N*	13	26.0-33.2	29.2	18.0-25.9	21.5	2.2-3.9	2.9	---	---	0.3-0.4	0.32
NO_3-N*	13	0	0	0	0	0	0	---	---	0.4-1.8	0.75
TKN*	13	27.4-35.0	30.9	---	---	---	---			0.5-0.8	0.60
Total P*	13	9.0-11.4	10.0	---	---	---	---	---	---	4.2-6.5	5.00
Ortho-P*	13	8.0-10.3	8.9	16.2-19.3	17.6	7.1-10.0	8.8	2.77-5.90	4.2	4.0-6.3	4.70
Alkalinity* (As $CaCO_3$)	5	335-360	341.0	330-355	340.0	280-310	289.0	235-275	254.0	---	---
pH	13	6.9-7.0		7.0-7.10		7.0-7.10		7.10-7.40		7.4-7.8	
Temp. °C	13	20-23		22-25		22-25		23-24		---	
BOD:TKN:TP	13	10:2.5:1- 14:3.6:1	12:3:1								
COD:TKN:TP	13	27:2.5:1- 35:3.6:1	30:3:1								

*Expressed in mg/ℓ.
Recycle solids conc. (MLVSS) = 6180 - 7820 = 6665 mg/ℓ.
Inflow = 17.28 L/d (12 mℓ/min).
External recycle = 17.28 L/day.
Internal recycle = 5.5:1 (95 L/day).

Sludge P content, 6.0-7.5%; average, 7.0%.

DO range = 2.0 - 3.0 mg/ℓ (aerobic).

Anaerobic	Anoxic	Aerobic
Volume = 1.38 L	Volume = 2.21 L	Volume = 4.33 L

TABLE XVI

SUMMARY OF OPERATIONAL CHARACTERISTICS OF COMBINED NITROGEN-PHOSPHORUS REMOVAL SYSTEM AT 15-DAY SRT

	Influent		Anaerobic		Anoxic		Aerobic		Effluent	
Description	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
TSS*	30-50	40.0	2600-3400	3100	3100-3900	3500	3200-3900	3500	0-2	0.50
VSS*	20-30	25.0	2400-3050	2700	2800-3500	3000	2900-3400	3100	0-2	0.50
BOD*	85-120	105.0	13-21	19	1-3	2	1.0	1.0	1.0	1.00
COD*	200-400	305.0	95-135	120	9-22	16	9-15	12	9-15	12.00
NH_3-N*	24-40	31.0	22-29	25.5	2-5	3.55	---	---	0.3-0.60	0.40
NO_3-N*	---	0	---	0	---	0	---	---	0.3-2.0	1.00
TKN*	26-42	33.0	---		---		---		0.4-0.8	0.60
Total P*	8-16	12						4.5	3.0-7.3	5.35
Ortho-P*	7-15	10.7	18-31	25.0	8-13	9.50	1.6-6.6	4.3	3.0-7.0	5.20
Alkalinity (As $CaCO_3$)	320-345	330.0	320-350	330.0	275-295	280	240-270	260	---	---
pH	6.7-7.0		6.7-6.8		6.8-7.0		7.0-7.3		7.2-7.4	
Temp. °C	22-26		24-27		23-28		22-26		22-24	

BOD:TKN:TP	8:2.0:1-14:5:1	10:2.8:1
COD:TKN:TP	19:2.0:1-40:5:1	27:2.8:1

*Expressed in mg/ℓ.
Recycle solids conc. (MLVSS) = 6000 mg/ℓ.
Inflow = 17.28 ℓ/day (12 mℓ/min).
External recycle = 17.28 ℓ/day (12 mℓ/min).
Internal recycle = 6:1 (103 ℓ/day).
DO range = 2.0-3.0 mg/ℓ (aerobic).
Sludge P content = 6-10%; average = 8.5%.

Anaerobic	Anoxic	Aerobic
Volume = 1.38 ℓ	Volume = 2.21 ℓ	Volume = 4.33 ℓ.

TABLE XVII

SUMMARY OF OPERATIONAL CHARACTERISTICS OF COMBINED NITROGEN-PHOSPHORUS REMOVAL SYSTEM AT 10-DAY SRT

Description	Influent		Anaerobic		Anoxic		Aerobic		Effluent	
	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
TSS*	30-50	40.0	2000-2500	2300	2300-2900	2600	2400-3000	2700	0-10	5.0
VSS*	20-30	25.0	1700-2200	2000	2000-2500	2300	2100-2600	2350	0-10	4.0
BOD*	98-130	115.0	21-28	23	2-7	4	0.5-1.5	1.0	0.5-1.5	1.0
COD*	270-400	320.0	100-180	143	20-40	27	6-20	14	6-20	14.0
NH_3-N*	16-39	25.5	11-28	19	2-5	3.80	---	---	0.3-0.6	0.4
NO_3-N*	---	0	---	0	---	0	---	---	0.2-1.0	0.6
TKN*	18-43	28.0	---	---	---	---	---	---	0.4-0.8	0.6
Total P*	5.6-20.8	11.8	---	---	---	---	---	---	1.4-13.5	5.2
Ortho-P*	4.3-18.0	10.0	10-28	18.7	4.5-16.0	9.60	1.2-13.0	4.4	1.4-13.0	5.0
Alkalinity (As $CaCO_3$)	280-330	310.0	275-320	310.0	240-270	250	210-240	225	---	---
pH	6.6-7.2		7.0-7.2		7.0-7.5		7.2-7.7		7.3-7.7	
Temp. °C	22-25	---	23-27	---	23-27	---	22-26	---	22-24	

BOD:TKN:TP	7.0:2.0:1-15:4:1	11:2.7:1
COD:TKN:TP	20:2.0:1-38:4:1	31:2.7:1

*Expressed in mg/ℓ.
Recycle solids conc. (MLVSS) = 3200-5000 = 4500 mg/ℓ.
Inflow = 17.28 ℓ/day (12 mℓ/min).
External recycle = 13.00 ℓ/day (9 mℓ/min).
Internal recycle = 5.5-6.0:1 (95-103 ℓ/day).
DO range = 2.5-3.5 mg/ℓ (aerobic).
Sludge P content = 5.0-7.5%; average = 7.0%.

TABLE XVIII

SUMMARY OF OPERATIONAL CHARACTERISTICS OF COMBINED NITROGEN-PHOSPHORUS REMOVAL SYSTEM AT 7-DAY SRT

Description	No. of Data Points	Influent		Anaerobic		Anoxic		Aerobic		Effluent	
		Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
TSS*	15	30-55	42.0	1100-1500	1330	1400-1960	1726	1640-2140	1910	1.0-8.0	4.0
VSS*	15	20-35	30.0	920-1460	1268	1370-1780	1613	1500-1900	1764	1.0-7.0	4.0
BOD_5*	15	65-132	107.0	15.0-40.0	33	2.0-7.0	4.7	1.0-3.0	2.0	1.0-3.0	2.0
COD*	15	186-326	278.0	45-146	120	11.0-27.0	20	8.0-18.0	12.0	8-18	12.0
NH_3-N*	15	16.8-29.2	25.4	16.0-28.2	23.6	1.6-3.6	3.0	0.3-0.4	0.35	0.3-0.4	0.35
NO_3-N*	15	0	0	0	0	0	0	---	---	0.1-0.7	0.5
TKN*	15	18.0-31.0	27.0	---	---	---	---	---	---	0.5-0.7	0.6
Total P*	15	5.0-9.7	7.5	---	---	---	---	---	---	3.0-5.4	3.9
Ortho-P*	15	3.8-9.0	6.5	5.7-11.0	8.4	3.5-8.0	5.0	2.7-5.2	3.7	3.0-5.2	3.7
Alkalinity* (As $CaCo_3$)	5	330-350	340.0	330-350	340	275-295	282	265-290	275	---	---
pH	15	6.9-7.1		7.0-7.3		7.0-7.3		7.2-7.6		7.4-7.9	
Temp. °C	15	22-24		24-27		24-27		22-26			
BOD:TKN:TP	15	10:3.0:1-17:4.0:1	15:3.6:1								
COD:TKN:TP	15	30:3.0:1-45:4.0:1	38:3.6:1								

*Expressed in mg/ℓ.
Recycle solids conc. (MLVSS)--3000-5000 = 4000 mg/ℓ.
Inflow--17.28 L/d.
External recycle--8.64 L/d.
Internal recycle--5.5-6.0:1 (95-103 L/d).
Sludge P content--2.7-4.0%, avg. 3.1%.
DO range--3.0-4.0 mg/ℓ (aerobic).

TABLE XIX

SUMMARY OF OPERATIONAL CHARACTERISTICS OF COMBINED NITROGEN-PHOSPHORUS REMOVAL SYSTEM AT 3-DAY SRT

Description	No. of Data Points	Influent		Anaerobic		Anoxic		Aerobic		Effluent	
		Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.	Range	Avg.
TSS*	12	30.0-50.0	40.0	480-620	555	820-1000	870	820-1000	895	4.0-9.0	6.0
VSS*	12	20.0-35.0	25.0	460-560	500	750-960	807	760-950	830	4.0-8.0	6.0
BOD_5*	12	98.0-136.0	120.0	30-62	43	4.0-13.0	6.5	5.0-8.0	6.0	5.0-8.0	6.0
COD*	12	276-380	328.0	95-285	200	24-67	48	22-45	32.0	22-45	32.0
NH_3-N*	12	24.0-29.6	27.4	25.0-31.2	28.6	8.6-14.5	11.2	3.0-6.0	4.9	3.0-6.0	4.9
NO_3-N*	12	0	0	0	0	0	0	---	---	0.4-1.1	0.7
TKN*	12	25.6-32.0	29.3	---	---	---	---	---	---	3.4-6.8	5.2
Total P*	12	10.1-18.0	13.0	---	---	---	---	---	---	6.2-11.5	8.0
Ortho-P*	12	9.0-15.6	11.6	11.0-17.3	13.6	7.0-12.5	9.6	5.4-11.0	7.7	6.0-11.3	7.8
Alkalinity* (As $CaCo_3$)	5	325-345	335.0	320-340	330	290-320	300	280-310	290	---	---
pH	12	6.5-7.0		7.0-7.4		7.1-7.4		7.2-7.5		7.4-7.9	
Temp. °C	12	25.0-29.0		27-34		24-34		24-33			
BOD:TKN:TP	12	8:1.5:1-11:3.0:1	9.4:2.3:1								
COD:TKN:TP	12	15:1.5:1-30:3.0:1	26:2.3:1								

*Expressed in mg/ℓ.
Recycle solids conc. (MLVSS)--1000-1700 = 1300 mg/ℓ.
Inflow--17.28 L/d.
External recycle--5.76 L/d.
Internal recycle--4.5-5.0:1 (78-86 L/d).
Sludge P content--3.0-4.0%, avg. 3.6%.
DO range--3.0-4.0 mg/ℓ (aerobic).

The average mixed liquor volatile suspended solids concentrations in the aerobic (nitrification/P removal) reactor for the SRT's of 25, 15, 10, 7, and 3 days were 4340, 3100, 2350, 1764, and 830 mg/ℓ, respectively. The pH of the reactor varied from 7.0 to 7.9. The temperature for this reactor was the same as the other two reactors.

In general, the average effluent volatile suspended solids concentration varied between 0.5 and 6.0 mg/ℓ. The average external recycle volatile suspended solids concentrations for 25, 15, 10, 7, and 3 days were 6665, 6000, 4500, 4000, and 1300 mg/ℓ, respectively. The average alkalinity of the effluent varied between 225 and 290 mg/ℓ as $CaCo_3$. The operational performance of this combined nitrogen-phosphorus removal system for BOD, COD, NH_3-N, and phosphorus removal will be presented separately.

BOD Removal

The average influent soluble BOD_5 concentrations into the anaerobic reactor for 25, 15, 10, 7, and 3 day SRT's were 116, 105, 115, 107, and 120 mg/ℓ, respectively. The corresponding average effluent BOD_5 concentrations from the anaerobic reactor were 18.5, 19.0, 23.0, 33.0, and 43.0 mg/ℓ. The average values of F/M at the different operational conditions were 0.40 (25 day SRT), 0.50 (15 day SRT), 0.74 (10 day SRT), 1.10 (7 day SRT), and 2.94 (3 day SRT). Figure 30 shows the cumulative percent BOD removal in each reactor for different SRT's. In the anaerobic reactor, for the SRT's of 25, 15, 10, 7, and 3 days, the percent BOD removal was observed as 68, 62, 53, 53, and 50 percent, respectively. Mass substrate loading (F/M) in terms of BOD_5 was plotted against substrate utilization (U), as shown in Figure 31. Figure 32 represents the recip-

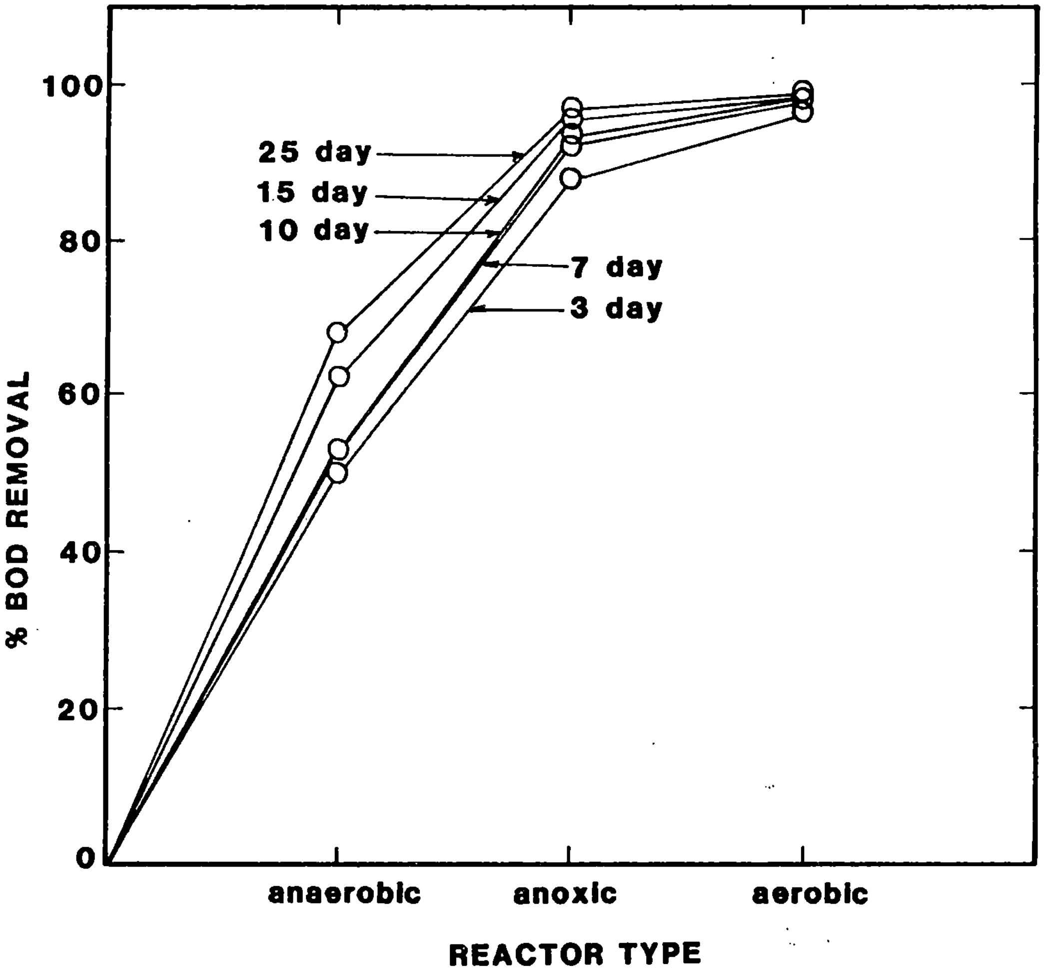


Figure 30. Percent BOD_5 Removal in Each Reactor for Combined Nitrogen-Phosphorus Removal System

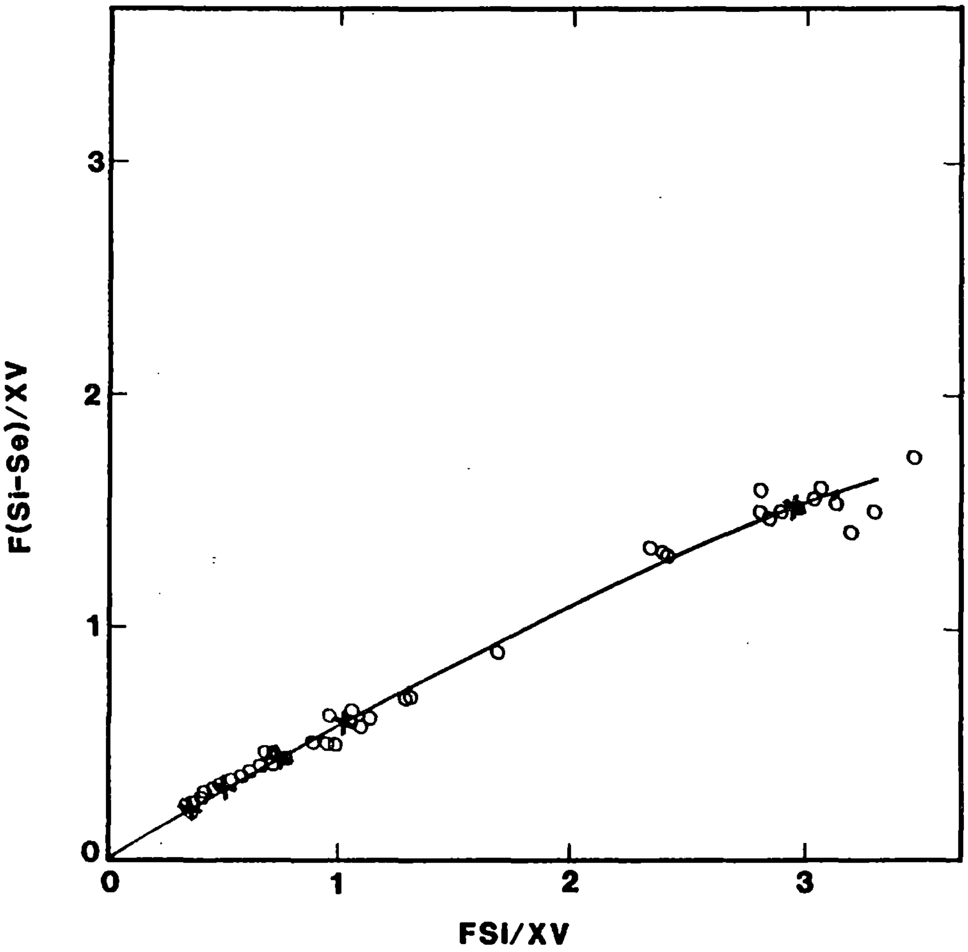


Figure 31. Substrate Utilization as a Function of Mass Substrate Loading in Terms of BOD_5 for Anaerobic Reactor of Combined Nitrogen-Phosphorus Removal System

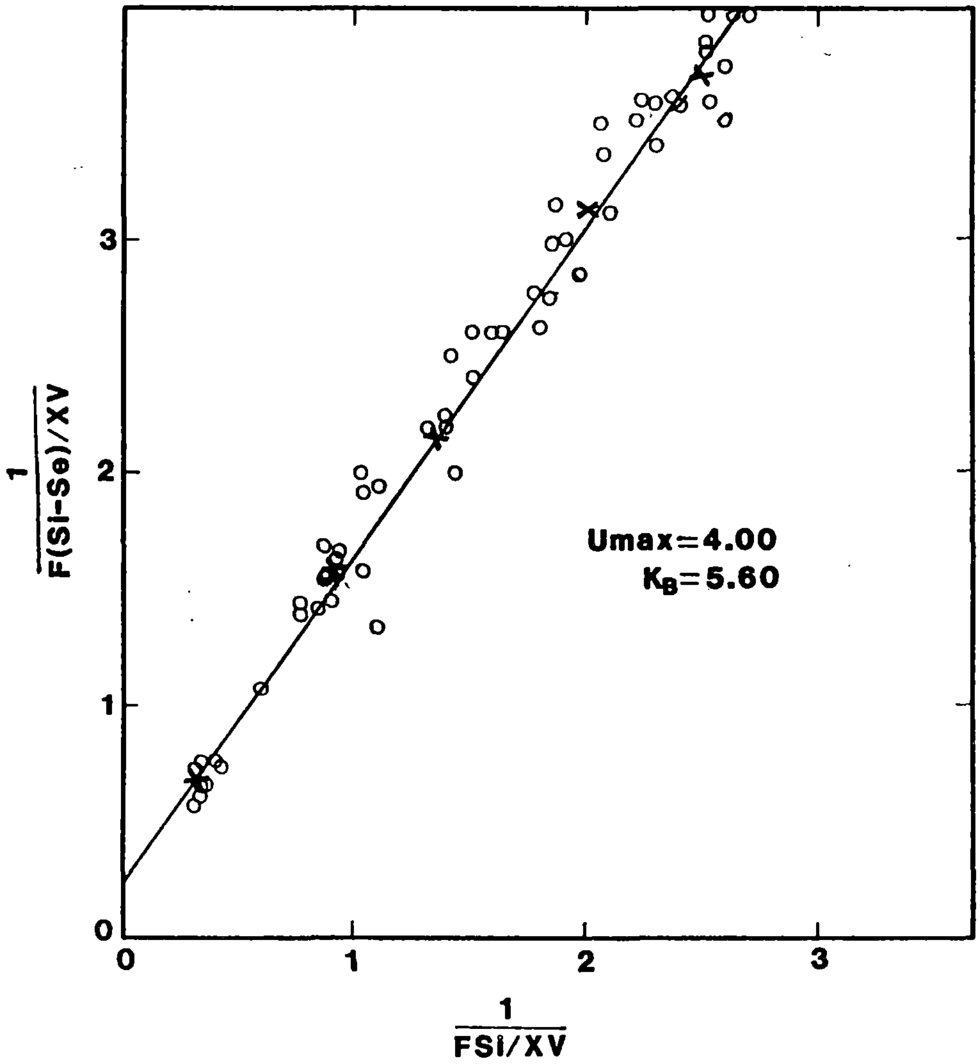


Figure 32. Graphical Determination of U_{max} and K_B in Terms of BOD_5 for Anaerobic Reactor of Combined Nitrogen-Phosphorus Removal System

rocal plot of F/M versus U. The BOD removal biokinetic constants, U_{max} and K_B, for the anaerobic reactor are 4.00 and 5.60, respectively.

The average BOD_5 fed into the anoxic reactor from the anaerobic reactor for the SRT's of 25, 15, 10, 7, and 3 days were 18.5, 19.0, 23.0, 33.0, and 43.0 mg/ℓ, respectively. The average BOD concentrations out of the anoxic reactor, which were fed into the aerobic (nitrification) reactor, were 2.0, 2.0, 4.0, 4.7, and 6.5 mg/ℓ. The average F/M values for the SRT's of 25, 15, 10, 7, and 3 days were 0.0676, 0.0970, 0.1511, 0.2471, and 0.5386, respectively. From Figure 30, the total percent BOD removal through the anoxic reactor (including anaerobic reactor) for the SRT's of 25, 15, 10, 7, and 3 days are 97, 96, 93, 92, and 87 percent, respectively. Thus the net percentages of BOD removal in the anoxic reactor alone, based on the raw wastewater BOD loading, are 29, 34, 40, 39, and 37 percent. Figure 33 shows the U versus F/M in terms of BOD_5 for the anoxic reactor. Figure 34 shows the graphical determination of the biokinetic constants, U_{max} and K_B, using the Kincannon and Stover model for the anoxic reactor. The values of U_{max} and K_B are 2.1 and 2.3, respectively. The average BOD_5 concentration in the final clarified effluent was around 1.0 mg/ℓ for all conditions except for the SRT of 3 days, which was around 6.0 mg/ℓ. From Figure 30, it can be seen that the percent BOD removal through the entire system was more than 97 percent. Figure 35 shows the graphical determination of Y_t and K_d for the BOD removal through the entire system. The values of Y_t and K_d are 1.0 and -0.02, respectively.

COD Removal

The average influent soluble COD concentrations into the anaerobic

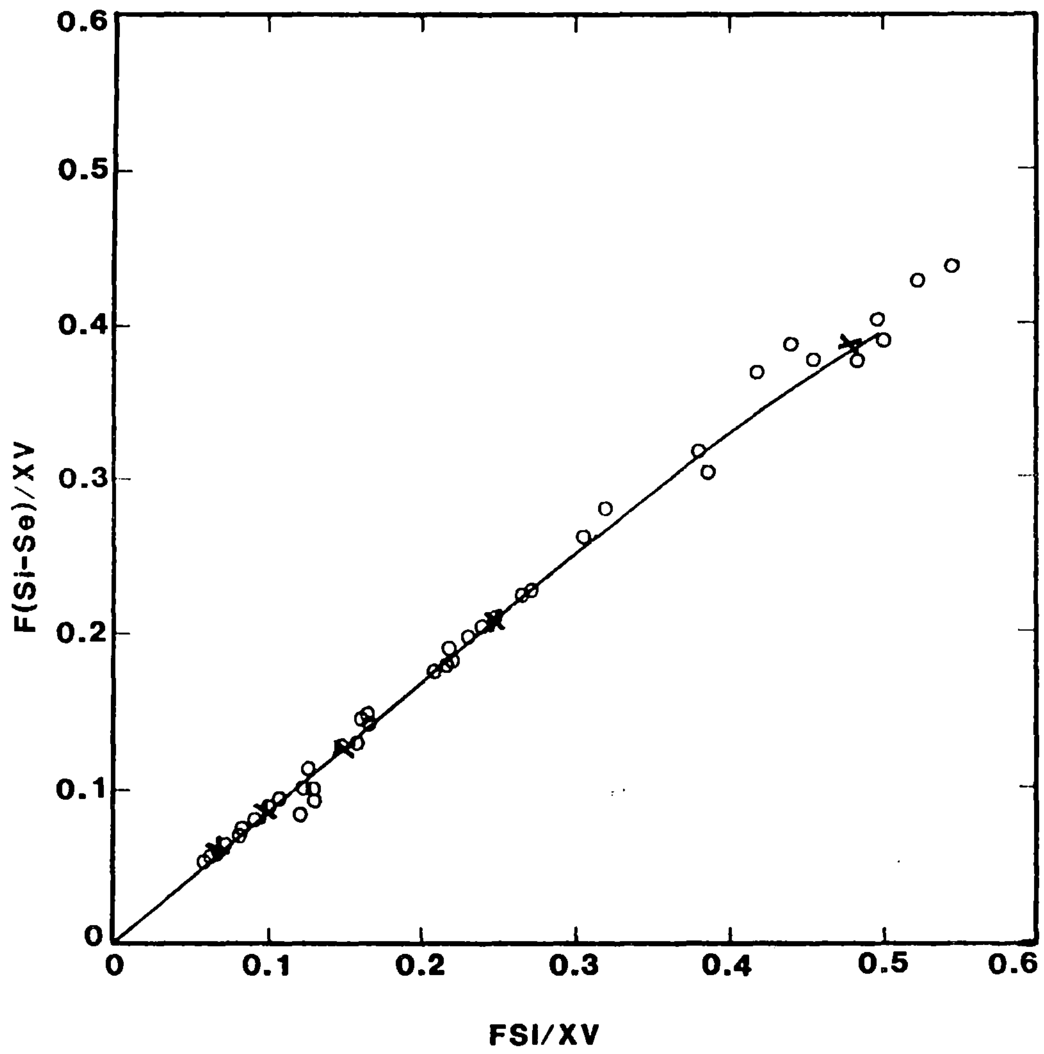


Figure 33. Substrate Utilization as a Function of Mass Substrate Loading in Terms of BOD_5 for Anoxic Reactor of Combined Nitrogen-Phosphorus Removal System

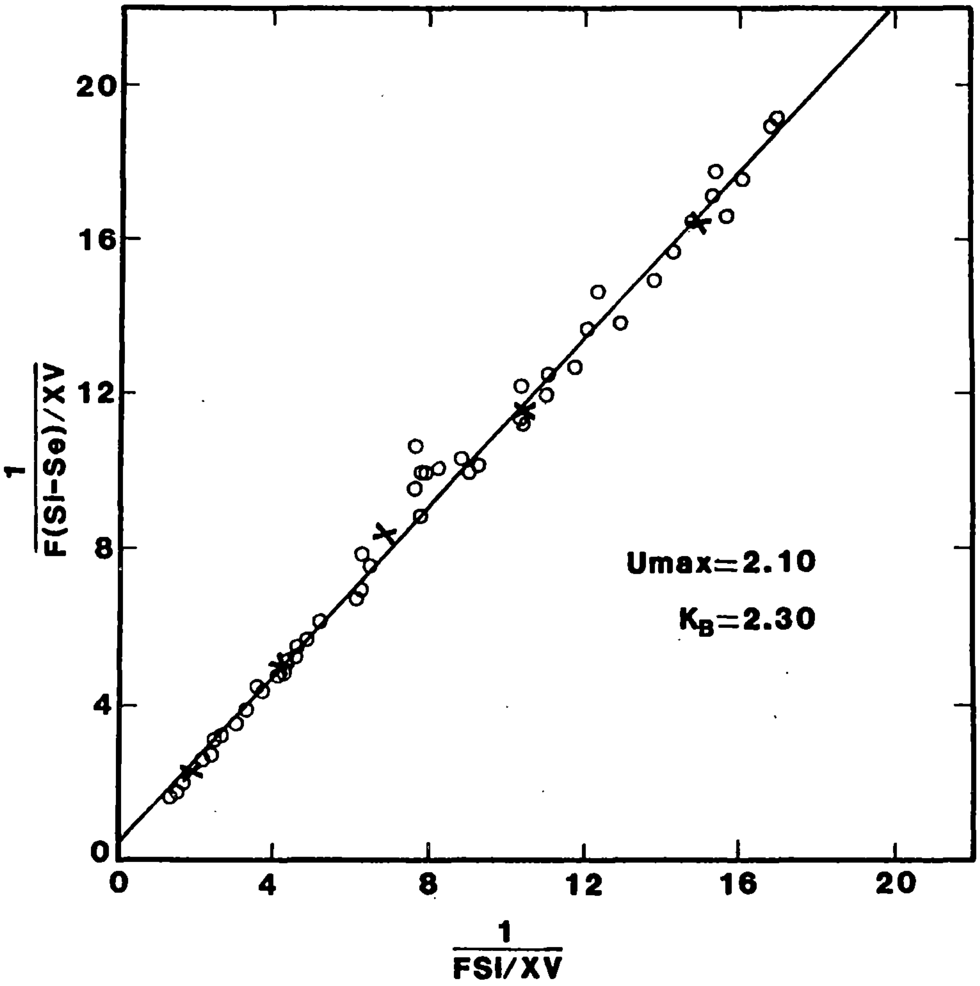


Figure 34. Graphical Determination of U_{max} and K_B in Terms of BOD_5 for Anoxic Reactor of Combined Nitrogen-Phosphorus Removal System

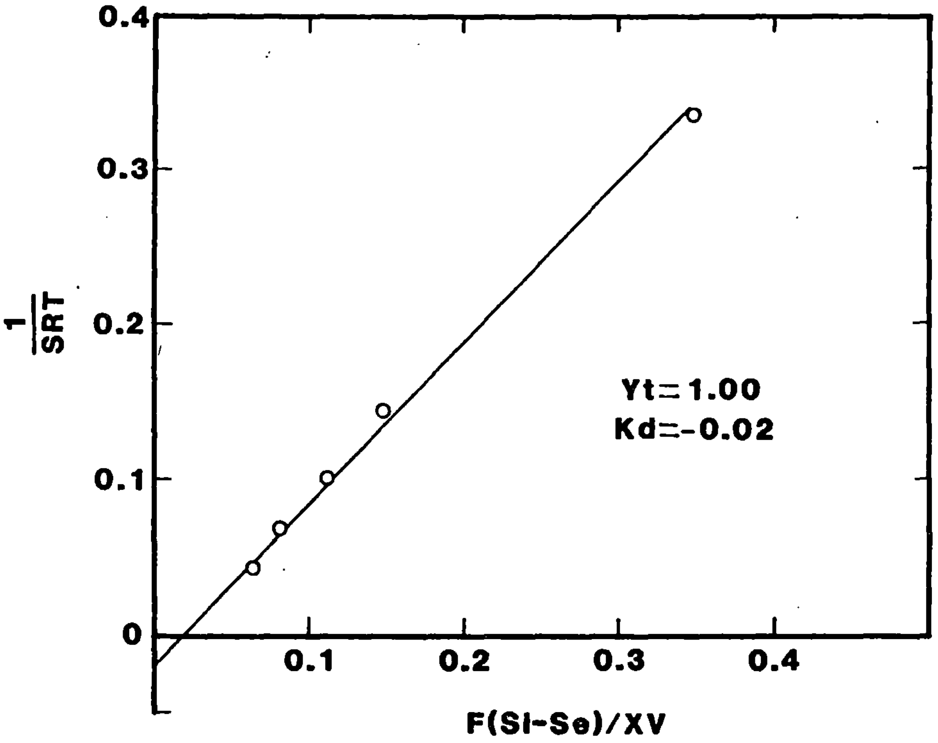


Figure 35. Graphical Determination of Y_t and K_d in Terms of BOD_5 for Combined Nitrogen-Phosphorus Removal System

reactor for 25, 15, 10, 7, and 3 day SRT's were 300, 305, 320, 278, and 328 mg/ℓ, respectively. The corresponding average COD concentrations out of the anaerobic reactor were 112, 120, 143, 120, and 200 mg/ℓ. The average values of F/M at different operational conditions in terms of COD were 1.02 (25 day SRT), 1.46 (15 day SRT), 2.0 (10 day SRT), 2.83 (7 day SRT), and 8.0 (3 day SRT). Figure 36 shows the cumulative percent COD removal in each reactor. In the anaerobic reactor, for the SRT's of 25, 15, 10, 7, and 3 days, the percent COD removal was observed as 26, 23, 20, 33, and 19 percent, respectively. Figure 37 shows the U versus F/M in terms of COD for the anaerobic reactor. Figure 38 shows the graphical determination of the COD removal biokinetic constants for the anaerobic reactor. The constants, U_{max} and K_B, of 1.66 and 4.93 are obtained from this figure.

The average COD fed into the anoxic reactor from the anaerobic reactor for the SRT's of 25, 15, 10, 7, and 3 days were 112, 120, 143, 120, and 200 mg/ℓ, respectively. The average COD concentrations out of the anoxic reactor, which were fed into the aerobic (nitrification) reactor were 18.0, 16.0, 27.0, 20.0, and 48.0 mg/ℓ. The average F/M values in terms of COD for the operated SRT's were 0.4066, 0.5937, 0.8696, 0.9383, and 2.5526. From Figure 36, the total percentage of COD removals through the anoxic reactor for the SRT's of 25, 15, 10, 7, and 3 days are 87.0, 86.5, 84.0, 89.0, and 81.0, respectively. The net percentage of COD removals in the anoxic reactor, based on the raw wastewater COD loading, are 61.0, 63.5, 64.0, 56.0, and 62.0 percent. Figure 39 shows the U versus F/M for the anoxic reactor. Figure 40 shows the graphical determination of biokinetic constants U_{max} and K_B for the anoxic reactor. The values of U_{max} and K_B for COD removal are 18.50 and 21.70, respectively.

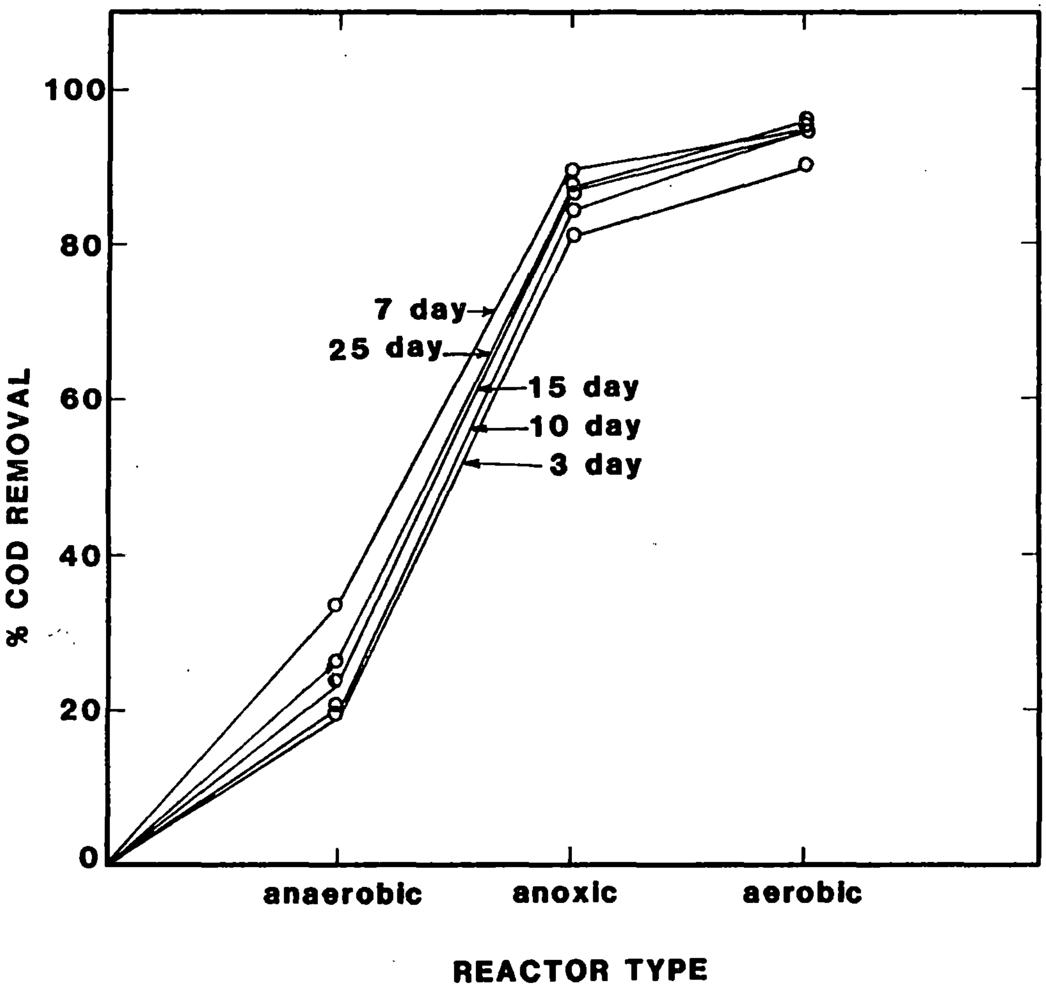


Figure 36. Percent COD Removal in Each Reactor for Combined Nitrogen-Phosphorus Removal System

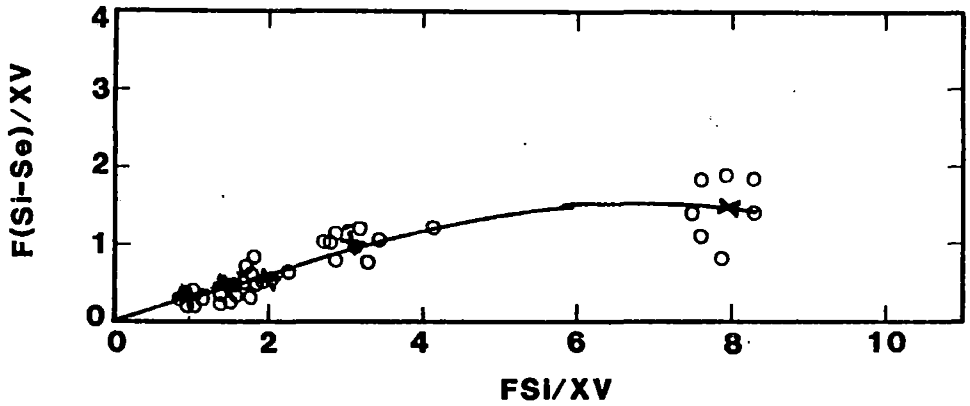


Figure 37. Substrate Utilization as a Function of Mass Substrate Loading in Terms of COD for Anaerobic Reactor of Combined Nitrogen-Phosphorus Removal System

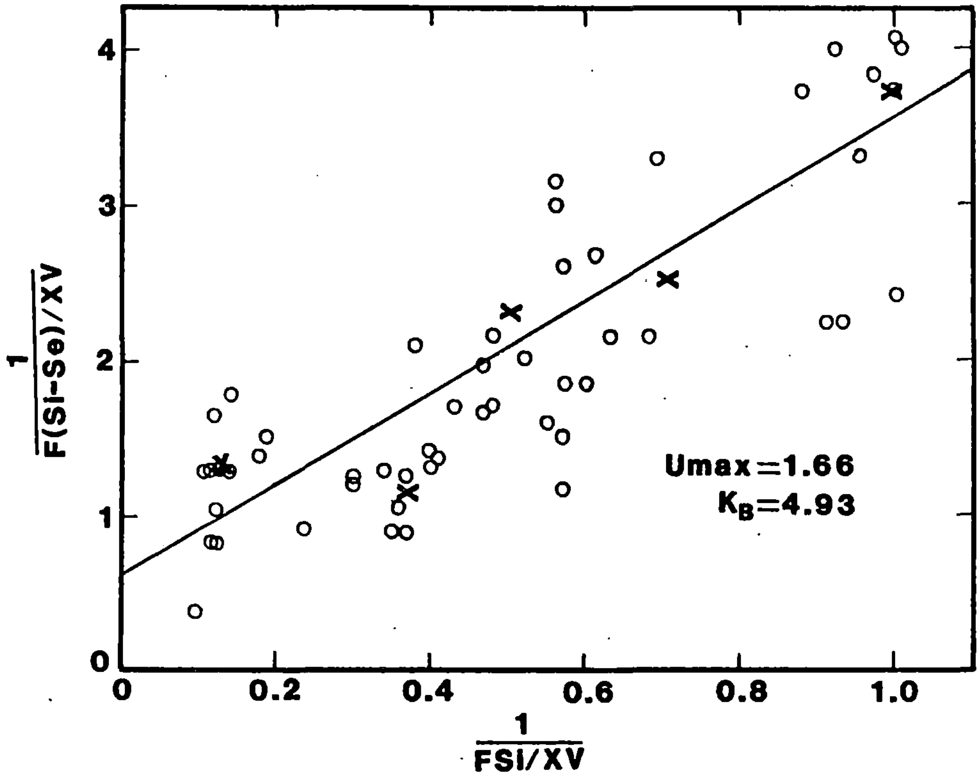


Figure 38. Graphical Determination of U_{max} and K_B in Terms of COD for Anaerobic Reactor of Combined Nitrogen-Phosphorus Removal System

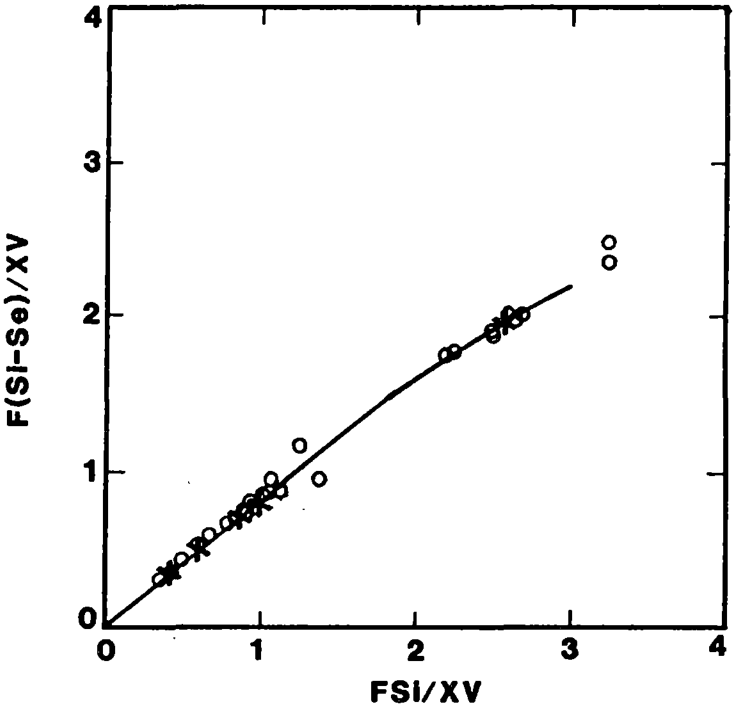


Figure 39. Substrate Utilization as a Function of Mass Substrate Loading in Terms of COD for Anoxic Reactor of Combined Nitrogen-Phosphorus Removal System

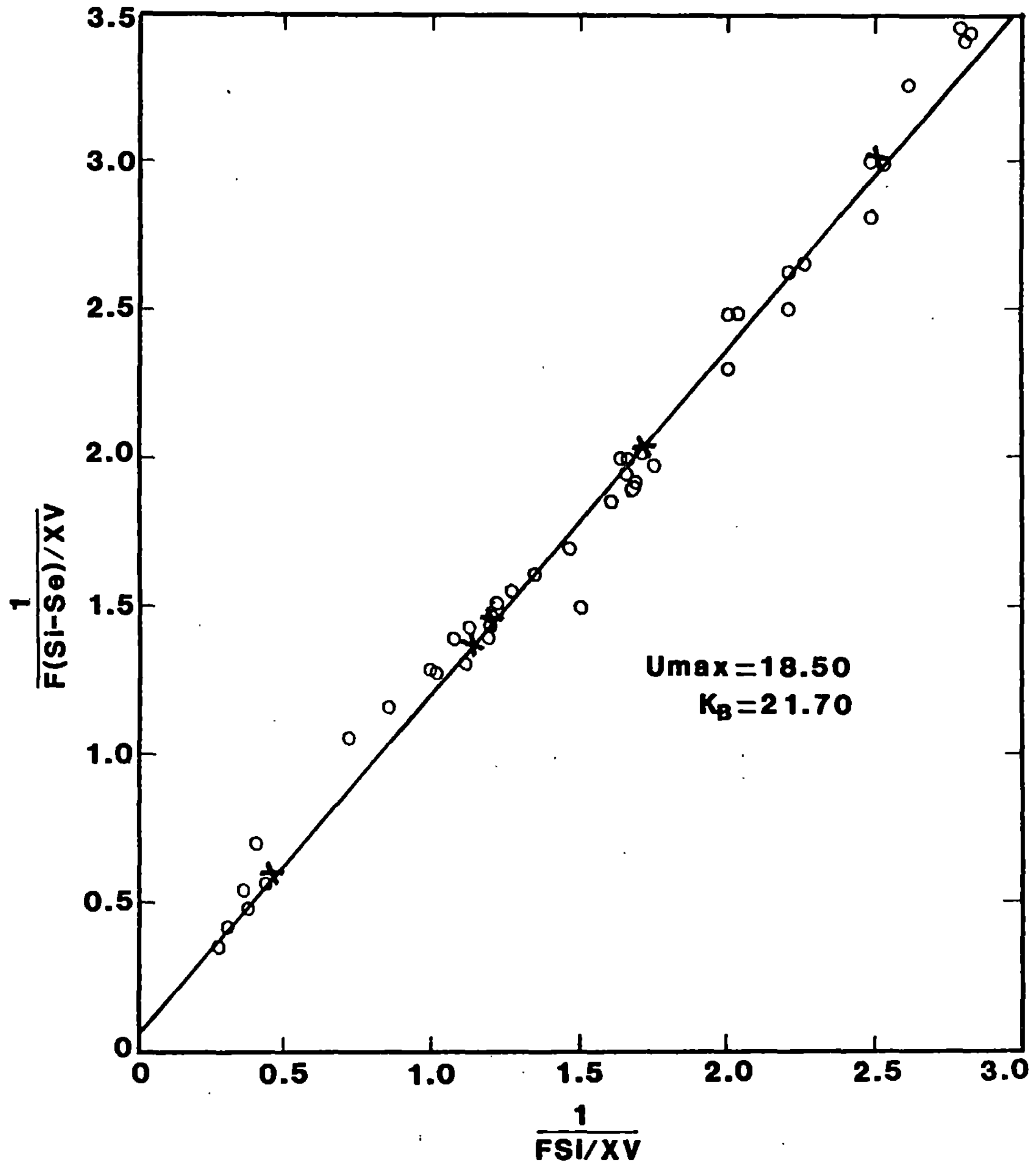


Figure 40. Graphical Determination of U_{max} and K_B in Terms of COD for Anoxic Reactor of Combined Nitrogen-Phosphorus Removal System

The average COD concentration in the final clarified effluent (out of aerobic reactor) was around 12.0 mg/ℓ for all conditions except for the SRT of 3 days, which was around 32.0 mg/ℓ. From Figure 36, it can be seen that the percent COD removal through the entire system was around 95 percent for all conditions except for 3 day SRT, which was around 90 percent. Figure 41 shows the graphical determination of Y_t and K_d for COD removal through the entire system. The values are 0.40 and -0.02.

NH3-N Removal

The average NH_3-N concentration of the raw wastewater varied between 25.4 and 31.0 mg/ℓ. The average TKN for the raw wastewater ranged between 27.0 and 33.0 mg/ℓ. The changes in the NH_3-N concentration and mass NH_3-N loading for the anaerobic, anoxic, and aerobic reations are shown in Figures 42 through 51 for the SRT's of 25, 15, 10, 7, and 3 days. An increase in mass NH_3-N was observed in the anaerobic reactor for all conditions. This can be seen from the mass NH_3-N versus time plots (Figures 43, 45, 47, 49, 51). Figure 52 shows that the net average percentage of mass NH_3-N increased (released) as a function of SRT for the anaerobic reactor. From this figure, it can be seen that a maximum NH_3-N of 50 percent was released at the 15 day SRT. The release was less for the 25 day SRT as well as the 10, 7, and 3 day SRT's. The average NH_3-N concentration in the final clarified effluent was around 0.35 mg/ℓ for all SRT's except for the 3 day SRT, for which it was 4.90 mg/ℓ. The TKN was around 0.6 mg/ℓ for 25, 15, 10, and 7 day SRT's, whereas 5.2 mg/ℓ was observed for the 3 day SRT. The average NO_3-N concentrations in the final effluent were 0.75, 1.00, 0.60, 0.45, and 0.70 mg/ℓ for the SRT's of 25, 15, 10, 7, and 3 days, respectively. There was no NO_3-N

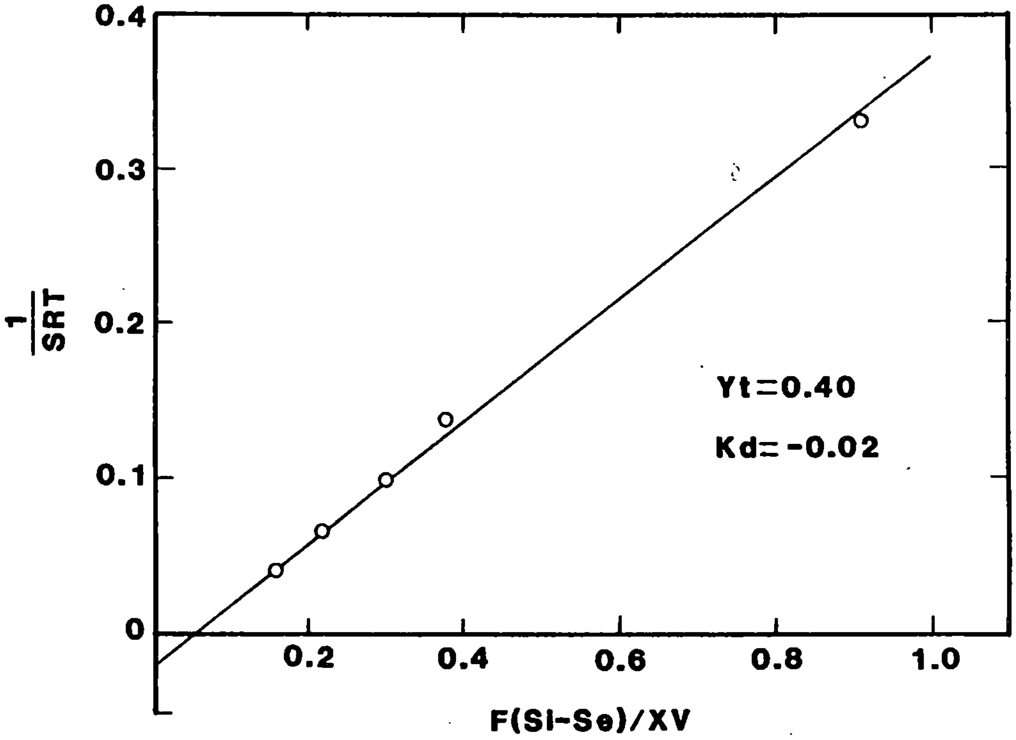


Figure 41. Graphical Determination of Y_t and K_d in Terms of COD for Combined Nitrogen-Phosphorus Removal System

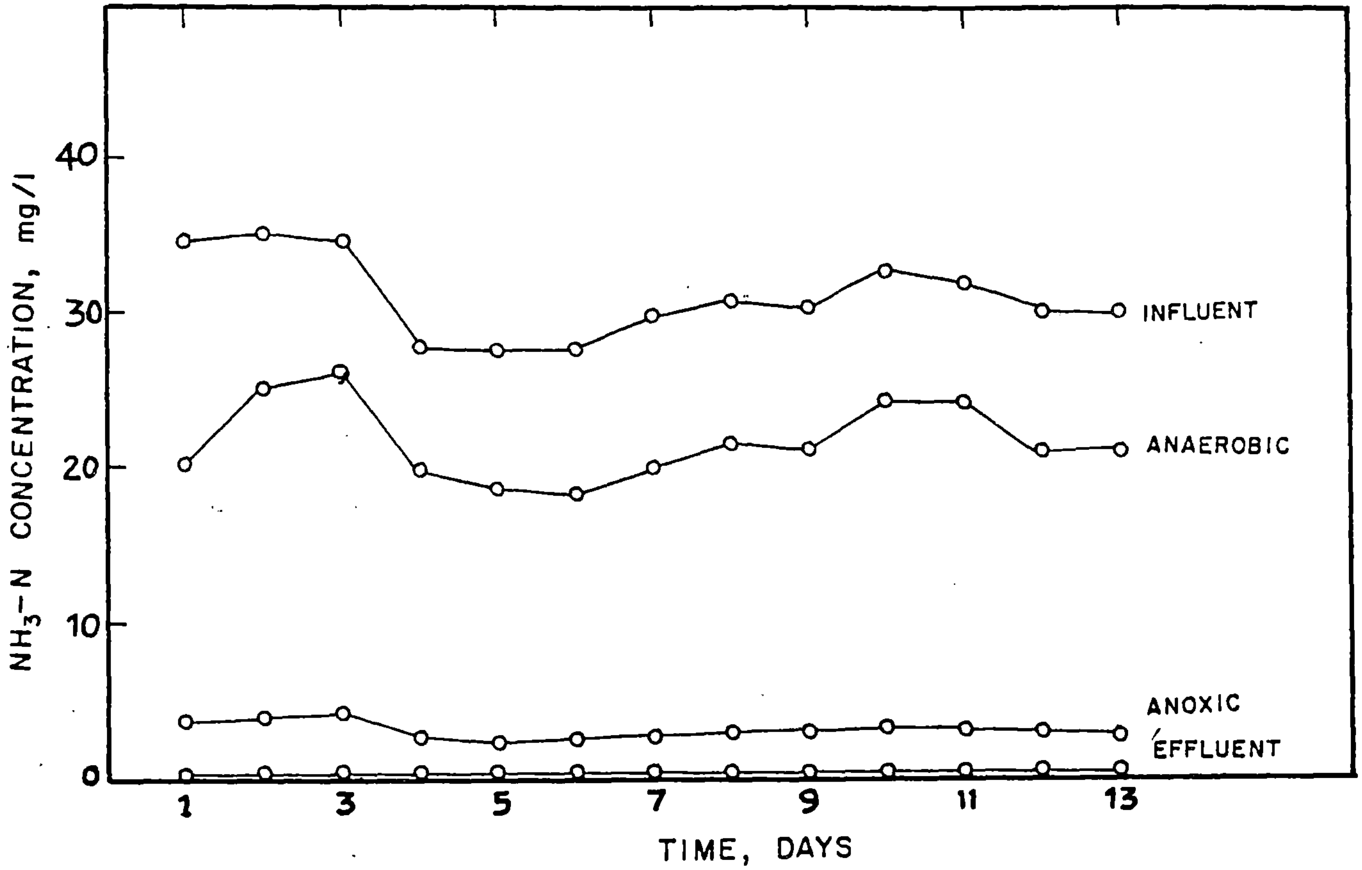


Figure 42. NH_3-N Concentration Versus Time for Combined Biological Nitrogen-Phosphorus Removal System at 25-Day SRT

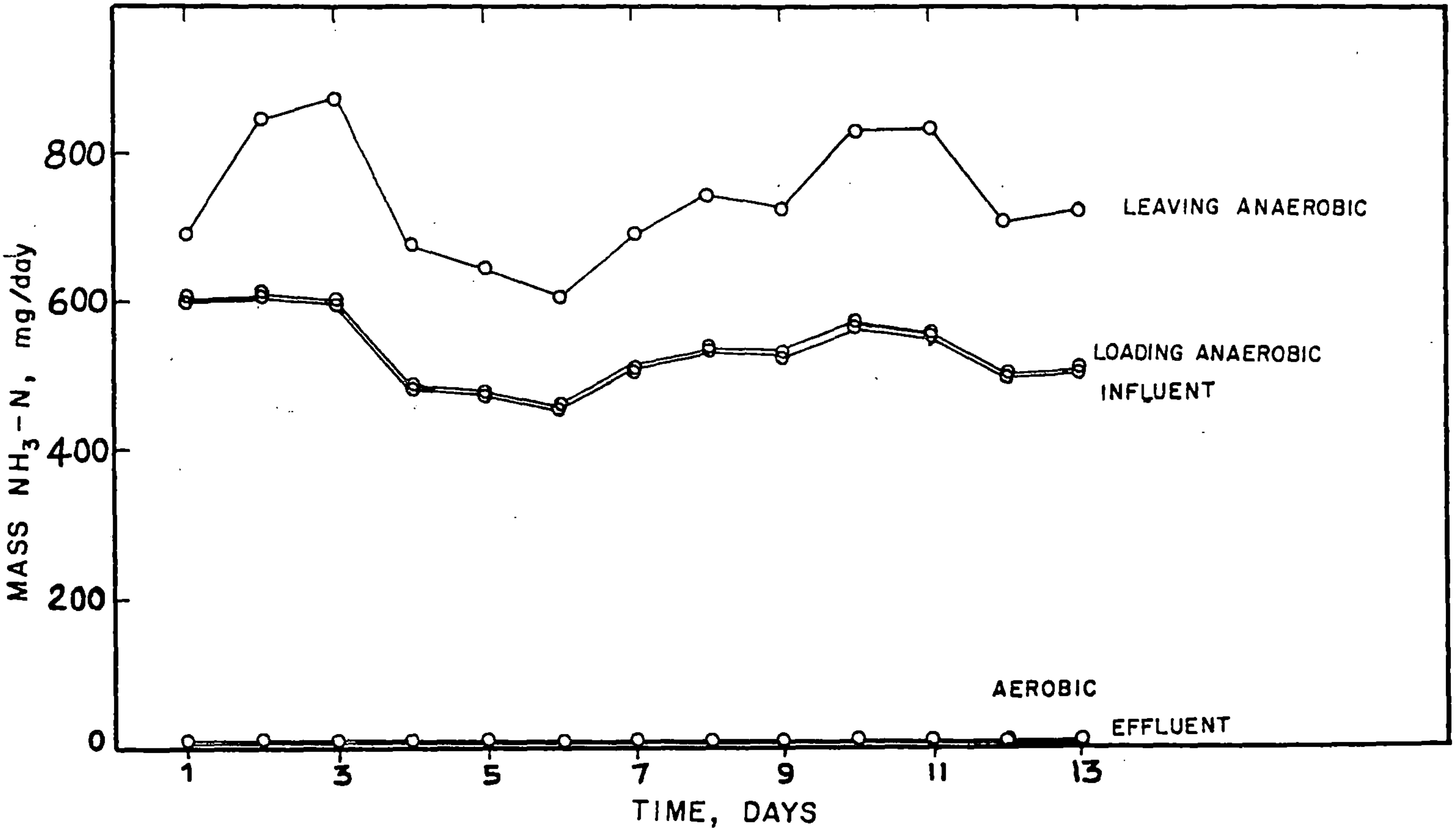


Figure 43. Mass NH_3-N Versus Time for Combined Nitrogen-Phosphorus Removal System at 25-Day SRT

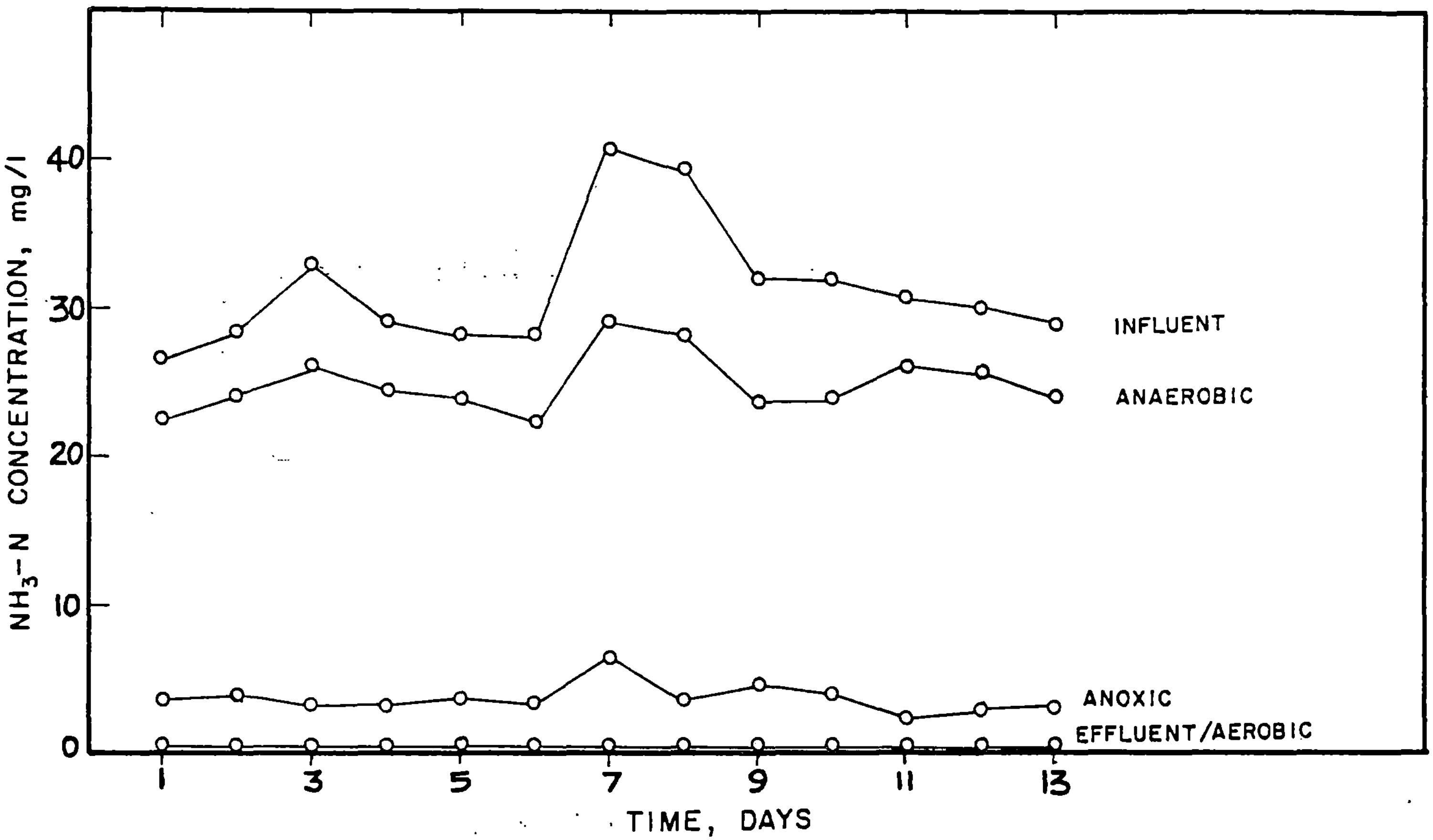


Figure 44. NH_3-N Concentration Versus Time for Combined Nitrogen-Phosphorus Removal System at 15-Day SRT

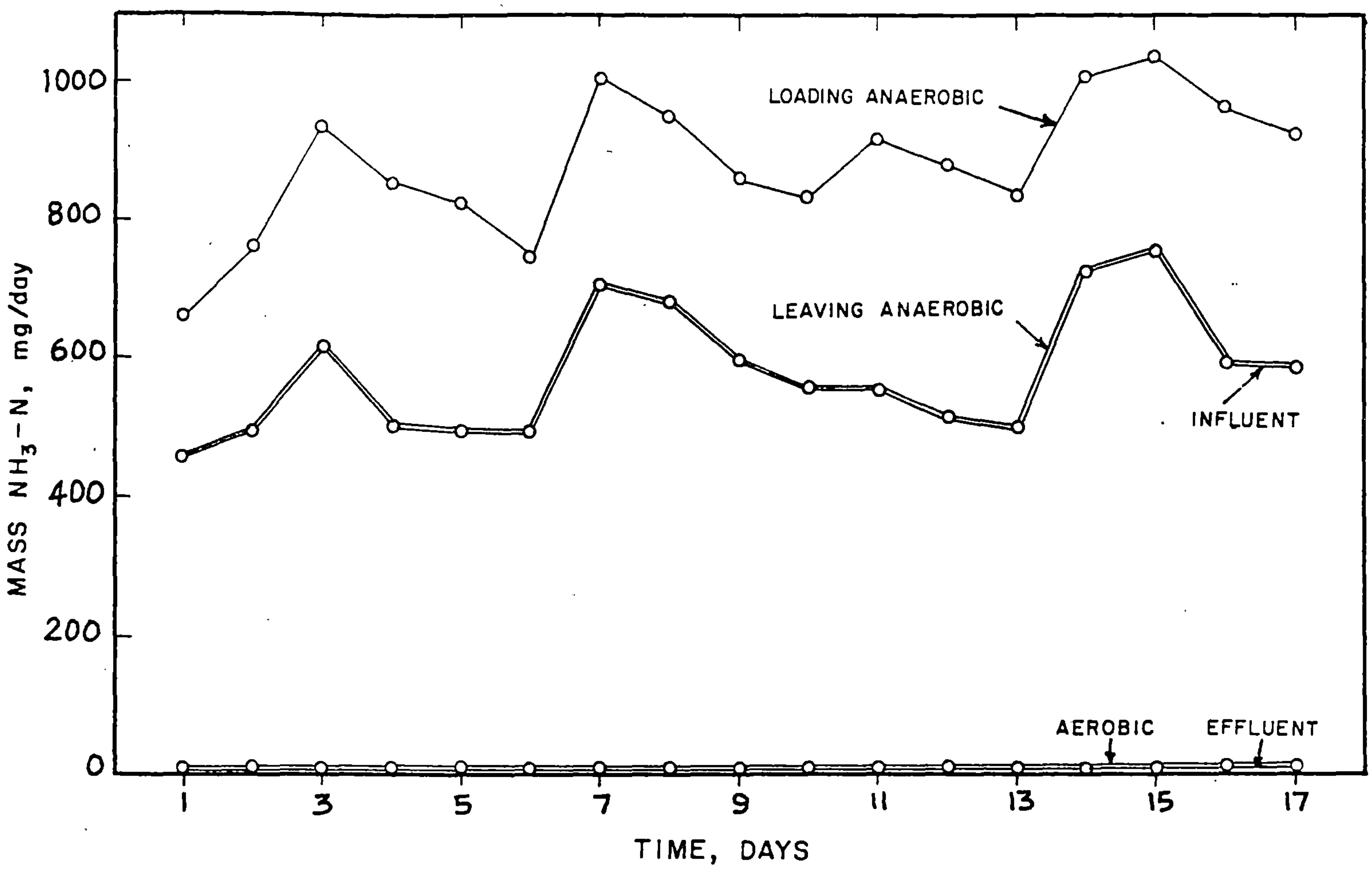


Figure 45. Mass NH_3-N Versus Time for Combined Nitrogen-Phosphorus Removal System at 15-Day SRT

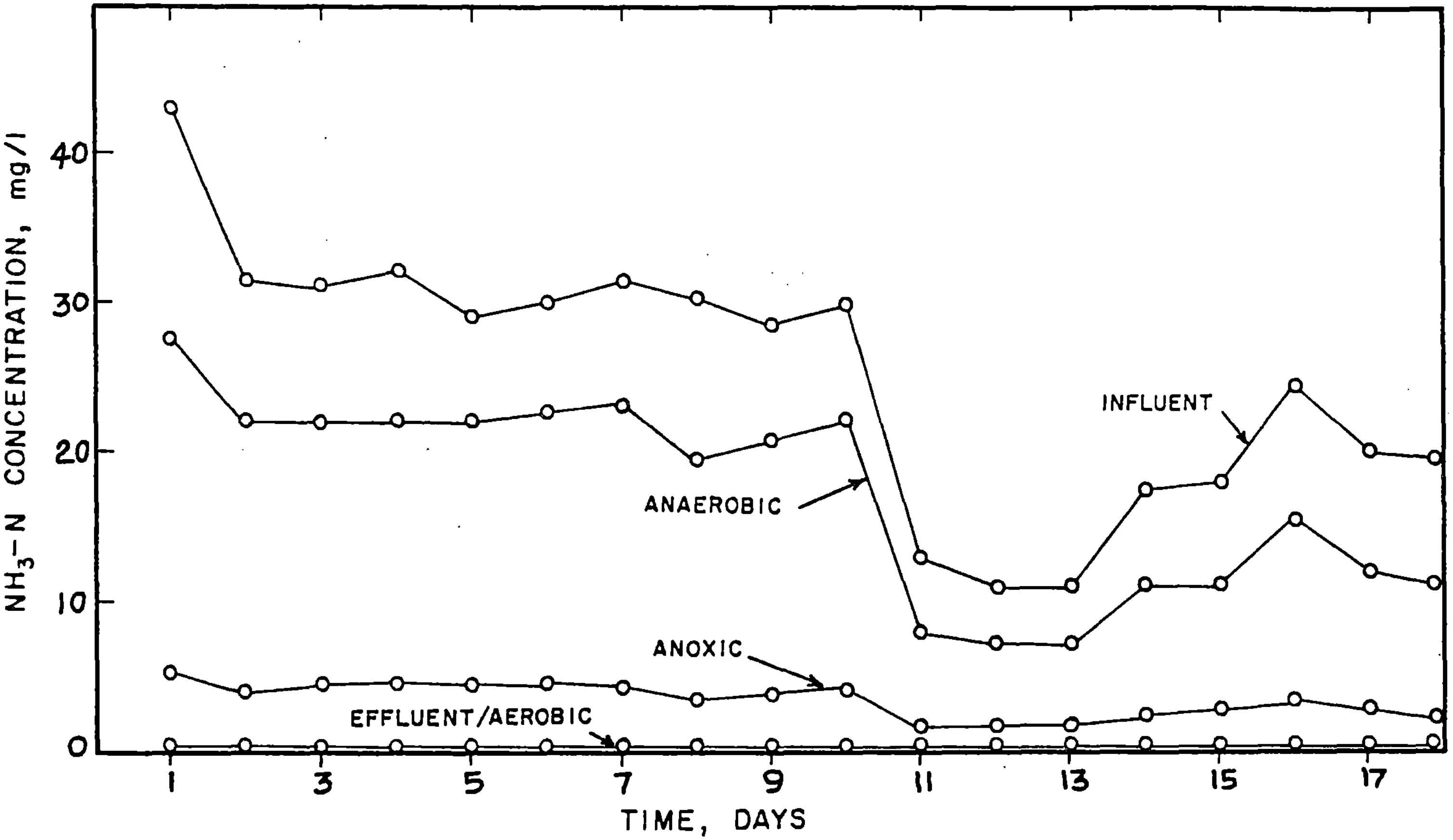


Figure 46. NH_3-N Concentration Versus Time for Combined Nitrogen-Phosphorus Removal System at 10-Day SRT

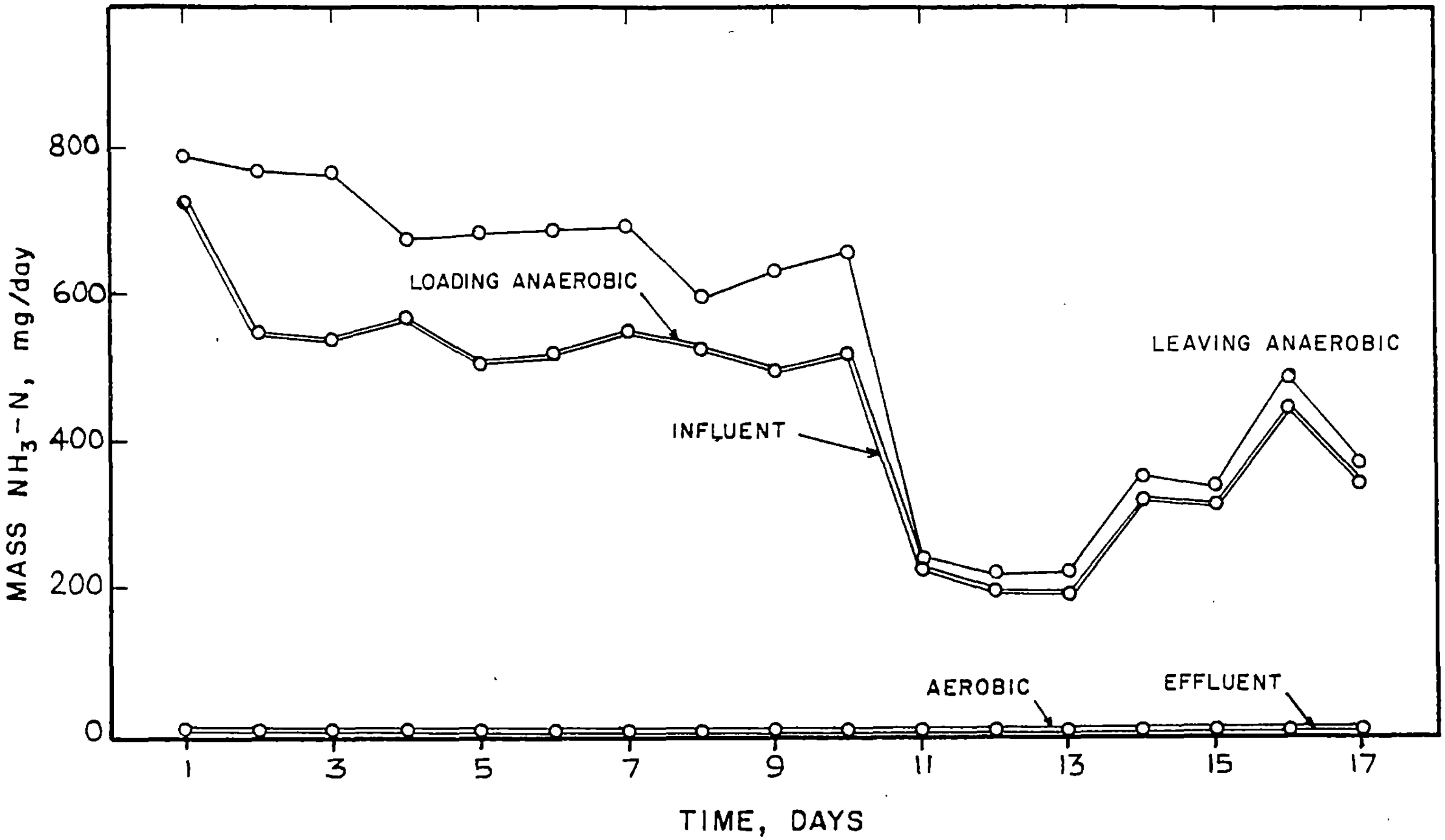


Figure 47. Mass NH_3-N Versus Time for Combined Nitrogen-Phosphorus Removal System at 10-Day SRT

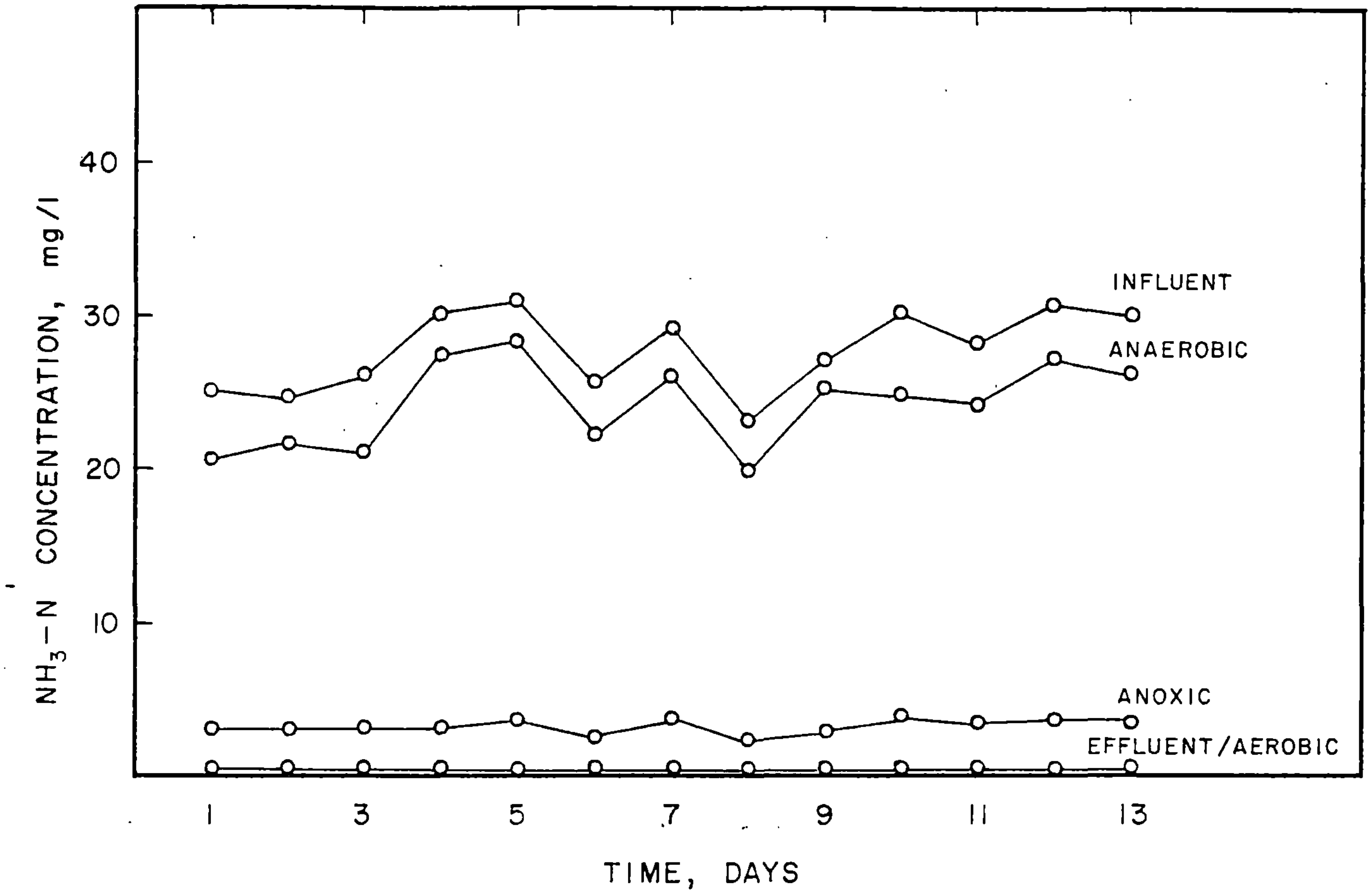


Figure 48. NH_3-N Concentration Versus Time for Combined Nitrogen-Phosphorus Removal System at 7-Day SRT

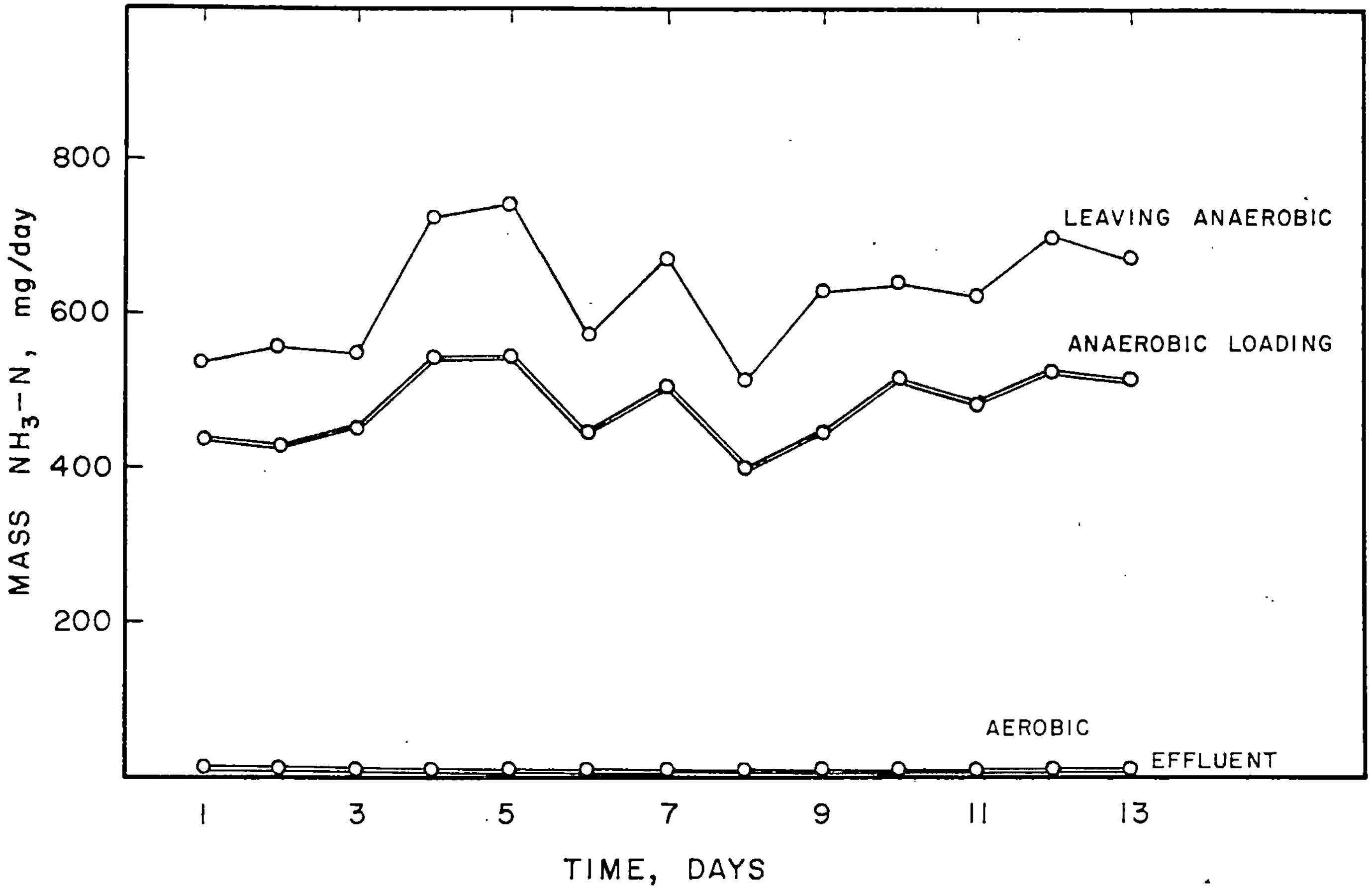


Figure 49. Mass NH_3-N Versus Time for Combined Nitrogen-Phosphorus Removal System at 7-Day SRT

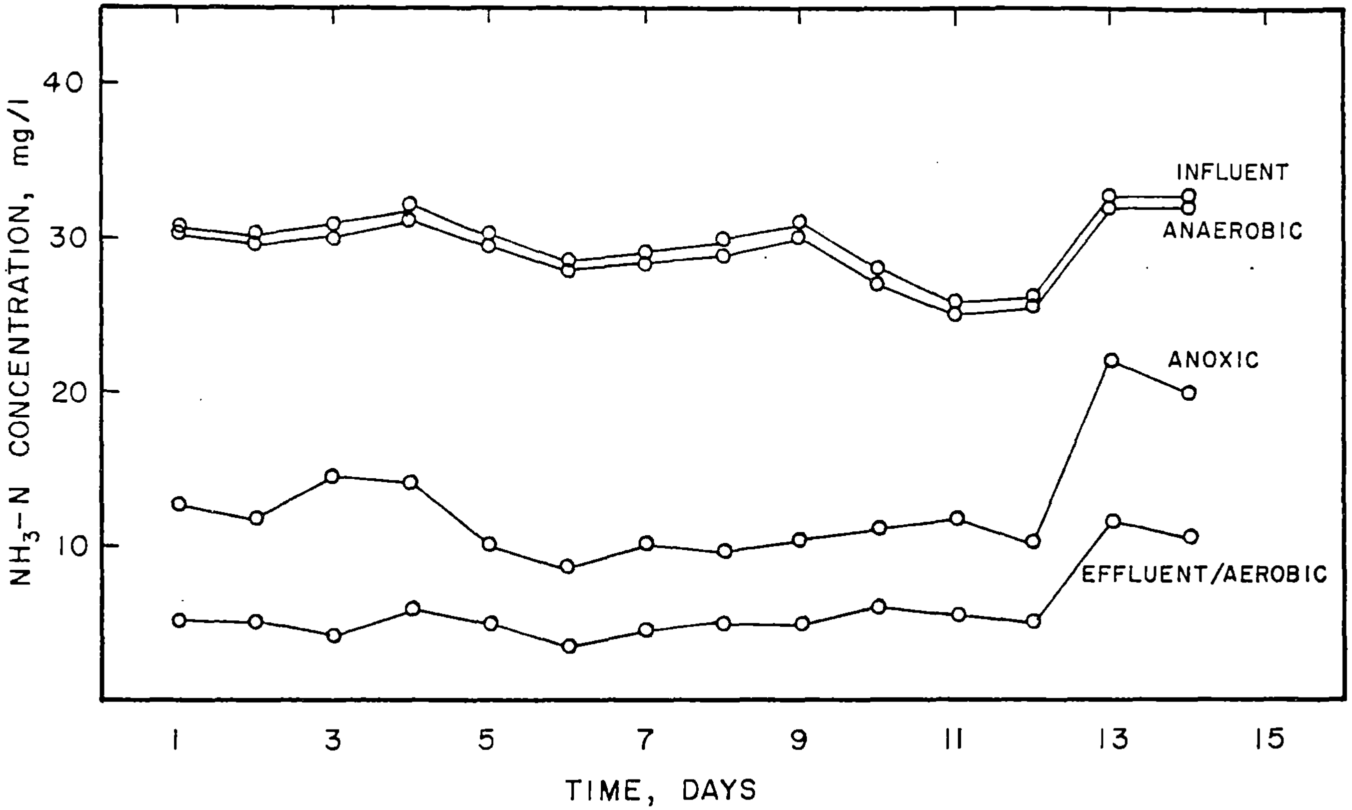


Figure 50. NH3-N Concentration Versus Time for Combined Nitrogen-Phosphorus Removal System at 3-Day SRT

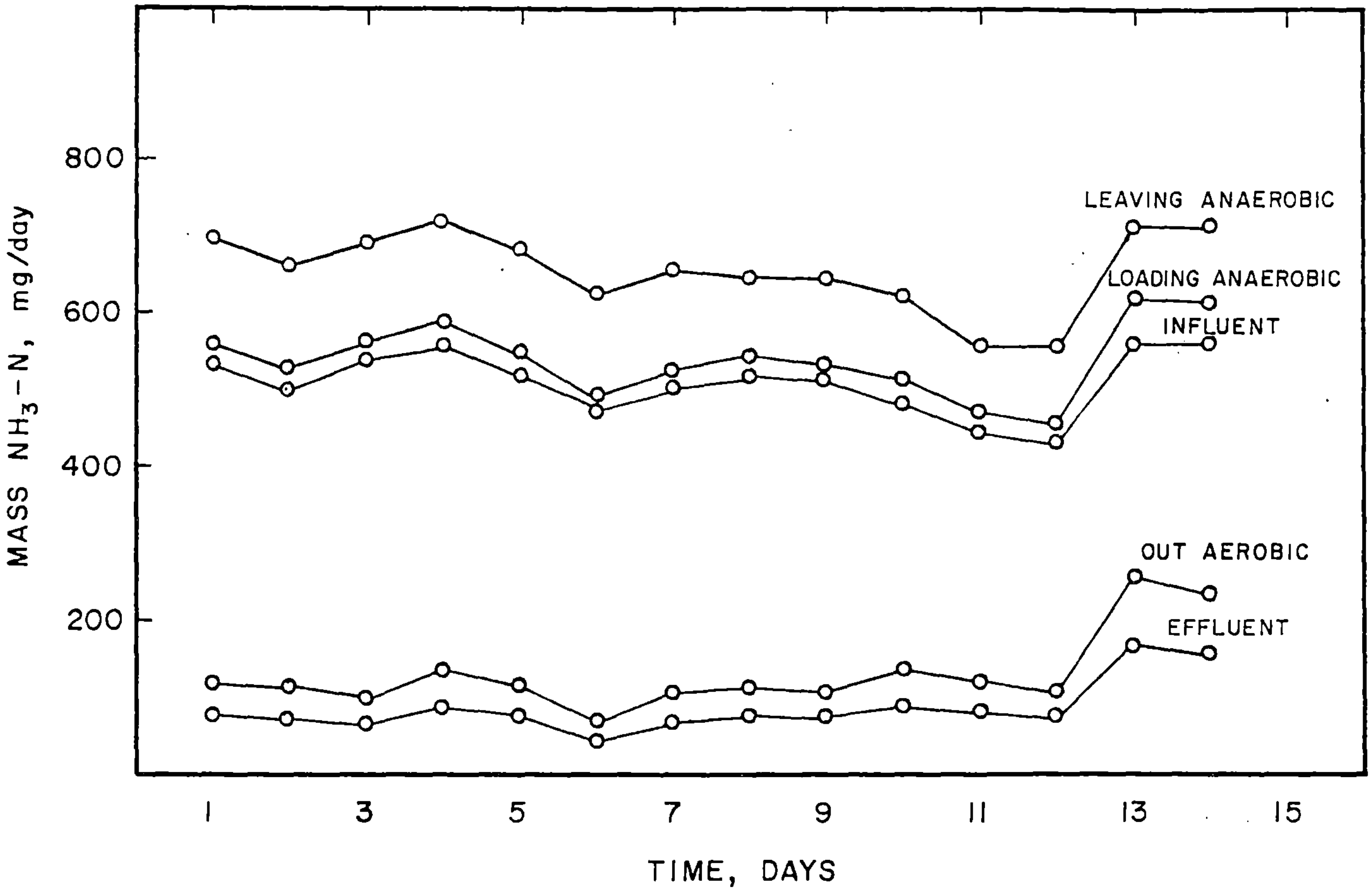


Figure 51. Mass NH_3-N Versus Time for Combined Nitrogen-Phosphorus Removal System at 3-Day SRT

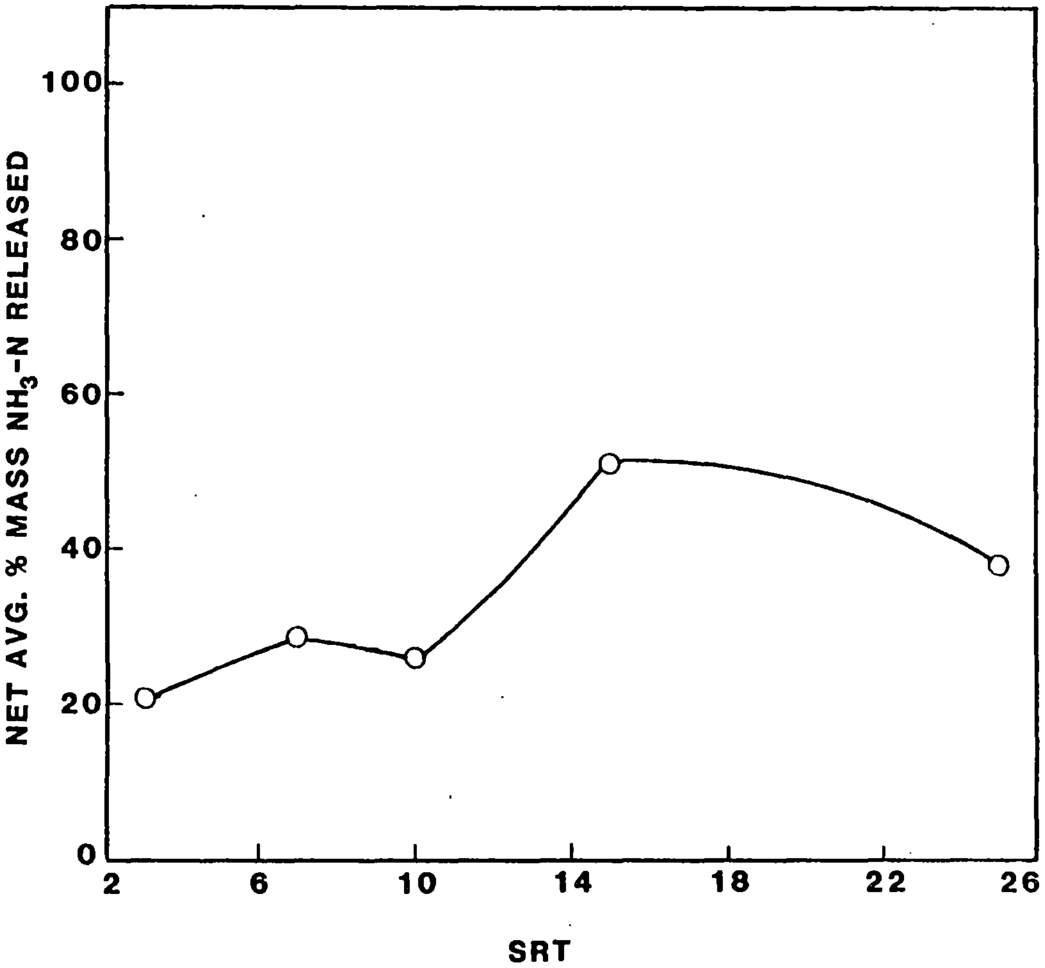


Figure 52. Net Average Percent Mass NH_3-N Released as a Function of SRT for Anaerobic Reactor of Combined Nitrogen-Phosphorus Removal System

concentration observed in the anoxic reactor. Thus complete denitrification was achieved in the anoxic reactor by recycling the nitrified mixed liquor from the aerobic reactor at the rate of 5:1 to 6:1 based on forward flow. The average F/M values in terms of NH_3-N (out of the anaerobic reactor) to the aerobic reactor were 0.0393, 0.0631, 0.0594, 0.0815, and 0.1803 for the SRT's of 25, 15, 10, 7, and 3 days, respectively.

Figure 53 shows the percentage of NH_3-N removed as a function of SRT. From this figure it can be seen that the removal was more than 98 percent, except for the 3 day SRT (0.1803 F/M) for which it was 83 percent. Figure 54 shows the U versus F/M in terms of NH_3-N for the aerobic reactor. Figure 55 shows the graphical determination of the biokinetic constants U_{max} and K_B for NH_3-N removal (nitrification). The values are 1.00 and 0.97. From Figure 56, Y_t and K_d are determined as 5.12 and -0.05. Biokinetic constants for BOD, COD, and NH_3-N removal are summarized in Table XX.

Phosphorus Removal

From Tables XV through XIX, the average ortho-P concentrations of the influent (raw wastewater) varied from 6.5 to 11.6 mg/ℓ. The average total phosphorus concentrations varied between 7.5 and 13.0 mg/ℓ. The influent low phosphorus concentration of 6.5 mg/ℓ was observed for the 7 day SRT operating condition. The final clarified effluent ortho-P concentrations varied based on the influent concentration and operating condition. The average ortho-P concentrations were 4.7, 5.2, 5.0, 3.7, and 7.8 mg/ℓ for the SRT's of 25, 15, 10, 7, and 3 days. The corresponding total phosphorus concentrations were 5.00, 5.35, 5.20, 3.85, and 8.00 mg/ℓ.

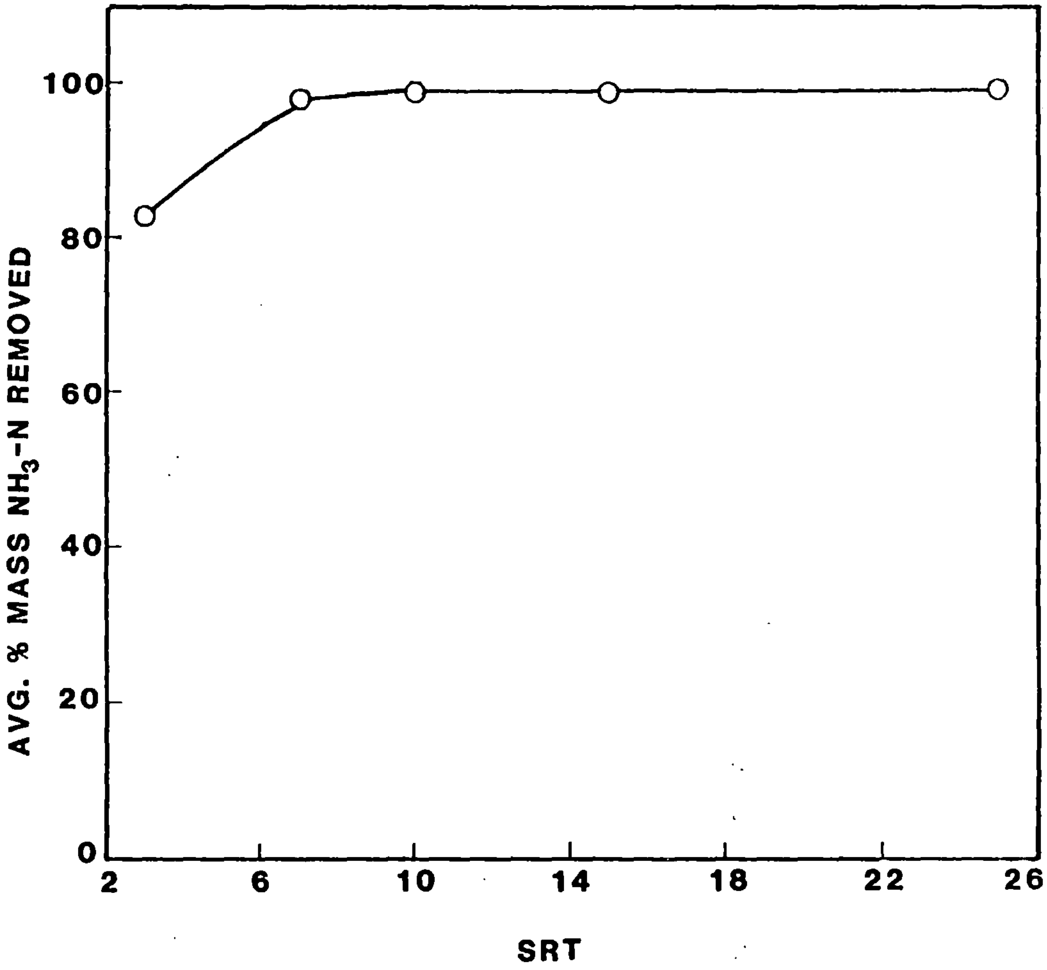


Figure 53. Average Percent Mass NH_3-N Removed as a Function of SRT for Combined Nitrogen-Phosphorus Removal System

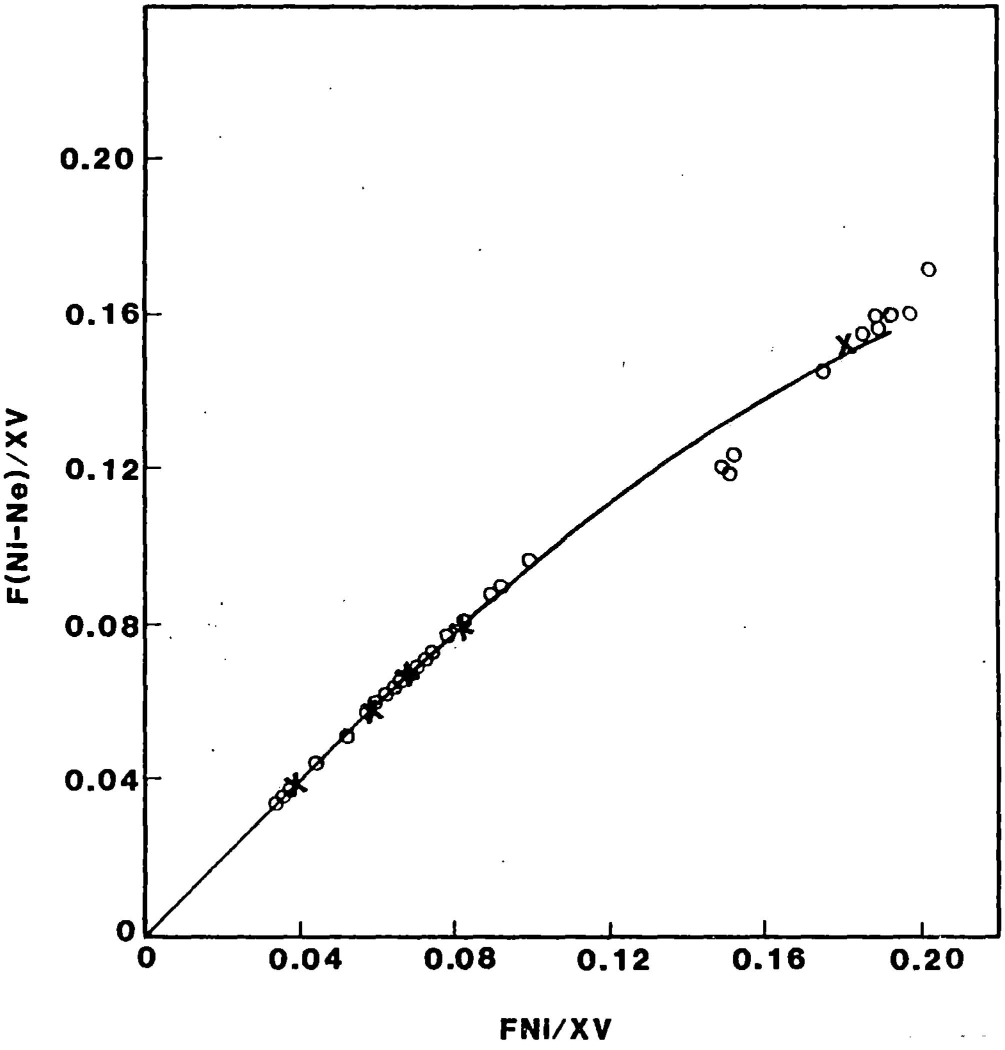


Figure 54. Substrate Utilization as a Function of Mass Substrate Loading in Terms of NH_3-N for Aerobic Reactor of Combined Nitrogen-Phosphorus Removal System

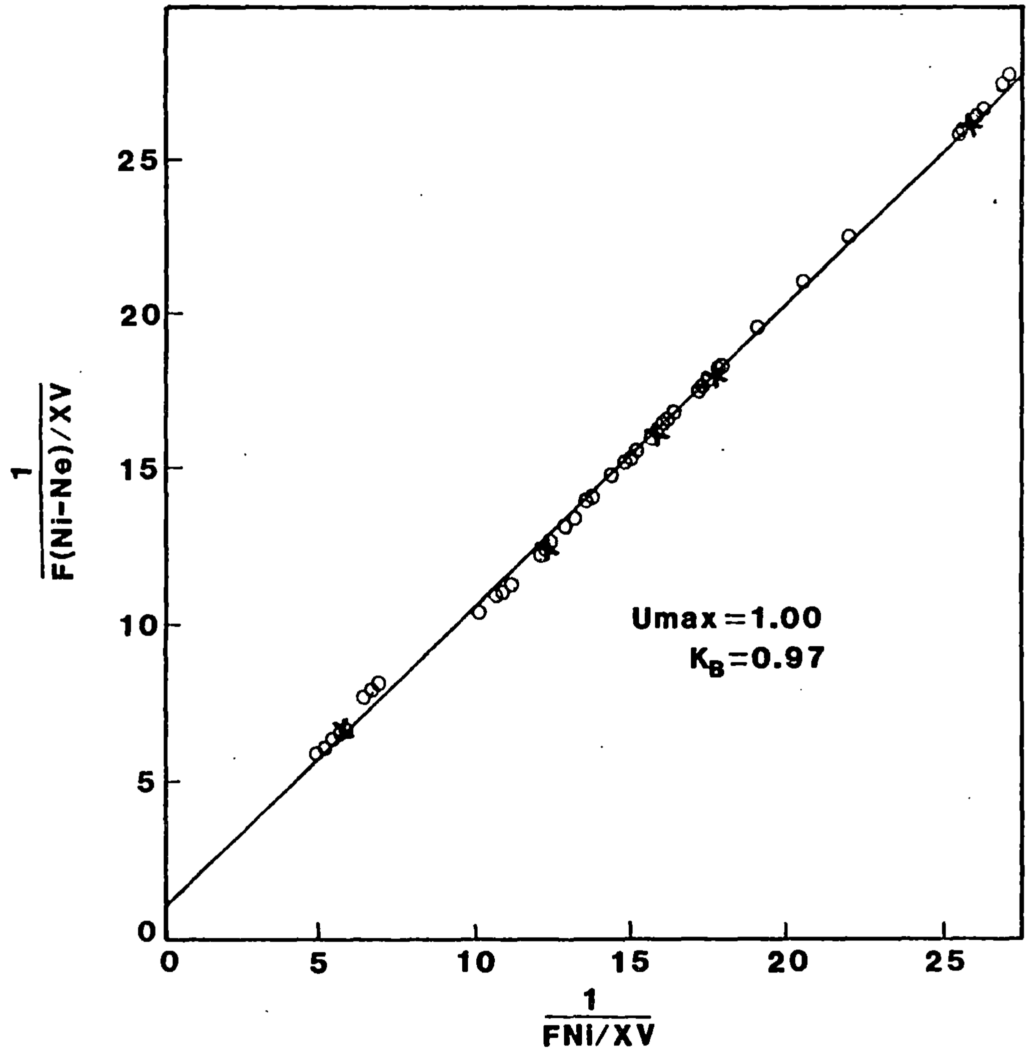


Figure 55. Graphical Determination of U_{max} and K_B in Terms of NH_3-N for Aerobic Reactor of Combined Nitrogen-Phosphorus Removal System

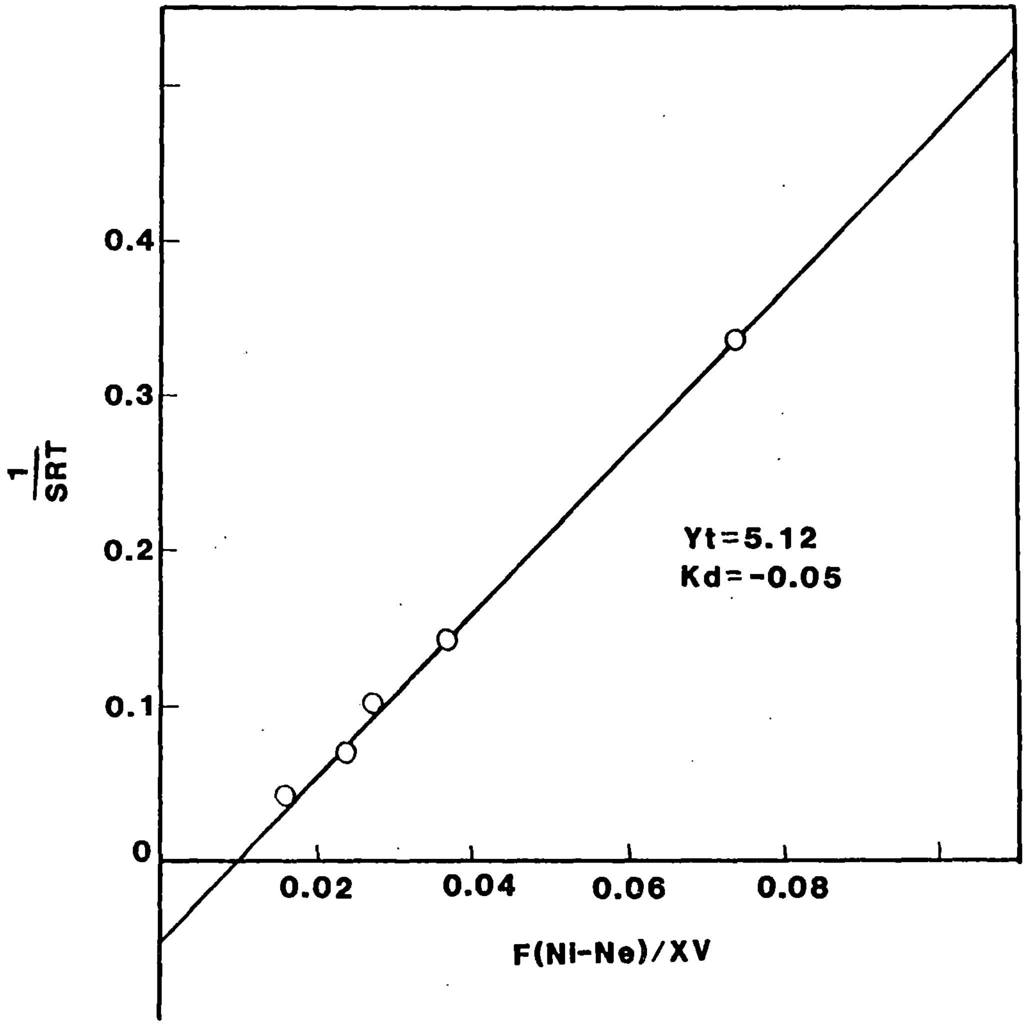


Figure 56. Graphical Determination of Y_t and K_d in Terms of NH_3-N for Combined Nitrogen-Phosphorus Removal System

TABLE XX

SUMMARY OF KINETIC CONSTANTS FOR COMBINED NITROGEN-PHOSPHORUS REMOVAL SYSTEM

	Anaerobic		Anoxic		Aerobic		Total System	
Description	U_{max}	K_B	U_{max}	K_B	U_{max}	K_B	Y_t	$-K_d$
BOD	4.00	5.60	2.10	2.30	---	---	1.05	0.02
COD	1.66	4.93	18.50	21.70	---	---	0.40	0.02
NH_3-N	---	---	---	---	1.00	0.97	5.12	0.05

The influent raw wastewater was analyzed for total phosphorus and ortho-phosphorus. The total phosphorus was higher than the ortho-phosphorus due to the presence of other forms of phosphorus in the influent such as organically bound phosphates and condensed (pyro, meta or other poly) phosphate. Filtered samples were collected from anaerobic reactor, anoxic reactor, aerobic reactor, and effluent, and analyzed for total and ortho-phosphorus concentrations. The total phosphorus and ortho-phosphorus concentrations were the same in these reactors and in the effluent, due to the breakdown of different forms of phosphates into ortho-phosphates in the anaerobic reactor. Therefore, the feed was analyzed for both total and ortho-phosphorus and remaining stages were analyzed only for ortho-phosphorus.

For each operating condition (SRT), the ortho-P concentration (except influent which is total P) was plotted against time in days, for feed, anaerobic reactor, anoxic reactor, aerobic reactor, and the effluent. These are shown in Figures 57, 59, 61, 63, and 65. From these figures, it can be seen there was considerable release of phosphorus in the anaerobic reactor. In order to have a better understanding, the mass phosphorus in mg/day is also plotted against time in days for all SRT's. The concentration plots did not show the actual phosphorus released in the anaerobic reactor due to external recycle, which dilutes the concentration of phosphorus in the anaerobic reactor. There was a phosphorus loading on the anaerobic reactor due to external recycle also. Thus the mass phosphorus loading was calculated for each reactor and plotted against time. The mass phosphorus going out in the effluent was also plotted. These are shown in Figures 58, 60, 62, 64, and 66. From both concentration and mass plots, we can see that the maximum release of

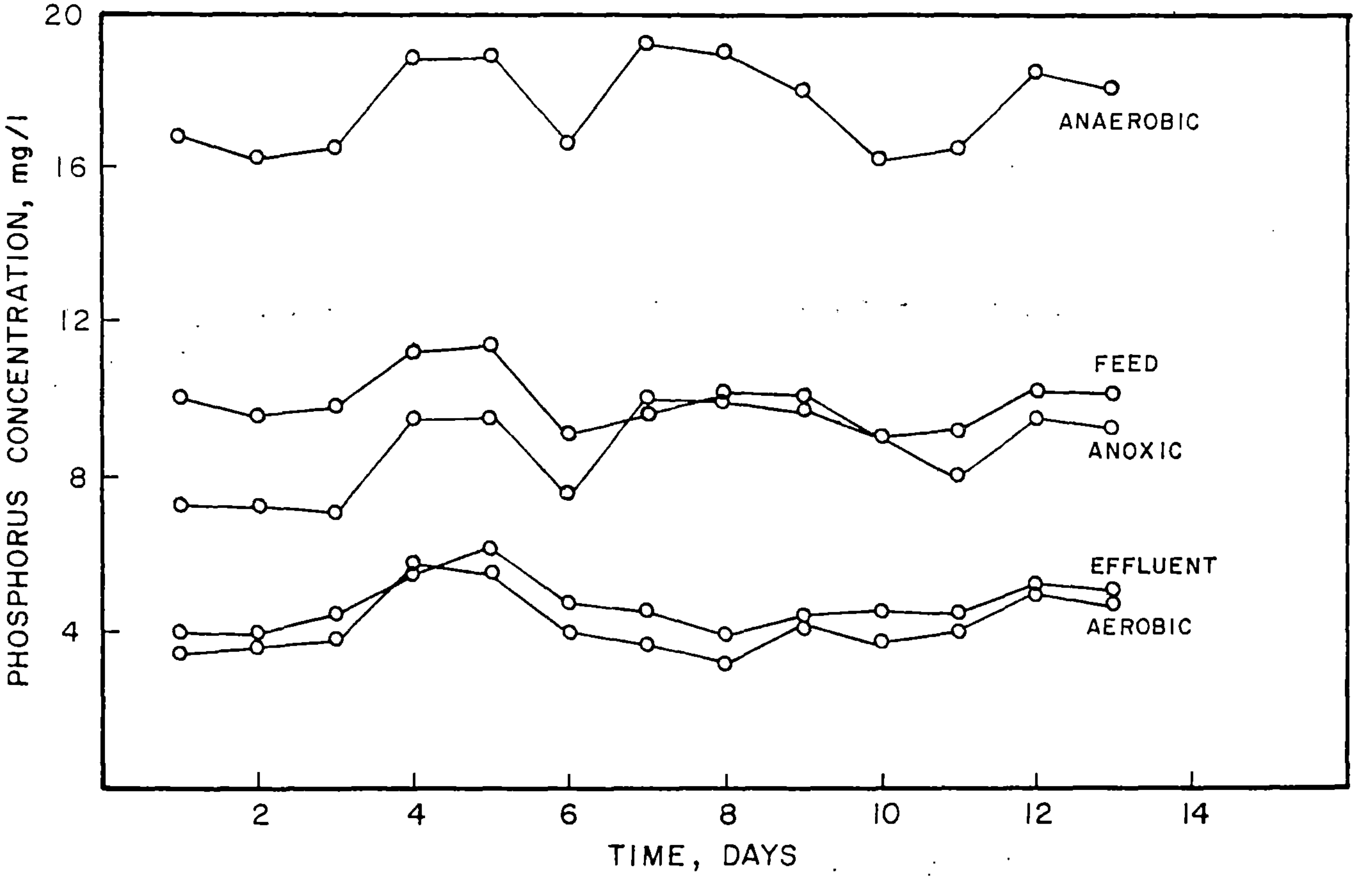


Figure 57. Ortho-P Concentration Versus Time for Combined Nitrogen-Phosphorus Removal System at 25-Day SRT

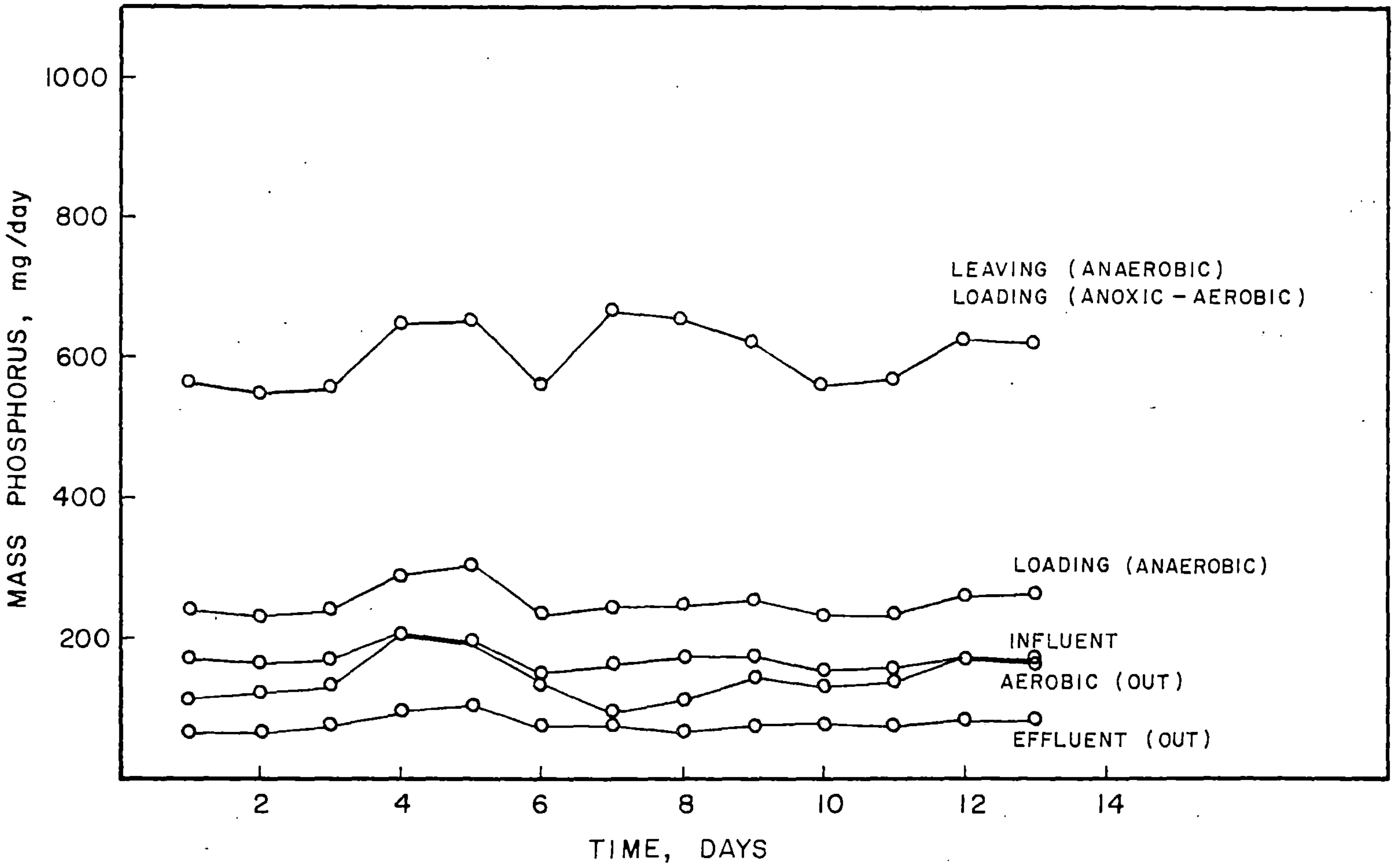


Figure 58. Mass Ortho-P Versus Time for Combined Nitrogen-Phosphorus Removal System at 25-Day SRT

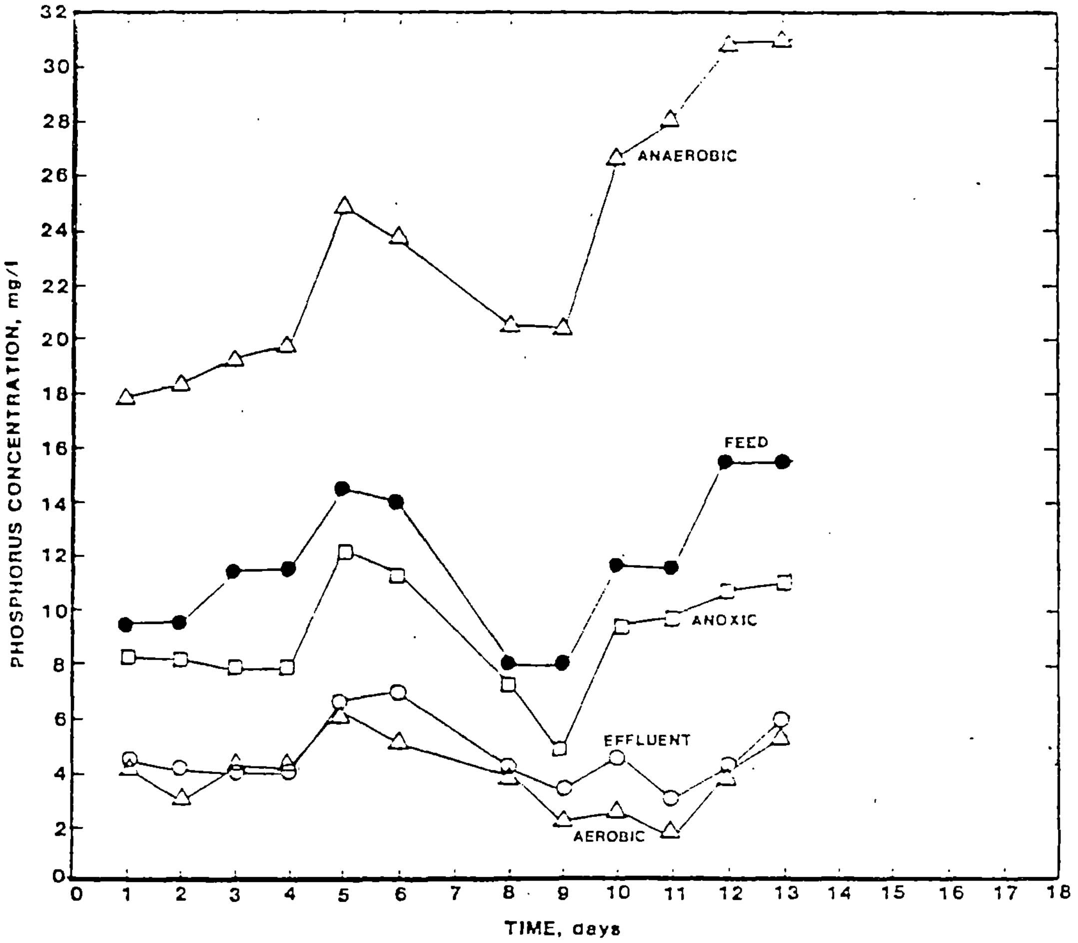


Figure 59. Ortho-P Concentration Versus Time for Combined Nitrogen-Phosphorus Removal System at 15-Day SRT

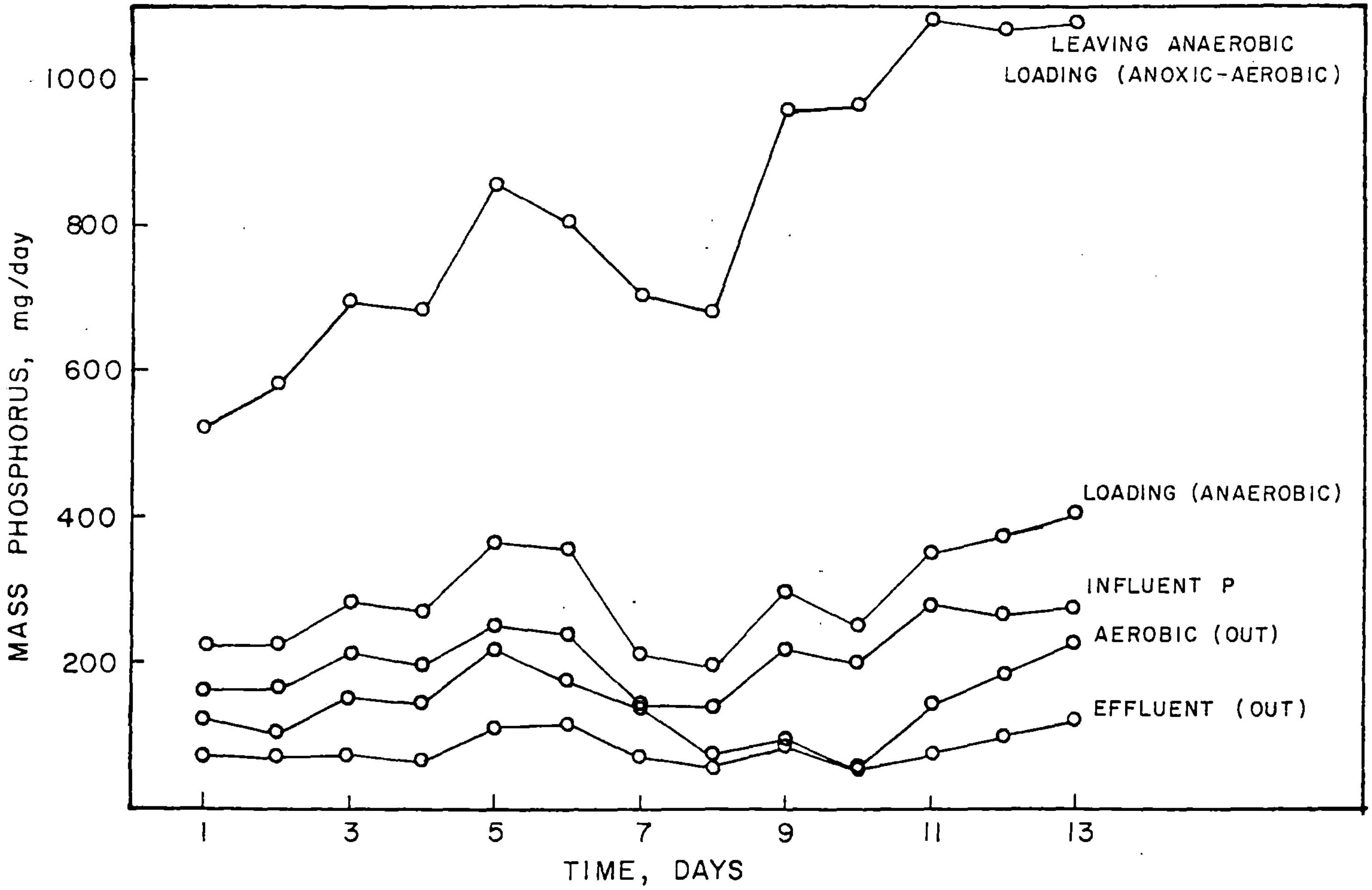


Figure 60. Mass Ortho-P Versus Time for Combined Nitrogen-Phosphorus Removal System at 15-Day SRT

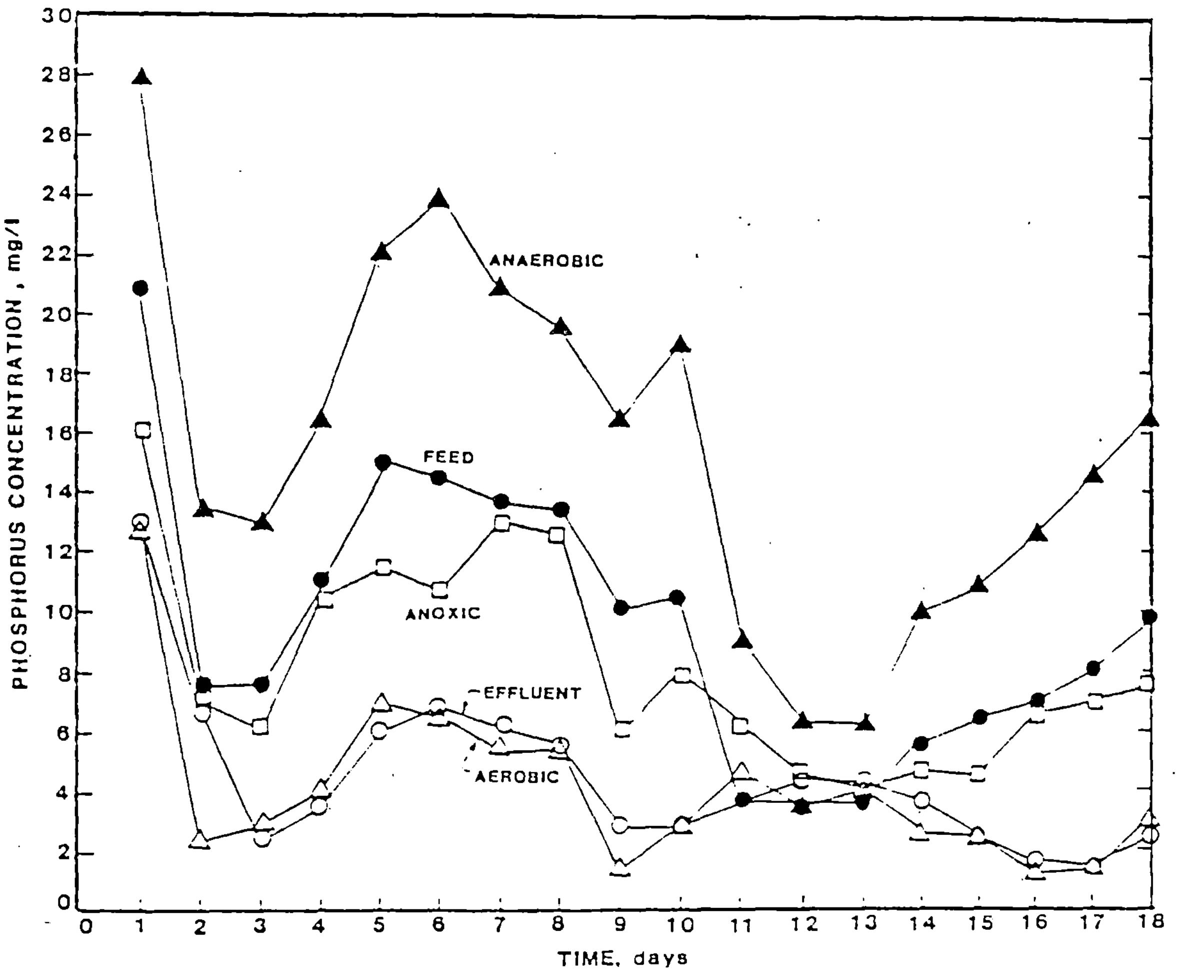


Figure 61. Ortho-P Concentration Versus Time for Combined Nitrogen-Phosphorus Removal System at 10-Day SRT

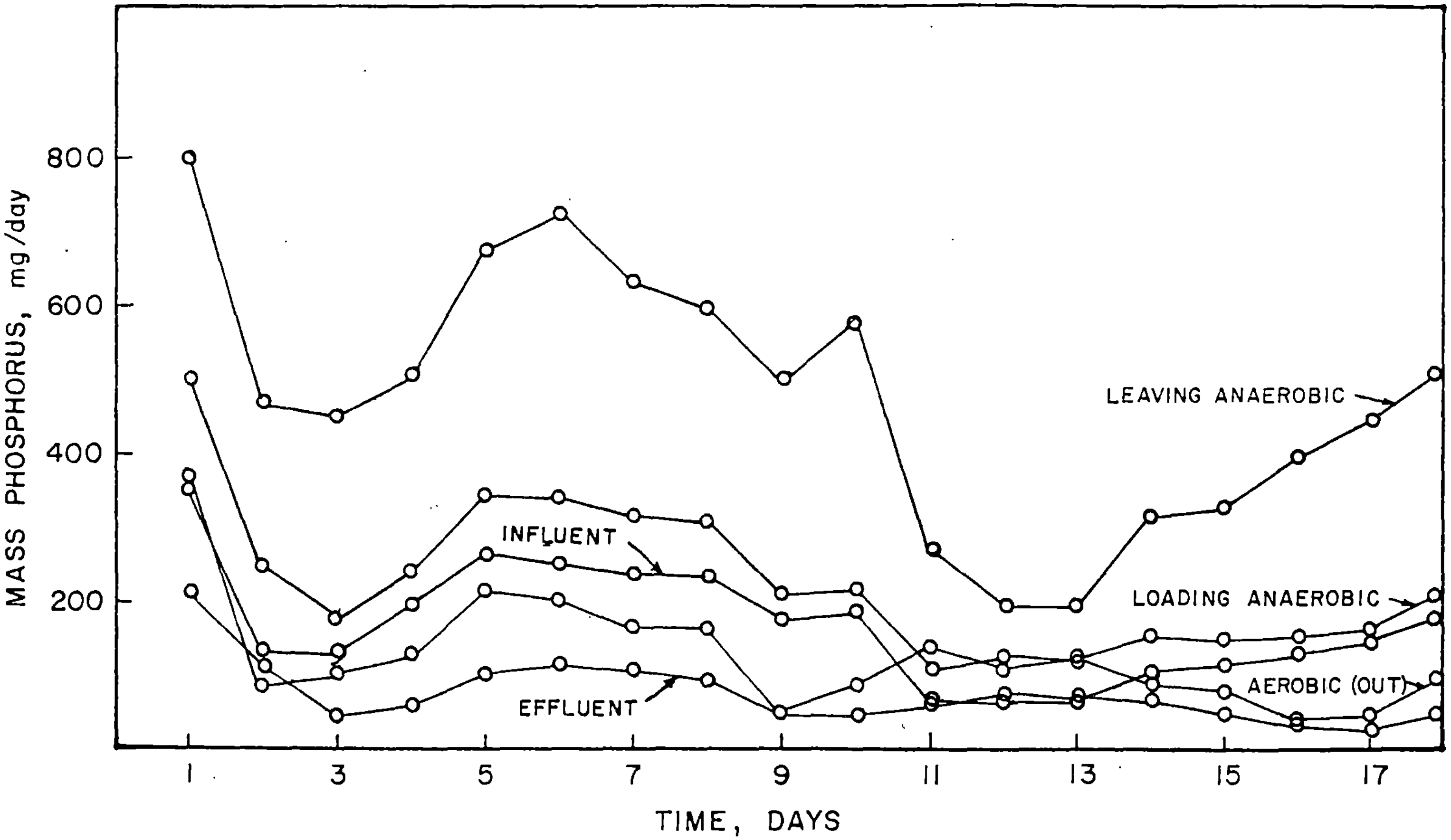


Figure 62. Mass Ortho-P Versus Time for Combined Nitrogen-Phosphorus Removal System at 10-Day SRT

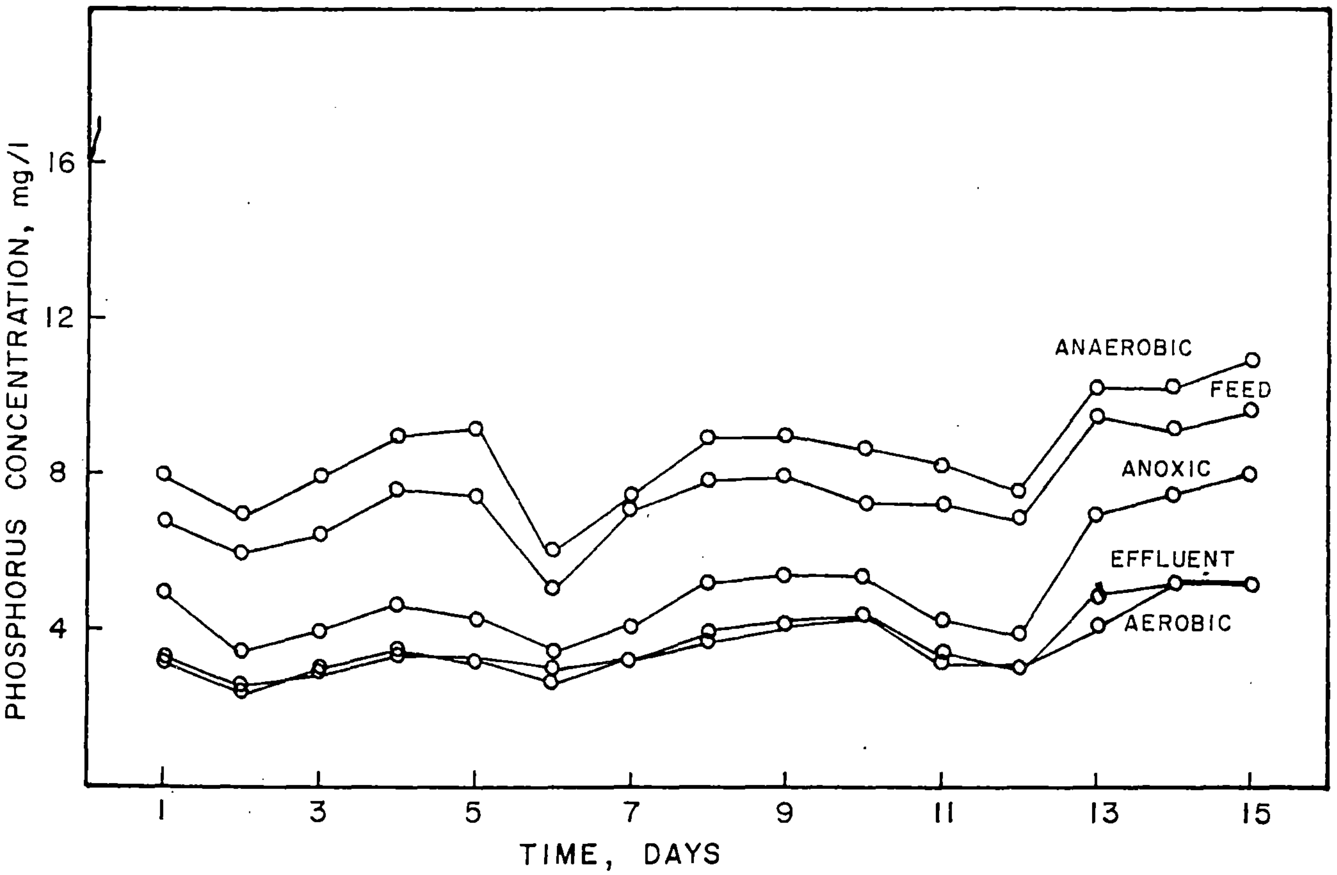


Figure 63. Ortho-P Concentration Versus Time for Combined Nitrogen-Phosphorus Removal System at 7-Day SRT

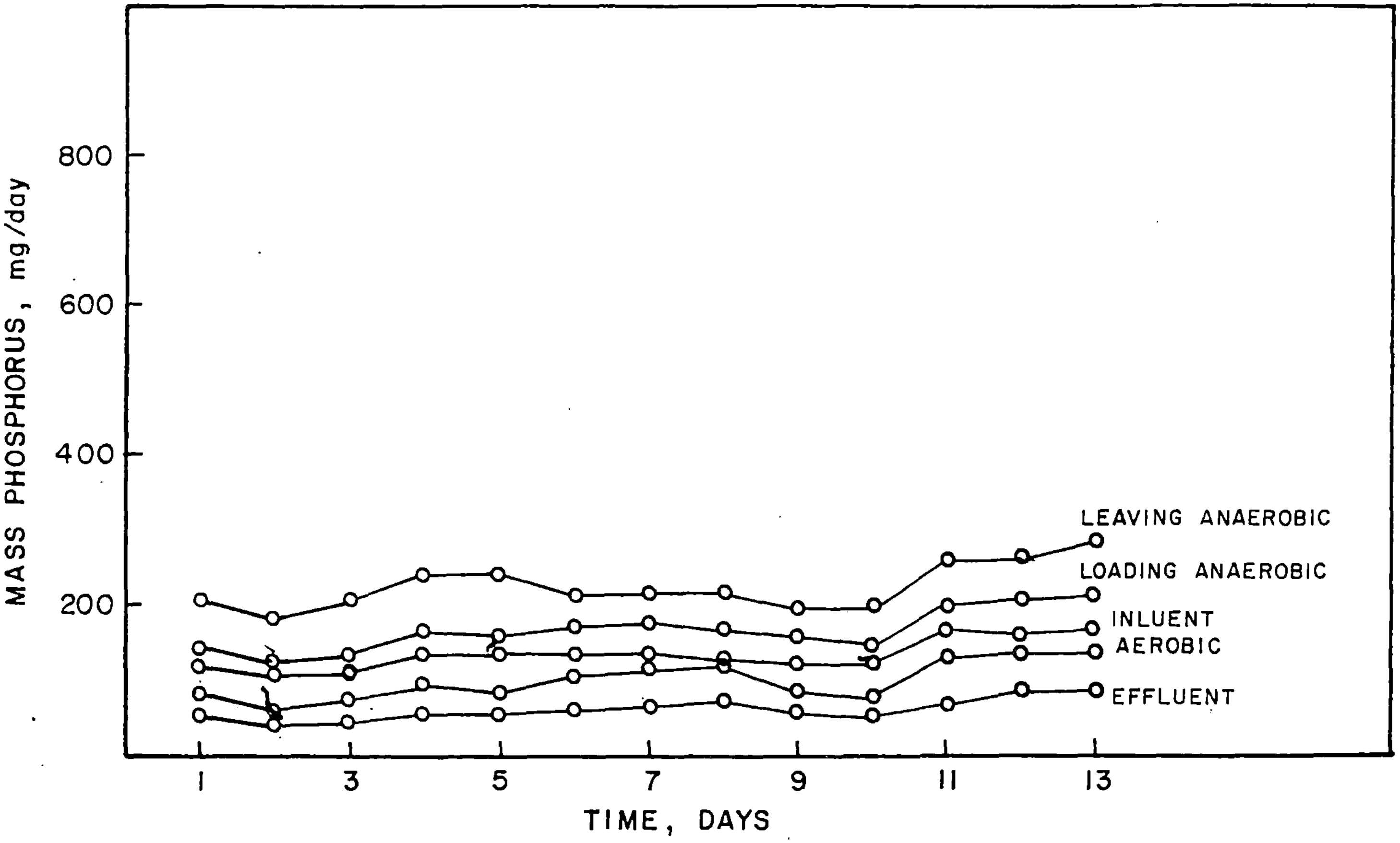


Figure 64. Mass Ortho-P Versus Time for Combined Nitrogen-Phosphorus Removal System at 7-Day SRT

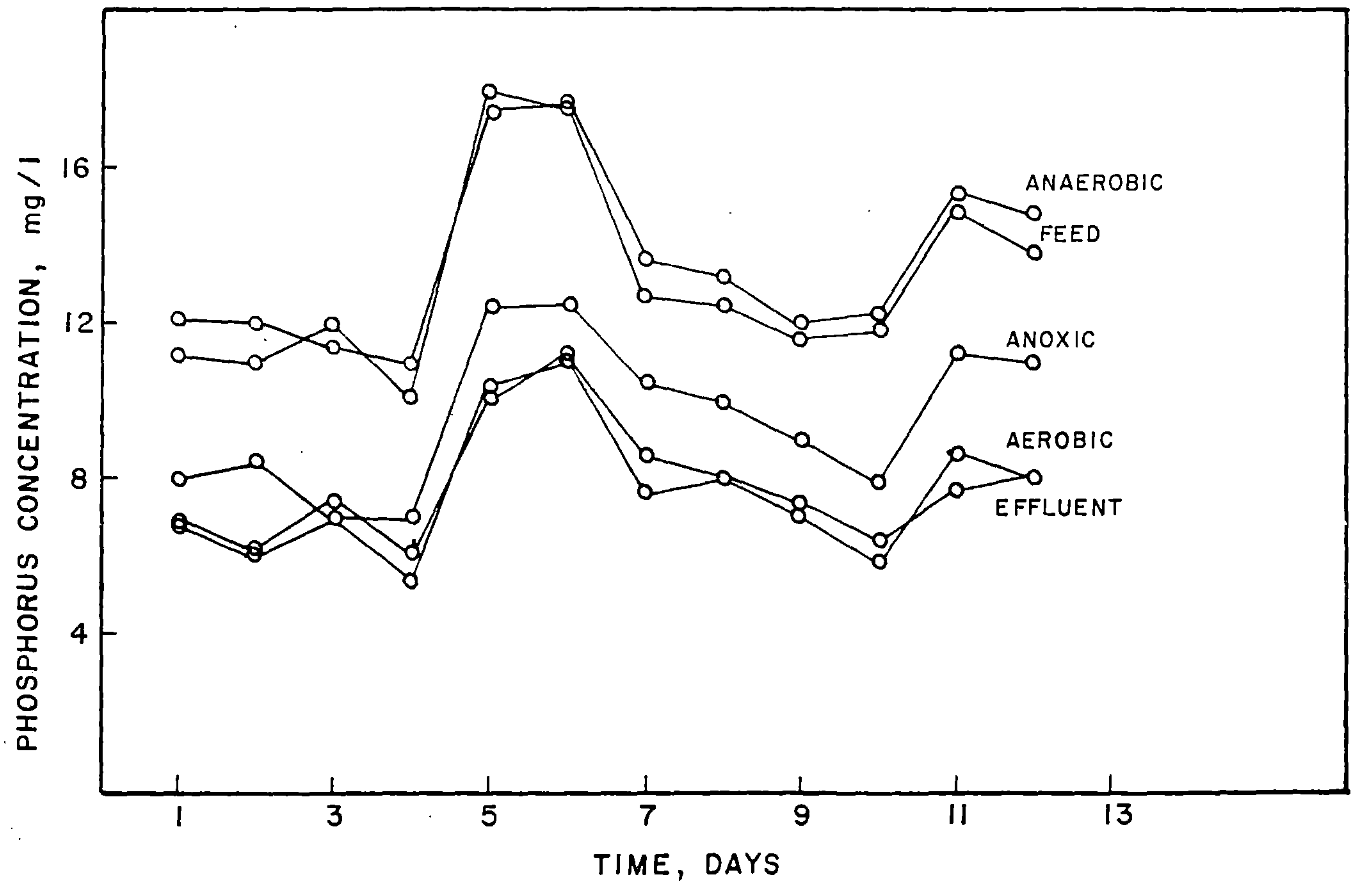


Figure 65. Ortho-P Concentration Versus Time for Combined Nitrogen-Phosphorus Removal System at 3-Day SRT

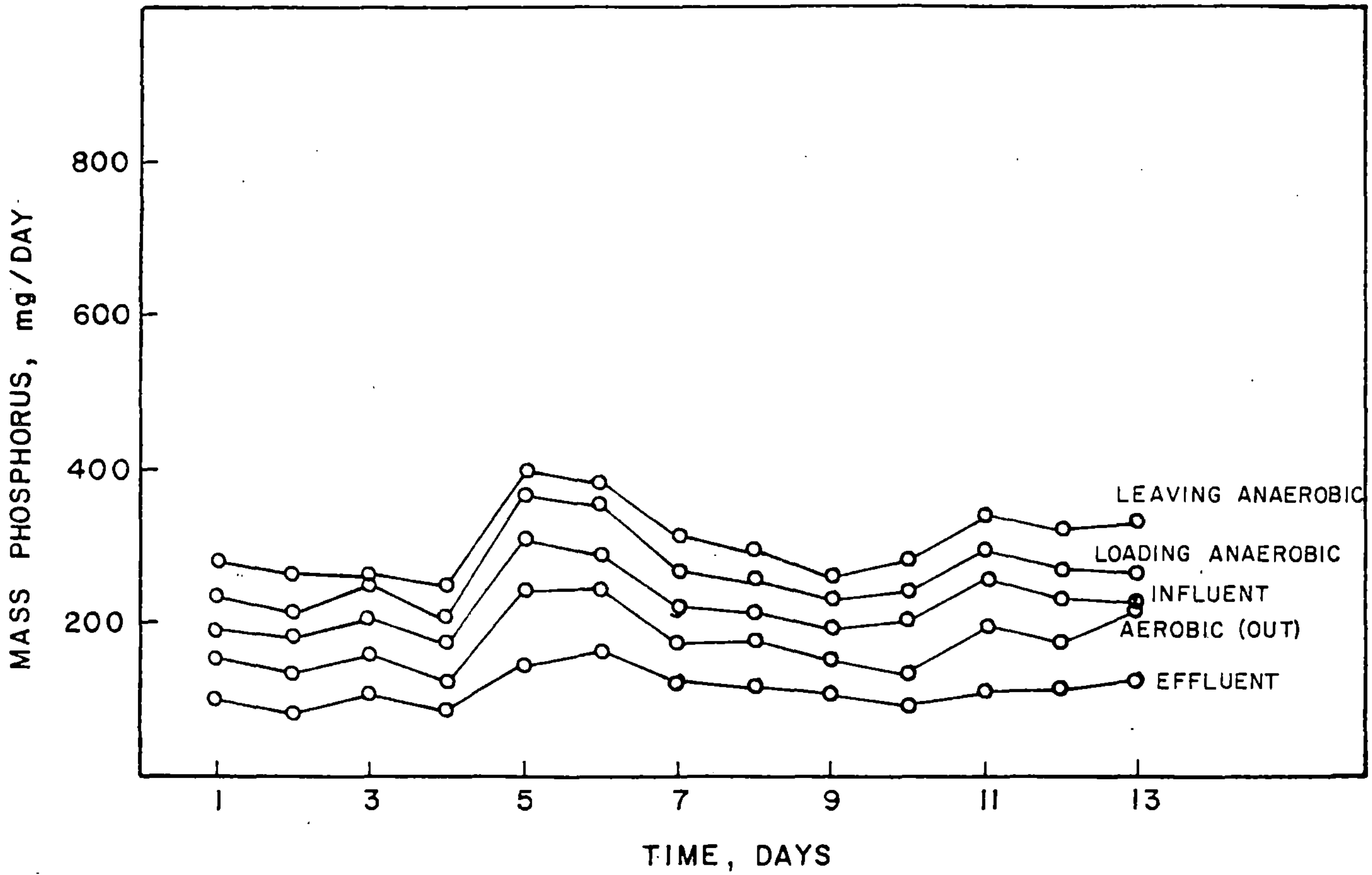


Figure 66. Mass Ortho-P Versus Time for Combined Nitrogen-Phosphorus Removal System at 3-Day SRT

phosphorus in the anaerobic reactor occurred for the SRT of 15 days: the release has almost twice that of the influent mass loading of phosphorus. At the 25 day SRT, the release was less than at the 15 day SRT but still around 1.3 times that of the influent mass loading. From the 10 day SRT, the release of phosphorus in the anaerobic reactor started reducing and reached very little release for the SRT of 3 days. These changes can be clearly observed in Figures 57 through 66. The P removal and release in the system stopped during the rainy period. This is shown in Figures 57 and 58 for the 10 day SRT during 11 days through 14 days. From the concentration plots (Figures 57, 59, 61, 63, 65), it can be seen that the removal of phosphorus occurred in the aerobic (nitrification) reactor. The effluent concentration of phosphorus was slightly higher than the aerobic reactor phosphorus concentration.

Figure 67 shows the net average percentage of mass ortho-P released in the anaerobic reactor as a function of SRT. A maximum release of 182 percent based on influent mass-P loading was observed at the 15 day SRT operation. At the 25 day SRT, the release was 140 percent. The percent phosphorus release started dropping at the 10 day SRT down to the 3 day SRT as shown in Figure 67.

Figure 68 represents the net P released (-U) as a function of phosphorus applied (P/M). This figure also shows the same trend as Figure 67. The maximum release was observed for the P/M value of 0.08 (15 day SRT). Figure 69 shows the average percent phosphorus content of the sludge for the different SRT's. Here also the maximum sludge phosphorus content was observed for the SRT of 15 days. The average percent phosphorus content of the sludge for the SRT's of 25, 15, 10, 7, and 3 days were 7.0, 8.5, 7.0, 3.1, and 3.5 percent, respectively. The average

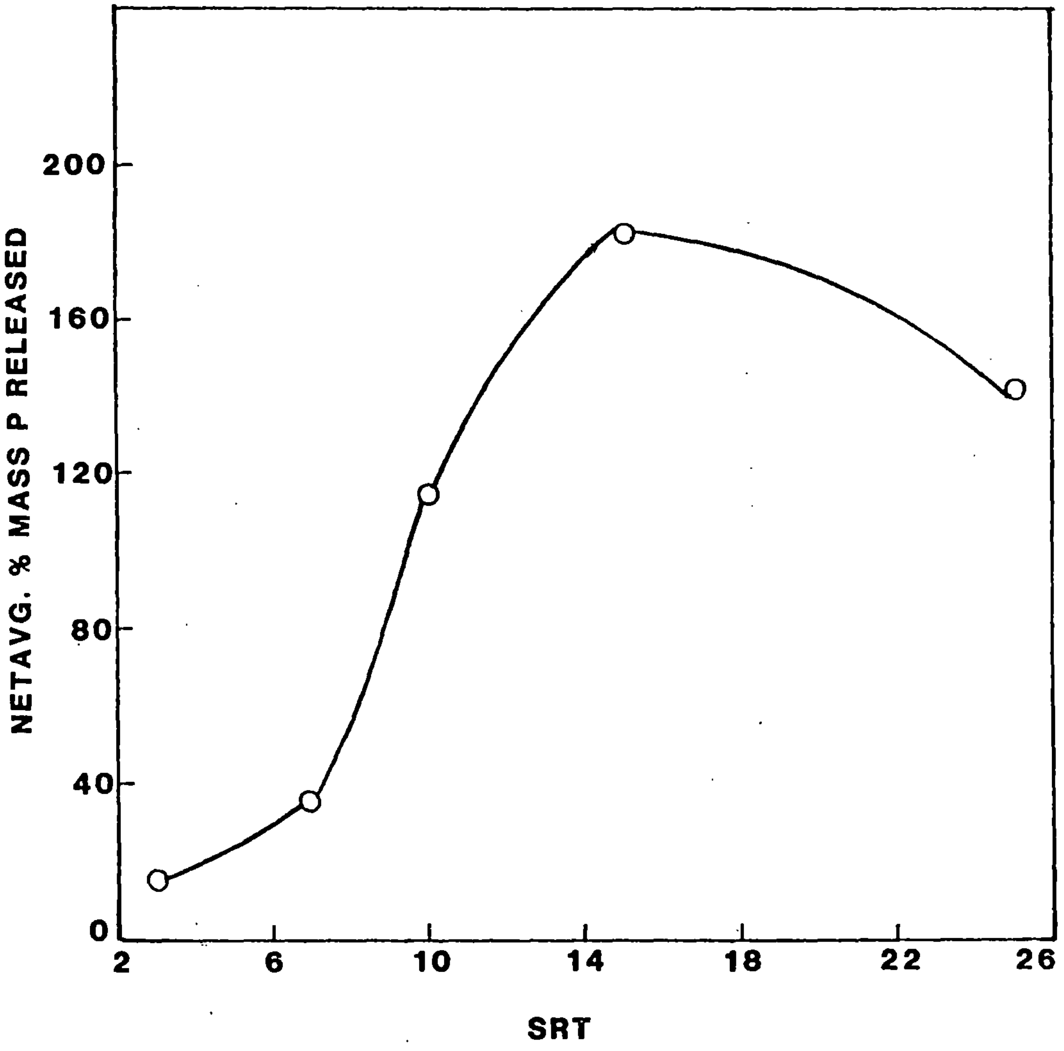


Figure 67. Net Average Percent Mass Ortho-P Released as a Function of SRT for Anaerobic Reactor of Combined Nitrogen-Phosphorus Removal System

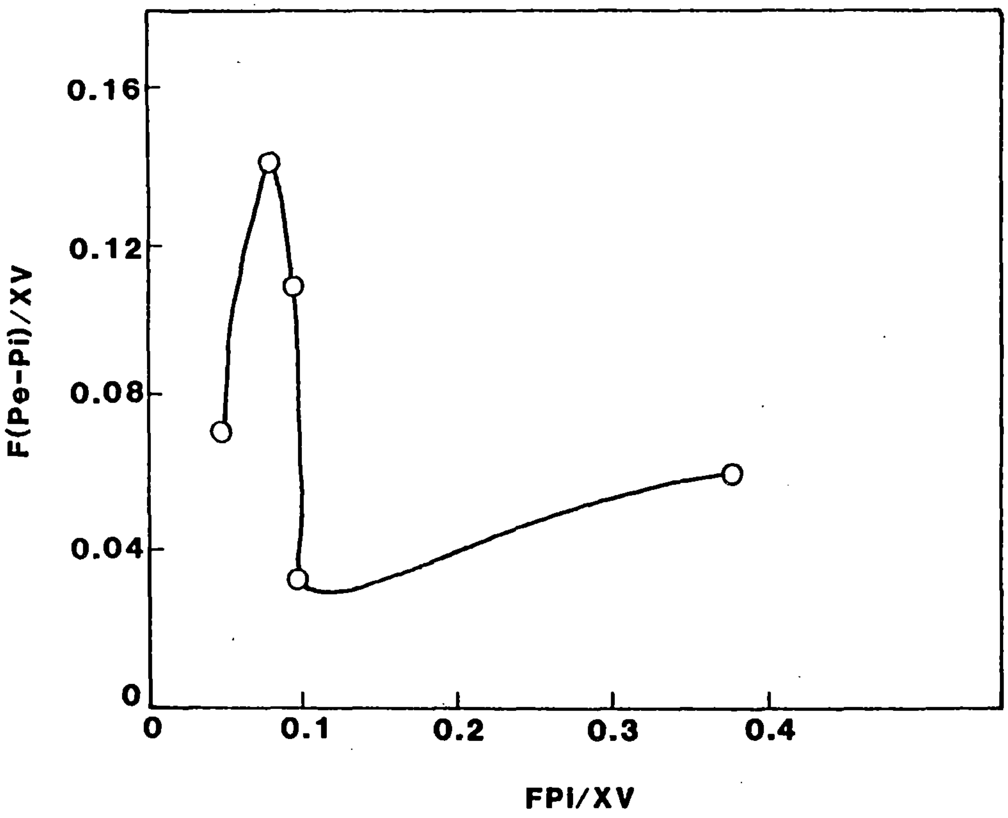


Figure 68. Net P Released as a Function of P Applied (F/M) for Anaerobic Reactor of Combined Nitrogen-Phosphorus Removal System

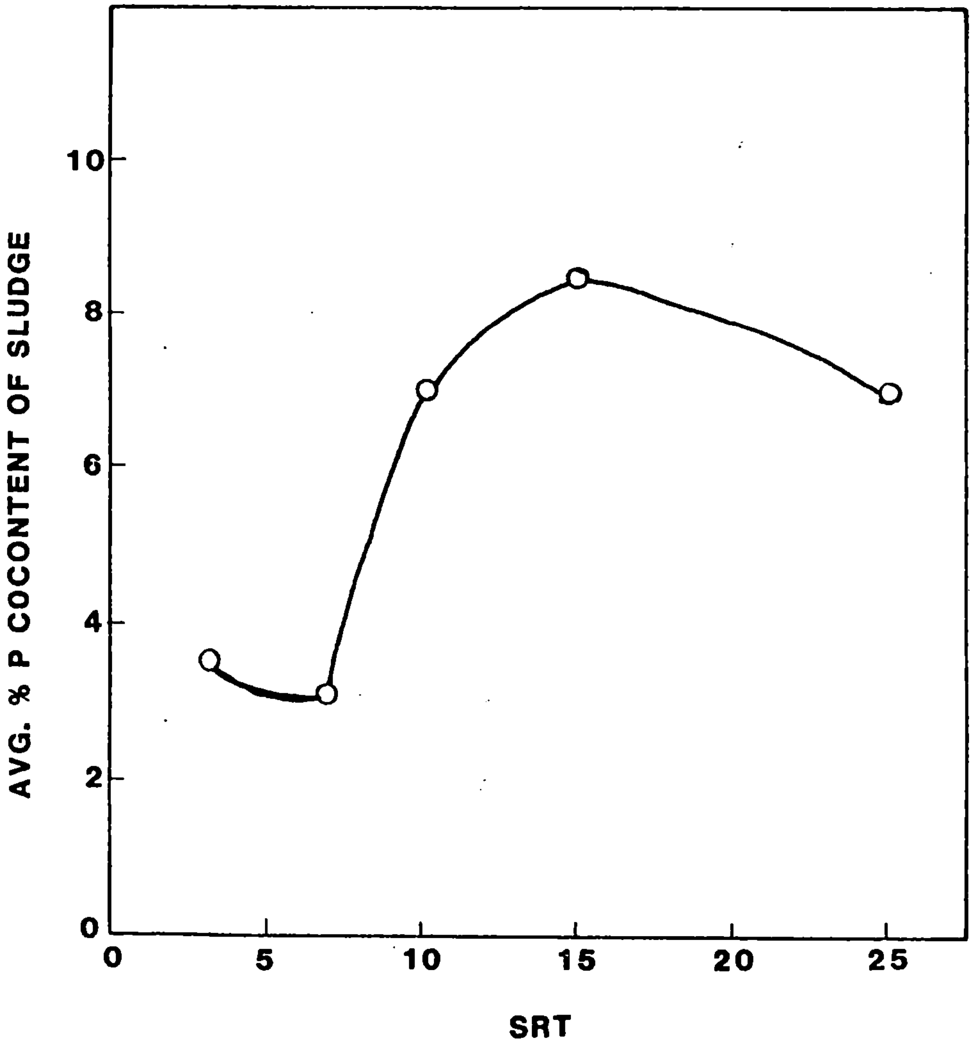


Figure 69. Average Percent Phosphorus Content of Sludge as a Function of SRT for Aerobic Reactor of Combined Nitrogen-Phosphorus Removal System

phosphorus concentrations removed for the SRT's of 25, 15, 10, 7, and 3 days were 5.00, 6.65, 6.60, 3.65, and 5.00 mg/ℓ, respectively.

Figure 70 represents the average percent mass phosphorus removed as a function of SRT. A maximum removal of 66 percent was achieved at the SRT of 15 days; 65 percent removal was observed for the SRT of 10 days; whereas it was 55 percent for the 25 day SRT. Then the removal started decreasing as shown in Figure 70 and reached 40 percent for the 3 day SRT. Figure 71 shows the mass phosphorus removed as a function of mass phosphorus applied to the aerobic reactor from the anaerobic reactor. Maximum phosphorus removal was achieved for the P/M value of 0.061 (15 day SRT). The extension of the curve, which is shown in the dotted line, intercepts the X-axis at an P/M value of 0.022.

Figure 72 shows a graphical representation of the settling characteristics of the aerobic reactor sludge for the combined nitrogen-phosphorus removal system. Zone settling velocities of the sludge mass in the aerobic unit increase with decreasing sludge retention times (SRT's) as shown in Figure 73. The values for zone settling velocities varied from 0.2 ft/hr at 25 days SRT to about 9.6 ft/hr at the 3 day SRT. A decrease in zone settling velocity was observed for higher SRT's of 25, 15, and 10 days when the system was removing phosphorus. Figure 74 represents the sludge volume index as a function of SRT.

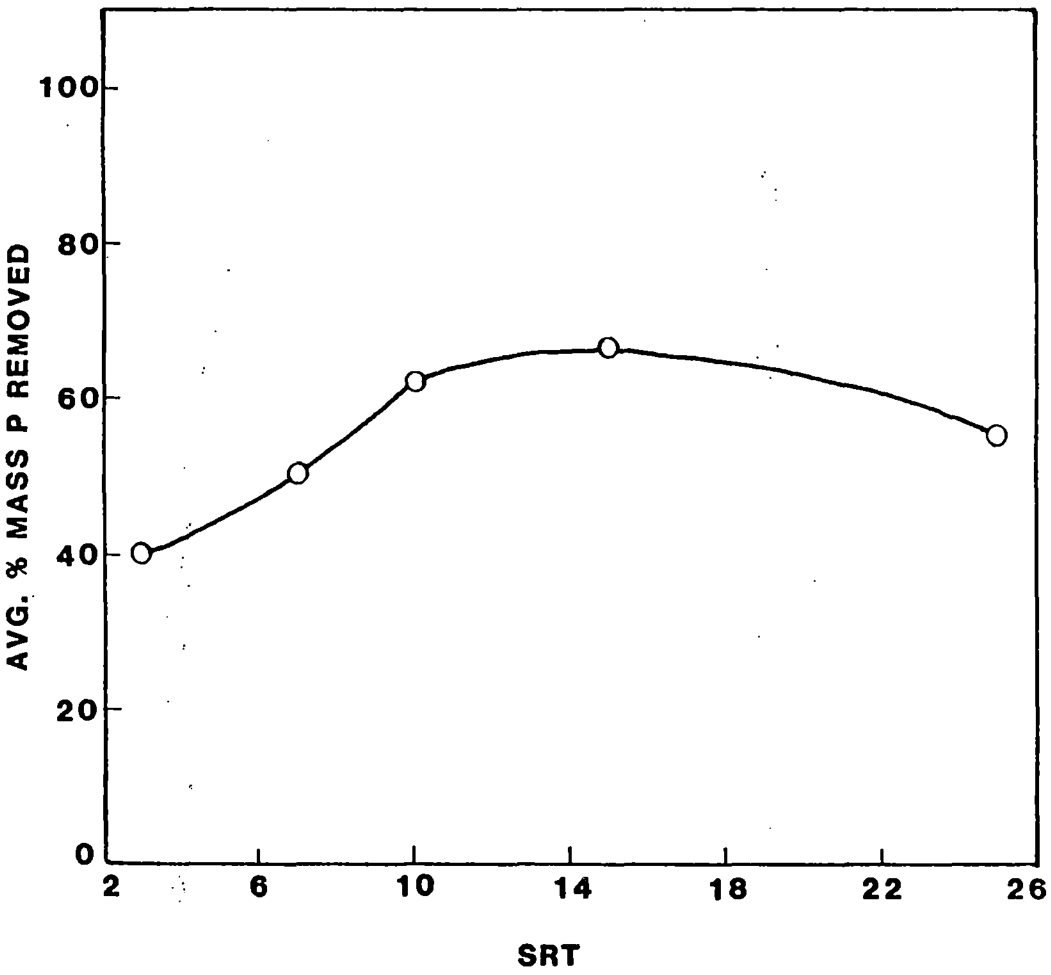


Figure 70. Average Percent Mass Phosphorus Removed as a Function of SRT for Aerobic Reactor of Combined Nitrogen-Phosphorus Removal System

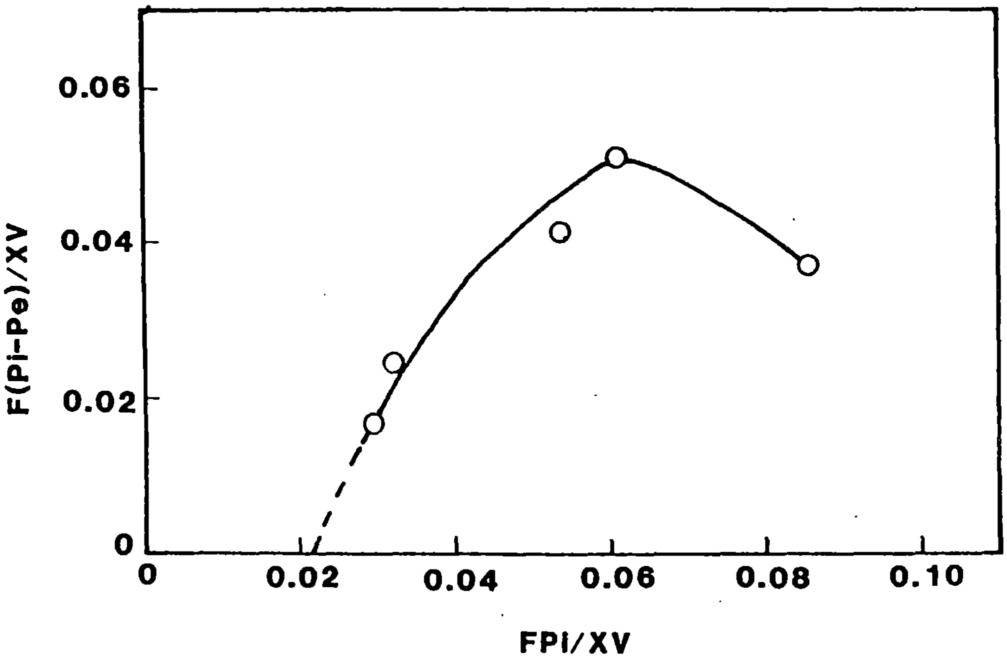


Figure 71. Phosphorus Removed as a Function of Mass Phosphorus Applied for Aerobic Reactor of Combined Nitrogen-Phosphorus Removal System

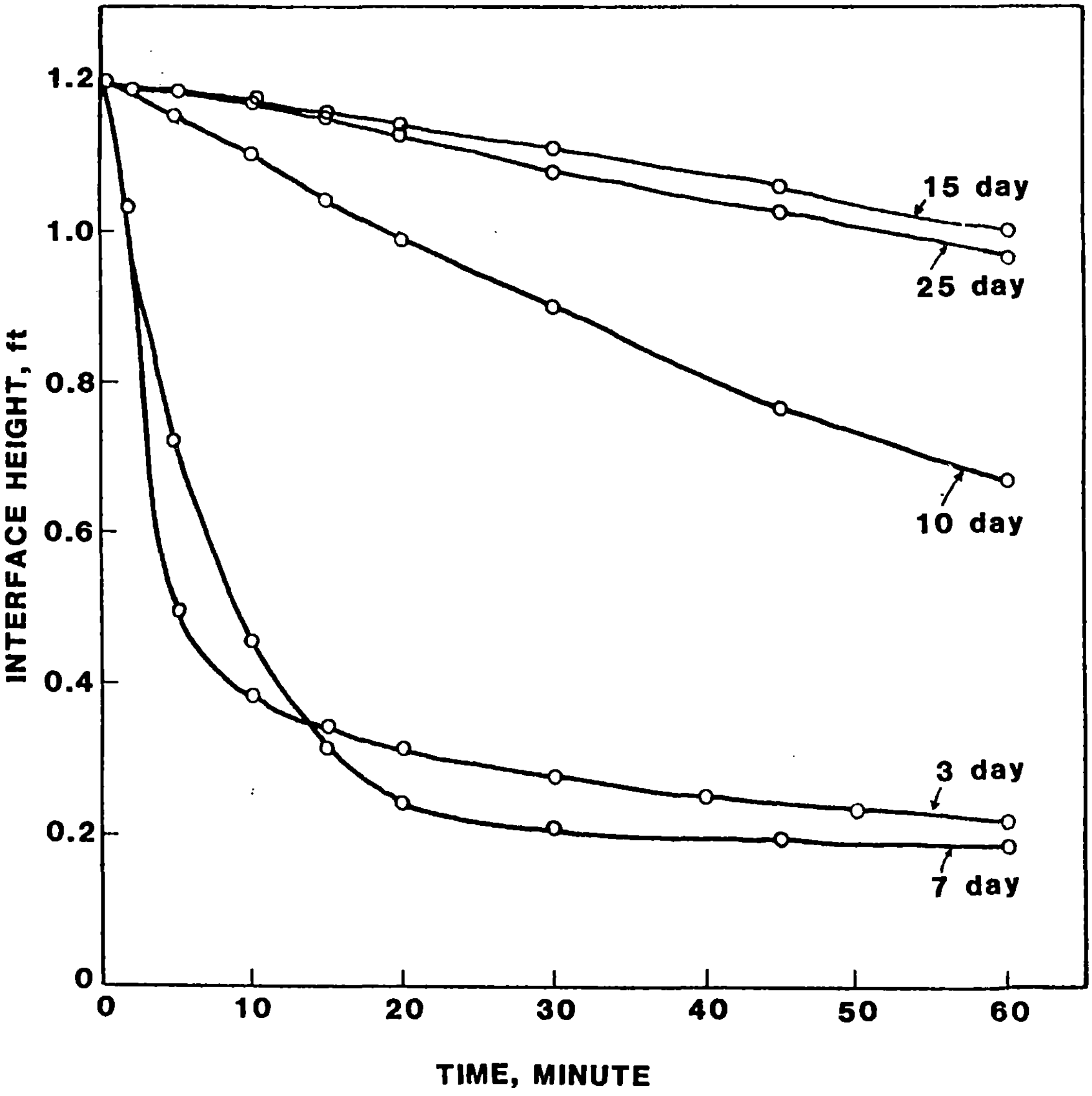


Figure 72. Graphical Representation of Settling Characteristics of Aerobic Reactor Sludge for Combined Nitrogen-Phosphorus Removal System

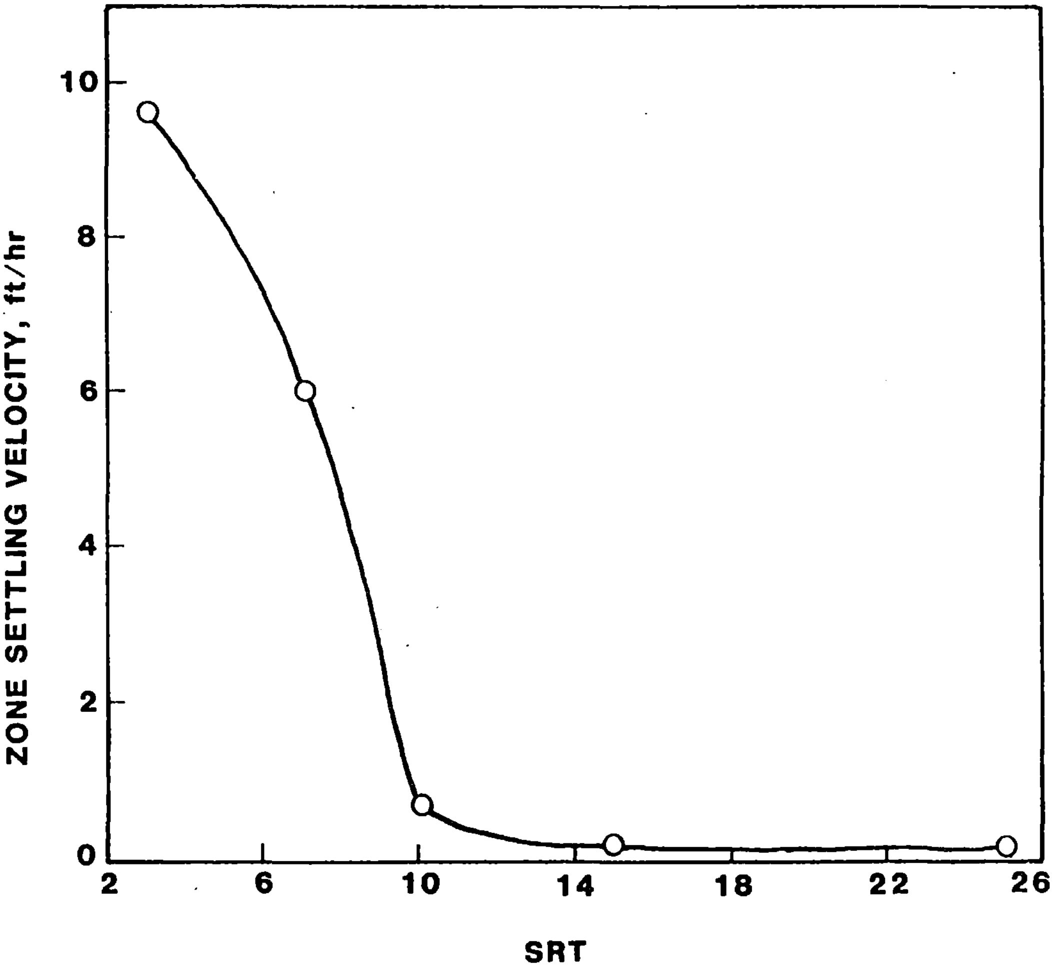


Figure 73. Zone Settling Velocity as a Function of SRT for Combined Nitrogen-Phosphorus Removal System

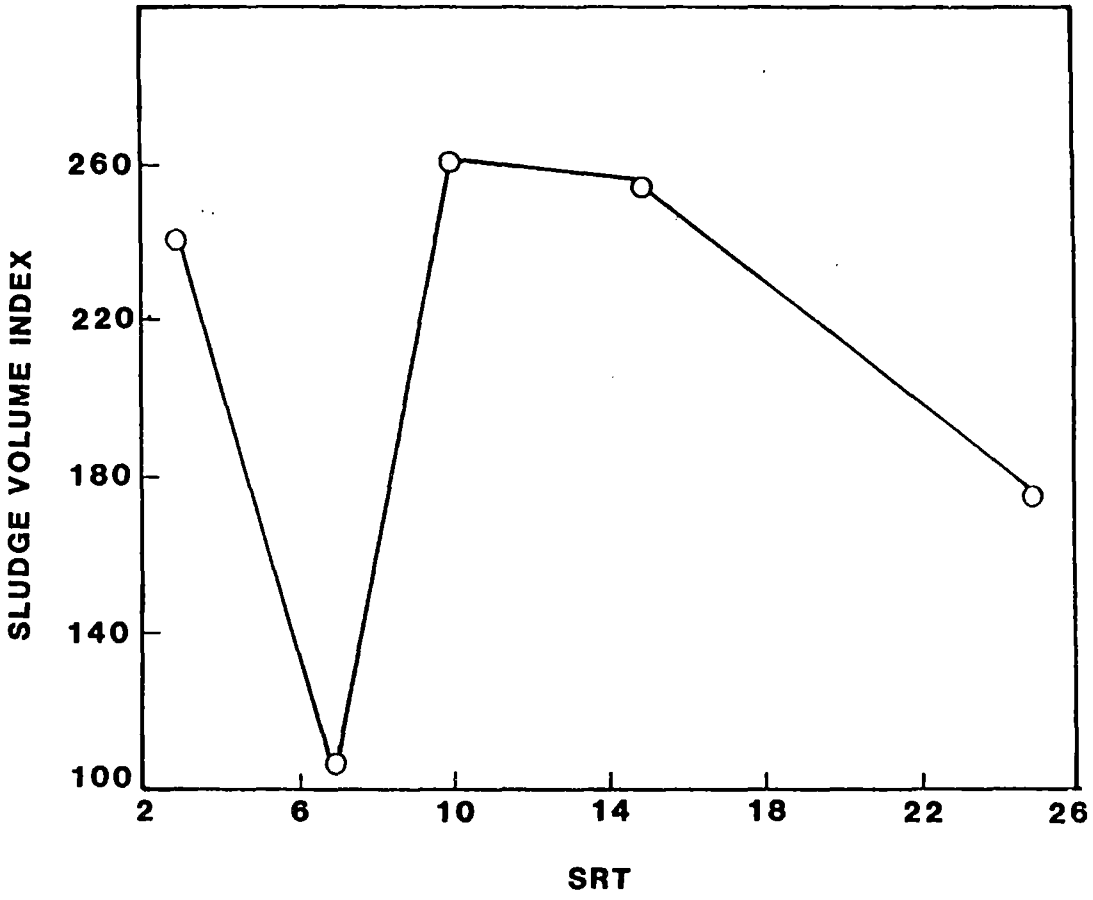


Figure 74. Sludge Volume Index as a Function of SRT for Combined Nitrogen-Phosphorus Removal System

CHAPTER V

DISCUSSION

One-Stage Nitrifying System

Municipal wastewater was collected from Oklahoma State University's Environmental Engineering pilot plant building on McElroy Street for feeding to the one-stage nitrifying system. This system was operated at different SRT's (F/M values) and near constant BOD/COD-to-NH_3-N ratio. The hydraulic flow rates were carefully controlled, and the reactors were operated by wasting of biological solids to establish desired SRT's, while temperature of the reactor varied between 21 and 30°C.

Data from this activated sludge reactor operated at different sludge retention times or, in other words, different F/M values in terms of BOD, COD, and NH_3-N are presented in the preceding chapter. Since complete nitrification was expected at the 10-day SRT, the system was first operated at 10 days, and then reduced to 5, 3, and 2 day SRT's, in order to evaluate the system for nitrification at low SRT's or high F/M values. Here the evaluation is completely based in particular to the BOD/COD-to-NH_3-N ratio which was around 110/275:30.

High percentages of BOD and COD removal were achieved for all operating conditions. The average effluent BOD_5 was never greater than 10.5 mg/ℓ including at the 1-day SRT. The average effluent COD was less than 52.0 mg/ℓ. The average effluent suspended solids were around 6.0 mg/ℓ during the entire operation of this system. Thus the effluent quality in terms of BOD, COD, and suspended solids was very good and acceptable to discharge in the environment without any additional treatment.

Ammonia-nitrogen (NH_3-N) and nitrate-nitrogen (NO_3-N) in the effluents varied over the range of sludge retention times (or F/M values) from 1 to 10 days. Essentially complete nitrification was achieved at sludge retention times of 10 and 5 days. The degree of nitrification decreased with decreasing sludge age (or increasing F/M value) below 5 days, as shown in Figures 15 and 16. Nitrification decreased to zero at an SRT of 1 day. The F/M value in terms of NH_3-N at this SRT was 0.269.

At this point, it is necessary to discuss some of the points regarding nitrification. The system was operated at very low soluble BOD_5 of 35 mg/ℓ and soluble COD of 75 mg/ℓ. The average NH_3-N concentration at this time was around 27.0 mg/ℓ. Basically, these were the original wastewater characteristics. The system was operated as low as 3/4 day SRT to stop the nitrification. But nitrification could not be stopped and there was around 6.0 mg/ℓ of nitrate-nitrogen in the effluent. In order to stop the nitrification, the soluble BOD_5 was increased to about 110 mg/ℓ (COD of 275 mg/ℓ) by adding isopropyl alcohol. Then this level of BOD and COD was maintained in the municipal wastewater throughout the entire study. Thus nitrification was occurring even at 3/4 day SRT, which indicates that SRT is not the criterion for nitrification to occur. When soluble BOD was increased to around 100 mg/ℓ, nitrification stopped at the 1-day SRT. The BOD/COD:NH_3-N ratio, or F/M in terms of BOD/COD, is very important in defining the nitrification limit. Therefore, it is better to evaluate the nitrifying system in terms of BOD/COD:NH_3-N ratio and F/M in terms of BOD/COD. But it is always easier to operate the system based on SRT to maintain a desired growth rate or solids level in the reactor.

Based on the BOD/COD:NH_3-N ratio of 110/275:30, complete nitrification was achieved for F/M values of 0.286/0.787 (10-day SRT), and 0.388/1.042 (5-day SRT) in terms of BOD/COD. The degree of nitrification or NH_3-N removal started decreasing at 91.0 percent for the F/M value of 0.490/1.170 (3 days), and 85.0 percent for the F/M value of 0.690/1.610 (2 days) in terms of BOD/COD. Nitrification decreased to zero for the F/M value of 1.040/2.750 (1 day) in terms of BOD/COD, but NH_3-N was still removed (21.5%) at this condition (see Figures 15 and 16). Again in these figures, it is hard to define the zero nitrification point. So the line extended from F/M values of 0.192 (2-day SRT) to 0.269 (1-day SRT) in terms of NH_3-N is only approximate. The removal of NH_3-N was strictly due to the incorporation of the ammonia into heterotrophic cell matter at the F/M value of 1.040/2.750/0.269 (1-day SRT) in terms of BOD/COD/NH_3-N.

Lan (21) reported from her research that the organisms isolated from a nitrifying activated sludge system is capable of metabolizing organic carbon as a carbon and energy source and nitrifying after the depletion of the organic carbon. Thus the decrease in NH_3-N removal (nitrification) for higher F/M values in terms of BOD/COD or at low SRT's in the one-stage nitrifying system was due to higher carbon concentration in the reactor at these conditions. During rapid heterotrophic growth, when the organic carbon source is still available, the heterotrophs do not need other energy sources such as NH_3-N for survival except for cell synthesis; hence nitrification is not essential for obtaining energy. That is one of the reasons why nitrification (NH_3-N removal) was less at higher F/M values or lower SRT's.

All nitrifying organisms are not obligately autotrophic (65) and in the presence of sufficient substrate will use organic carbon compounds as electron donors rather than reduced nitrogen (66). This could be another reason for the reduced nitrification at higher F/M values in terms of organic carbon.

Another explanation was due to an insufficient population of nitrifying organisms. The insufficient population of nitrifier was due to the high growth rate of the system at low SRT's. An inadequate population of nitrifiers can also be explained as a competition-type relationship between the carbon oxidation and nitrifying microorganisms. The carbon oxidation microorganisms are capable of faster growth rates and are not as sensitive to environmental changes as are the nitrifiers and would, therefore, be capable of a crowding out type of effect upon the nitrifiers. Another reasonable explanation for the reduced nitrification at lower SRT's or higher F/M values in terms of BOD/COD, as explained by Stover (36), is the possibility of the production of metabolic byproducts by the rapid growth of carbon oxidizing microorganisms which were inhibitory to the nitrification process.

The dissolved oxygen concentration was maintained between 2.0 to 4.0 mg/ℓ in the reactor, so that DO was not a limiting factor for nitrification. Nitrite-nitrogen (NO_2-N was zero in the effluent. This is due to rapid conversion of NO_2-N into NO_3-N in the presence of sufficient DO in the reactor.

Carbon Removal Biokinetic Constants

The biokinetic constants are calculated using the Kincannon and Stover model for BOD and COD removal. These values are summarized in Table VI for the one-stage nitrifying system. The rationale behind usage of the Kincannon and Stover model is because of its mass substrate loading and removal approach. The mass of nitrifiers will be very low, when compared to the mass of carbonaceous removal microorganisms in the one-stage nitrifying system for municipal wastewaters. Hence the carbon removal kinetic constants should agree for different BOD:NH_3-N or COD:NH_3-N ratios. The BOD and COD removal kinetic constants are shown in Table VI for the municipal wastewater with BOD/COD NH_3-N ratio of approximately 110/275:30.

Ammonia-Nitrogen Removal Kinetics

The kinetics of growth and substrate removal for nitrification are normally obtained from either pure culture or mixed culture, under a controlled environment. But in the actual treatment plants, it is not so. Also, the kinetics are available only for autotrophic nitrifying organisms (Nitrosomonas and Nitrobacter).

The physiological and biochemical characteristics associated with nitrogen oxidation by heterotrophs are unknown. Stover and Kincannon (33), from their studies on biological nitrification, found that the limiting SRT required to attain complete nitrification in one-stage nitrifying system was affected by COD:NH_3-N ratio, and the nitrifying microorganisms do not respond to spontaneous increase in nitrogen concentrations as well as the carbon oxidizing microorganisms respond to an increase in organic carbon sources. Stover and Kincannon (127) and Esfandi and Kincannon (59) also reported that shock loads of NH_3-N source did not affect nitrification in the activated sludge system. From these observations, it could be argued that during rapid heterotrophic growth, when the organic carbon source is still available, the heterotrophs do not need other energy sources such as NH_3-N for survival except for cell synthesis. Hence nitrification is not essential for obtaining energy; however, when rapid growth ceases or the available carbon source is limiting, they turn to available nitrogen for energy supply. Lan (21) reported from her research that the organism isolated from a nitrifying activated sludge system is capable of metabolizing organic carbon as a carbon and energy source and nitrifying after the depletion of the organic carbon. She verified the fact that the organism is incapable of growing in an inorganic medium and nitrapyrin has no effect on its nitrifying activity, which indicates that nitrification by this organism is heterotrophic in nature. She also reported that under appropriate conditions of carbon and nitrogen supply, especially when nitrogen is in excess of assimilatory needs, heterotrophic nitrification could be the predominant mode of nitrification in biological nitrification systems. Thus, equating Nitrosomonas and Nitrobacter alone for nitrification should be questioned, based on existing evidence for the potential of heterotrophic nitrification.

Nitrification due to this heterotrophic organism has not been accounted for in designing the nitrification systems. So evaluating the nitrification systems based on the growth rates of Nitrosomonas and Nitrobacter alone does not appear to be an appropriate method. The NH_3-N removal kinetic constants (U_{max} and K_B) obtained, using the Kincannon and Stover model shows promise as an alternate approach in evaluating and designing the nitrification systems. Here the biokinetic constants are obtained for the actual waste by operating the pilot scale activated sludge systems.

The biokinetic constants, U_{max} and K_B, in terms of NH_3-N for the one-stage nitrifying system are 0.89 and 0.83 (Table VI), respectively, with Y_t of 4.41 and K_d of -0.24 for the BOD/COD:NH_3-N ratio of 110/275:30. For the same ratio, the constants should also be the same. In order to verify this, data from Stover's thesis (36) were used to calculate the biokinetic constants U_{max} and K_B. Table XXI represents a summary of operational characteristics of the nitrifying one-stage system for different COD:NH_3-N ratios (Stover's thesis data). The average mass substrate loading (F/M) in terms of NH_3-N for the COD:NH_3-N ratio of 100:10 (10:1) were 0.0317, 0.0465, and 0.0734 for the SRT's of 10.4, 6.9, and 3.9 days, respectively. The corresponding average mass substrate removal (U) in terms of NH_3-N were 0.0317, 0.0458, and 0.0706. The F/M values for the COD:NH_3-N ratio of 500:50 (10:1) were 0.028, 0.029, and 0.035 for the SRT's of 12.6, 10.8, and 7.4 days, respectively. The corresponding U values were 0.028, 0.029, and 0.032. For the COD:NH_3-N ratio of 1000:100 (10:1), the F/M values in terms of NH_3-N were 0.032 and 0.038 for the SRT's of 10.3 and 7.8 days, respectively. The corresponding U values were 0.030 and 0.034. The F/M values for the ratio of 100:50 (2:1) were 0.043, 0.071, and 0.130 for the SRT's of 12.5, 6.5, and 4.3 days, respectively. The corresponding U values were 0.043, 0.068, and 0.120. For the COD:NH_3-N ratio of 1000:50 (20:1), the F/M values in terms of NH_3-N were 0.015, 0.017, and 0.022 for the SRT's of 13.5, 9.4, and 5.9 days, respectively. The corresponding U values were 0.015, 0.017, and

TABLE XXI

SUMMARY OF OPERATIONAL CHARACTERISTICS OF NITRIFYING ONE-STAGE ACTIVATED SLUDGE SYSTEM (36)

$COD:NH_3$-N	SRT (Days)	Biological Solids (mg/ℓ)	Influent NH_3-N (mg/ℓ)	Effluent NH_3-N (mg/ℓ)	Detention Time t_d (Days)
100:50 (2:1)	4.3	800	52.0	4.0	0.5
	6.5	1575	56.0	2.0	0.5
	12.5	2584	55.5	0.4	0.5
100:10 (10:1)	3.9	354	13.0	0.5	0.5
	6.9	550	12.8	0.2	0.5
	10.4	757	12.0	0.0	0.5
500:50 (10:1)	7.4	2851	50.0	5.0	0.5
	10.8	3780	55.0	0.5	0.5
	12.6	3910	55.0	0.6	0.5
1000:100 (10:1)	7.8	5527	105.0	11.0	0.5
	10.3	6953	110.0	4.0	0.5
1000:50 (20:1)	5.9	4720	52.5	2.0	0.5
	9.4	6180	54.0	1.4	0.5
	13.5	7240	55.0	0.9	0.5

0.021. Figures 75 through 81 represent the kinetic plots for the data from Table XXI. The biokinetic constants obtained from these figures are summarized in Table XXII. For the COD/NH_3-N ratio of 10:1, the constants U_{max}, K_B, and Y_t are 0.77, 0.76, and 4.57, respectively, which are in agreement with the constants of 0.89, 0.83, and 4.41 obtained from the author's research for the COD:NH_3-N ratio of 9:1. When the COD:NH_3-N ratio increased to 20:1, the constants U_{max} and K_B were reduced to 0.30 and 0.29 with an increase in Y_t to 17.0, whereas U_{max} and K_B were increased to 1.20 and 1.16 with a decrease in Y_t of 2.10 for the decrease in the COD:NH_3-N ratio of 2:1 (Table XXII).

Thus for the same COD:NH_3-N ratio, the kinetics are the same for the two different systems, with similar wastewater characteristics. The kinetics are different for different COD:NH_3-N ratios. This can be explained in terms of the ratio of the fraction of solids due to carbon oxidation and NH_3-N oxidation. For the same COD:NH_3-N ratio, with similar wastewater characteristics, the ratio of carbonaceous removal organisms to nitrifying organisms are the same or, in other words, the F/M values in terms of the proportionate ratio of COD and NH_3-N are the same. This can be clearly seen from the F/M values discussed earlier, i.e., for the different influent COD and NH_3-N concentrations, but for the same COD:NH_3-N the F/M values for a particular SRT is nearly the same. For example, for the COD:NH_3-N ratios of 100:10 (10:1), 500:50 (10:1), and 1000:100 (10:1), the F/M values in rerms of NH_3-N for the SRT of around 10.5 days were 0.031, 0.029, and 0.032, respectively. So although COD and NH_3-N concentrations in the influent were different, the F/M values are the same for the same COD:NH_3-N ratio. Since the Kincannon and Stover model uses this F/M approach, the nitrification kinetics can be

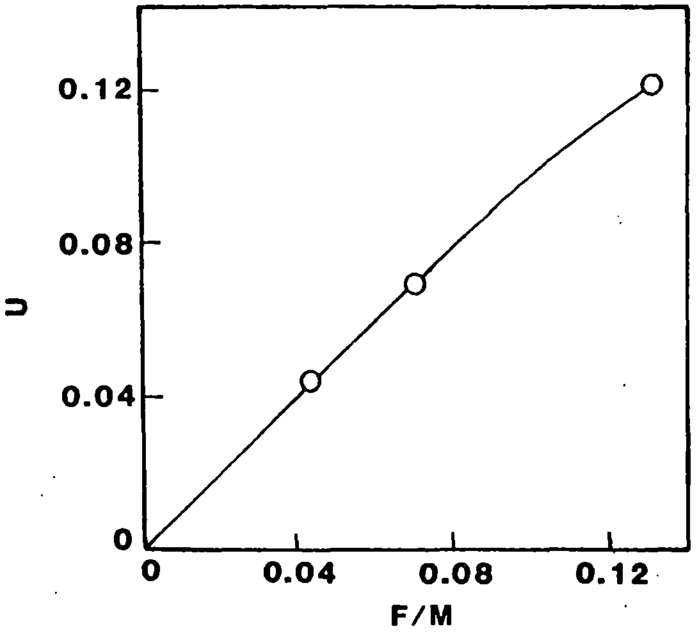


Figure 75. Substrate Utilization as a Function of Mass Substrate Loading in Terms of NH_3-N for Nitrifying One-Stage System for COD: NH_3-N of 2:1

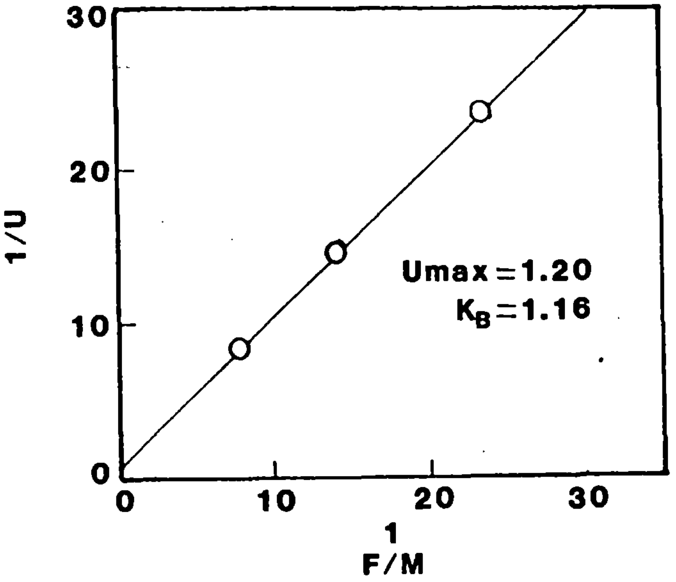


Figure 76. Graphical Determination of U_{max} and K_B in Terms of NH_3-N for Nitrifying One-Stage System for COD:NH_3-N of 2:1

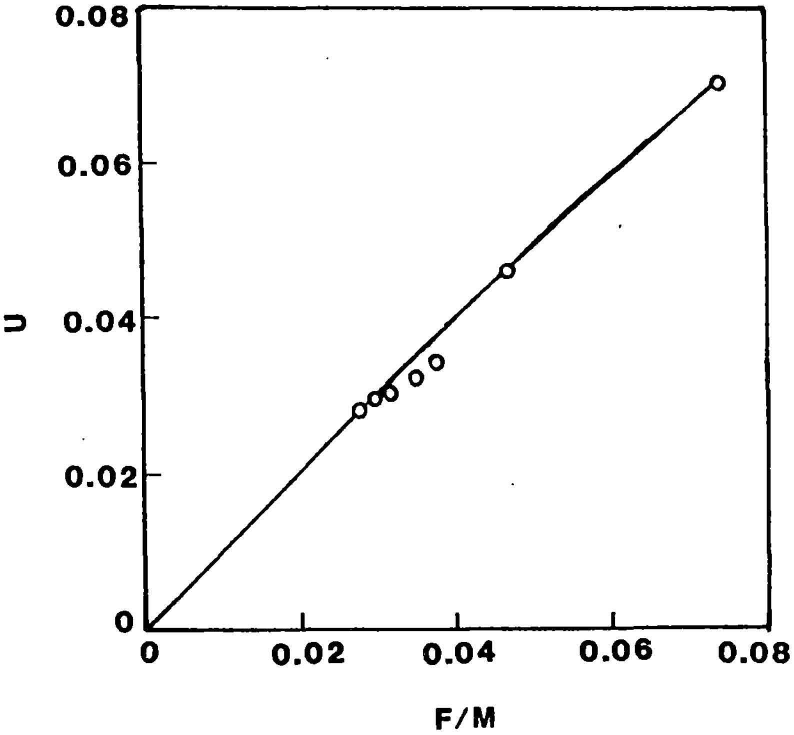


Figure 77. Substrate Utilization as a Function of Mass Substrate Loading in Terms of NH_3-N for Nitrifying One-Stage System for COD: NH_3-N of 10:1

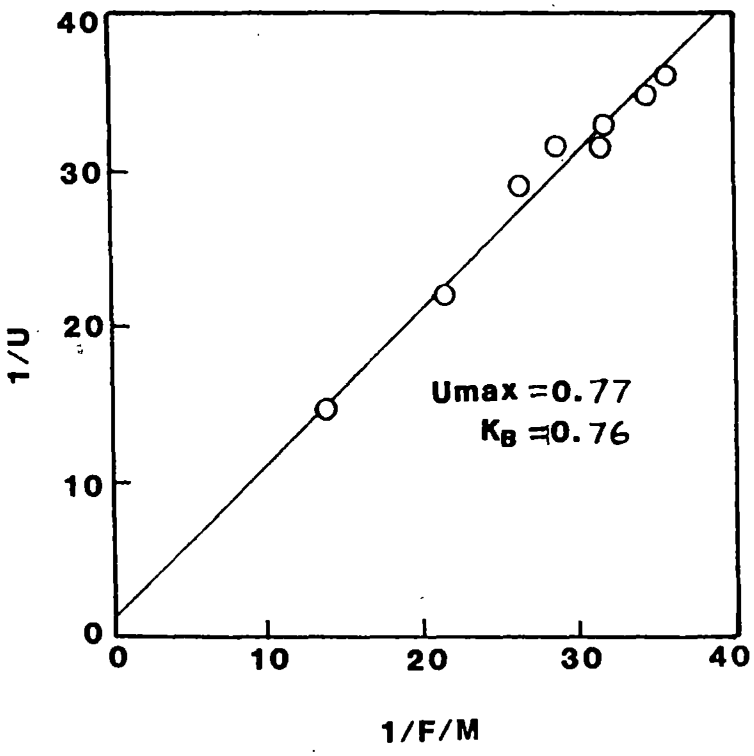


Figure 78. Graphical Determination of U_{max} and K_B in Terms of NH_3-N for Nitrifying One-Stage System for COD:NH_3-N of 10:1

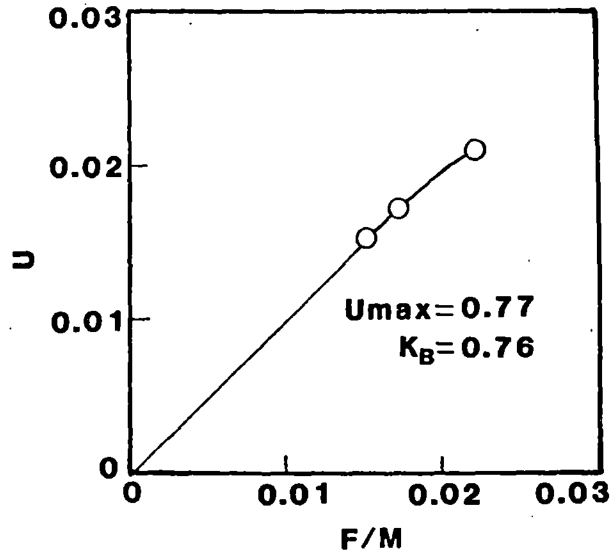


Figure 79. Substrate Utilization as a Function of Mass Substrate Loading in Terms of NH_3-N for Nitrifying One-Stage System for COD:NH_3-N of 20:1

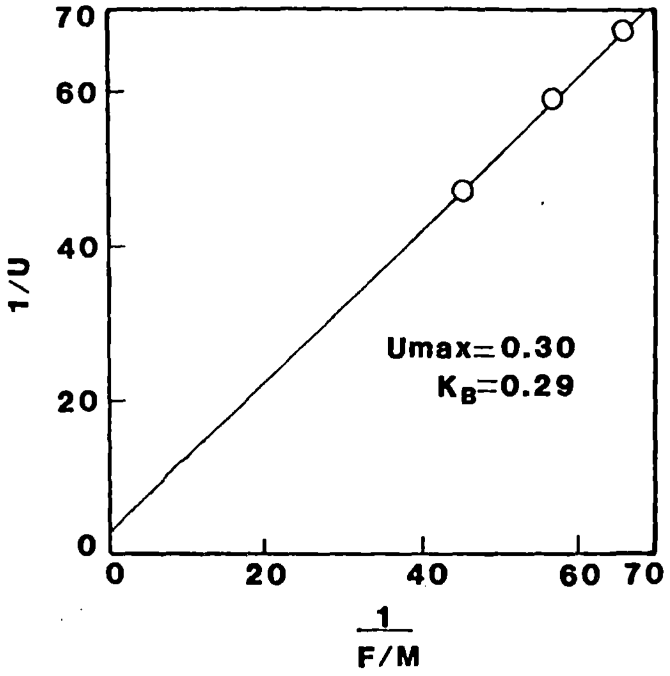


Figure 80. Graphical Determination of U_{max} and K_B in Terms of NH_3-N for Nitrifying One-Stage System for COD:NH_3-N of 20:1

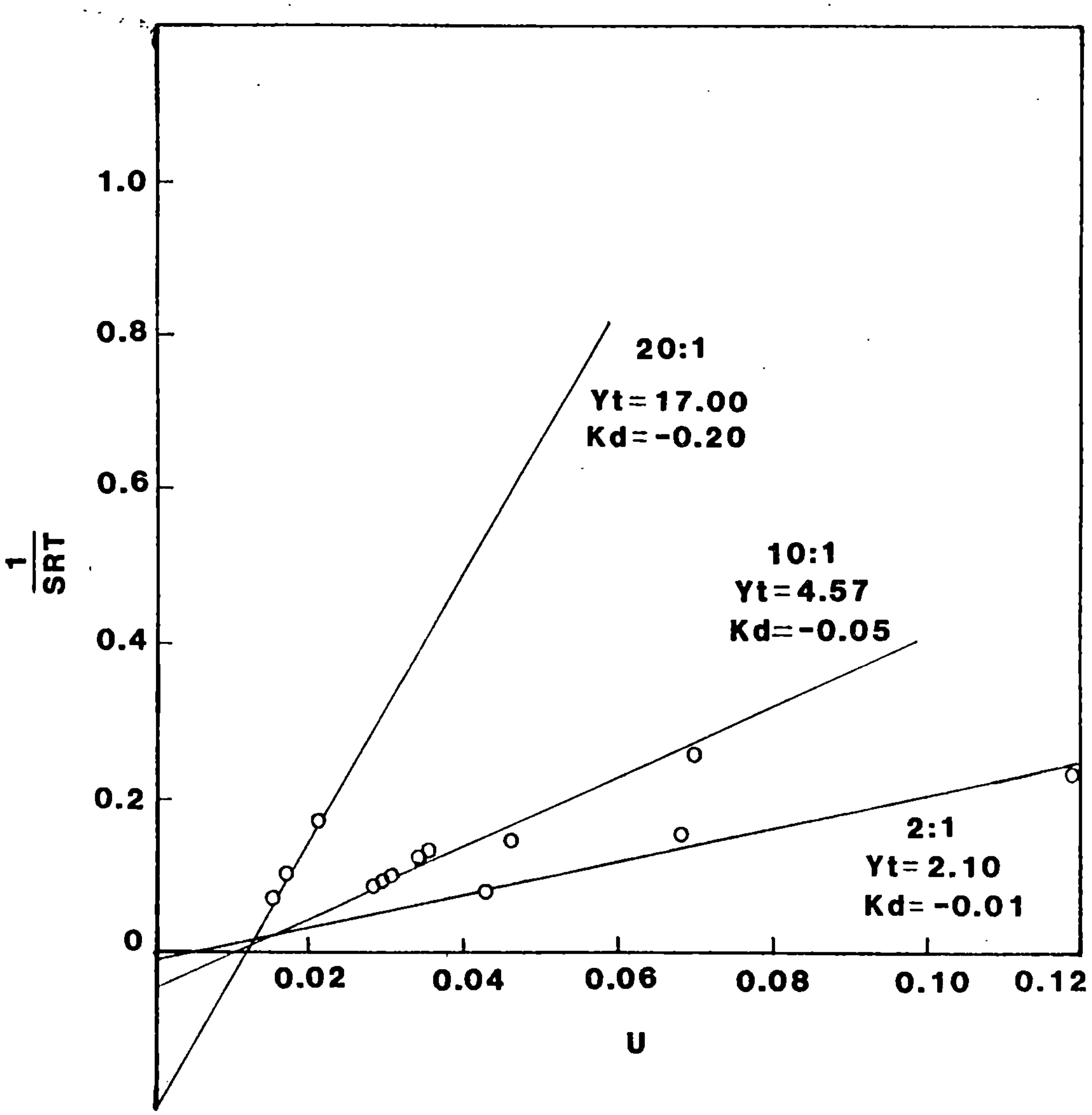


Figure 81. Graphical Determination of Y_t and K_d in Terms of NH_3-N for Nitrifying One-Stage System

TABLE XXII

SUMMARY OF NH_3-N REMOVAL KINETIC CONSTANTS FOR NITRIFYING ONE-STAGE ACTIVATED SLUDGE SYSTEM IN TERMS OF NH_3-N

COD:NH_3-N	U_{max}	K_B	Y_t	$-K_d$
2:1	1.20	1.16	2.10	0.01
10:1	0.77	0.76	4.57	0.05
20:1	0.30	0.29	17.00	0.20

defined using their model. That is the reason their model gives the same biokinetic constants for the same COD:NH_3-N ratio, with similar wastewater characteristics. The biokinetic constants were different for different COD:NH_3-N ratios because of the change in the ratio of the fraction of carbonaceous removal organisms to nitrifying organisms. This can be clearly seen from the summary of the biokinetic constants (Table XXII). This shows that the Kincannon and Stover model offers promise as an alternate approach in evaluating and designing a one-stage nitrifying system, using influent NH_3-N as substrate, for the specific BOD/COD:NH_3-N ratio characteristics of the wastewater.

Effect of Temperature on Nitrification

The temperature of the one-stage nitrifying system varied generally between 21 to 29°C. Most of the time it was around 24°C except for the 2-day SRT. This temperature variation did not affect the nitrification process. Instead it probably would have increased the rate of nitrification due to higher temperatures. Most of the laboratory studies by other researchers were carried out at 20°C and Stover (36) reported that at a temperature of 20°C, the nitrification stopped at the 3-day SRT. In the author's research, good NH_3-N removal (nitrification) was observed even at the 2-day SRT, which may be partially due to the higher temperature.

Three-Stage Nitrifying-Denitrifying System

Municipal wastewater collected from the Oklahoma State University Environmental Engineering pilot plant building was used for feeding this system as with the one-stage nitrifying system. The first carbonaceous removal reactor was operated at a constant SRT of 1 day. The other two nitrification and denitrification reactors were operated at different SRT's (F/M values). The hydraulic flow rates were carefully controlled and the reactors were operated by wasting of biological solids to establish desired SRT's, while temperatures of the reactor varied between 21 and 30°C.

Data from this activated sludge system operated at different conditions were presented in the preceding chapter. The first carbonaceous removal reactor was operated at the SRT of 1 day (an F/M value of 1.04 based on BOD_5 and 2.75 based on COD), in order to prevent nitrification. The second reactor was operated as a nitrification system. Since the settling was very good in the carbonaceous removal reactor, the effluent suspended solids were never higher than 6.0 mg/ℓ. Thus there was very little carry-over of suspended solids to the nitrification reactor. The effluent soluble BOD_5 averaged around 12.0 mg/ℓ, with a COD of about 55.0 mg/ℓ. The BOD_5 and COD removals were around 91 and 80 percent throughout the operation of this system. The $BOD_5/COD:NH_3\text{-}N$ ratio was around 110/275:30 on the first carbonaceous removal reactor which was the same as the one-stage nitrifying system discussed earlier.

The second nitrification reactor in the three-stage system was operated at different SRT's (at different F/M based on NH_3-N). The average influent ammonia-nitrogen concentration for the nitrification reactor was around 23.0 mg/ℓ, after losing around 7.0 mg/ℓ for synthesis of cells in the first carbonaceous removal reactor. For this nitrification reactor, the $BOD/COD:NH_3\text{-}N$ ratio was around 11/55:23. The settling of solids was so good that there was zero suspended solids in the effluent of this reactor, except for the 2-day SRT for which the solids were around 3.5 mg/ℓ. Complete nitrification was achieved for the F/M values of 0.22 (15-day SRT), 0.35 (8-day SRT), and 0.45 (5-day SRT) in terms of NH_3-N. The nitrification started decreasing from the F/M value of 0.74 (3-day SRT) and was down to 85 percent for the F/M value of 1.20 (2-day SRT). At the F/M value of 1.20, the effluent NH_3-N concentration from the nitrification reactor was around 3.3 mg/ℓ. A decrease in nitrification for the higher F/M values or lower SRT's was due to the decrease in the nitrifier population and an increase of carbon concentration in the reactor as discussed earlier for the one-stage nitrifying system. A decrease in the nitrifier population was due to the high growth rate of the system at low SRT's.

The average nitrate-nitrogen (NO_3-N) concentration in the effluent from the nitrification reactor varied from 16.4 to 19.5 mg/ℓ based on the SRT and influent NH_3-N concentration. The dissolved oxygen was maintained around 3.0 to 4.0 mg/ℓ in order to provide enough oxygen so that DO was not a limiting factor for nitrification in the nitrification reactor.

The biokinetic constants U_{max} and K_B were calculated and presented in Table XIV. The values of U_{max}, K_B, and Y_t are 13.10, 13.10, and 0.52, respectively, for the BOD/COD:NH_3-N ratio of 11/55:23. This ratio is entirely different from the one which was used for the one-stage nitrifying system. The organic matter coming into the second nitrification reactor from the first carbonaceous removal reactor is hard to biodegrade, since easily biodegradable organics will be removed in the first carbonaceous removal reactor. The BOD/COD:NH_3-N ratio for the nitrification reactor cannot be compared with the ratio of the one-stage nitrifying system. So the biokinetic constants cannot be compared based on

BOD/COD:NH_3-N for these two different reactor systems, even though both were nitrifying reactors. The design of these two systems employ different physical modes of operation involving different competing biological mechanisms.

In order to compare the kinetics for the second nitrification reactor in the three-stage system, the reactor needs to be operated at different BOD/COD:NH_3-N ratios of the effluent from the first carbonaceous removal reactor. This can be achieved by operating the first carbonaceous removal reactor at different F/M values in terms of BOD or COD in order to get different BOD/COD:NH_3-N ratios for the second nitrification reactor.

The third denitrification reactor was operated at different F/M values based on NO_3-N from the second (nitrification) reactor. Since most of the carbon was removed in the first two reactors, it was necessary to add an external carbon source for denitrification to occur. This external carbon source acted as the electron donor for denitrification in which NO_3-N is the final electron acceptor. The electron donor should be one with a low yield, if the quantity to be added is to be minimized. This has the added benefit of reducing the quantity of sludge produced as well. Generally, single-carbon compounds have low yields because the energy required to synthesize cell constituents from them is large. So the highly reduced single-carbon compound is methanol, which is widely available, of consistent quality, and relatively inexpensive. For all of these reasons, methanol was used as an external electron donor for the third denitrification reactor. The BOD_5 added to the reactor due to the addition of methanol was around 75 mg/ℓ. This amount was more than sufficient for the complete denitrification for the NO_3-N concentration of around 20.0 mg/ℓ. This amount of methanol was added for all conditions, so that the external electron donor is not a limiting factor for denitrification. Complete (100%) denitrification was achieved for the F/M values of 0.14 (15-day SRT), 0.25 (8-day SRT), and 0.32 (5-day SRT) in terms of NO_3-N. From the F/M value of 0.62 (3-day SRT), the denitrification started decreasing. The NO_3-N removal for the F/M values of 0.62 (3-day SRT), 1.00 (2-day SRT), and 1.58 (1-day SRT) in terms of NO_3-N were 99, 91, and 55 percent, respectively. High denitrification (91%) was achieved even at the 2-day SRT. Then the denitrification decreased rapidly to 55 percent for the 1-day SRT (1.58 F/M value). This shows that essentially there were not sufficient denitrifying microorganisms in the reactor at the lower SRT's or at the higher F/M values in terms of NO_3-N. As in the nitrification reactor, this low population is due to the high growth rate of the system at the lower SRT's. Another possibility for the reduced denitrification at low SRT's is due to the inhibition of methanol (80). At low SRT's, the excess methanol accumulation in the reactor might have inhibited the denitrification process. That is the reason why much scattering was observed in Figure 27 for the 1-day SRT (1.6 F/M value).

At these low SRT's (high F/M values), there was a leakage of NO_3-N in the final effluent. This varied around 0.2, 1.4, and 7.3 mg/ℓ for SRT's of 3, 2, and 1 days, respectively. Because of reduced denitrification at low SRT's of 2 and 1 days, more BOD_5 and COD were observed in the final effluent (Tables X, XI, and XII). This BOD_5 and COD was mainly due to the external carbon source (methanol) used as the electron donor, which has been used partially in the process of denitrification because of a higher growth rate of the system at low SRT's (high F/M values). Good settling was achieved in this reactor also, except at the 1-day SRT, in which the effluent suspended solids concentration was about 7.5 mg/ℓ. This is still within the limits of most discharge standards, so settling was never a problem in the three-stage nitrifying-denitrifying system.

The biokinetic constants, U_{max} and K_B, can also be calculated for the denitrification system using the Kincannon and Stover model. These constants are 10.00 and 9.70 with the yield coefficient, Y_t, of 0.60.

Effect of Temperature on Nitrification and Denitrification

As discussed earlier for the one-stage nitrifying system, the temperature of the three-stage nitrifying-denitrifying system also varied between 21 and 30°C. This temperature variation would have increased the rate of nitrification compared to a standard 20°C. This was discussed in detail for the one-stage nitrifying system, which is applicable here also for nitrification.

The effect of temperature variation during this study on the denitrification process may not be a concern, because the optimum temperature range for denitrification as reported by Kim and Chung (87) is 25 to 35°C. Focht and Chang (23) reported that temperature exerts a greater effect below 15°C than above it. Thus the temperature variation during the author's research did not affect the denitrification process; instead it was the optimum range for the denitrification process.

Combined Biological Nitrogen-Phosphorus Removal System

The influent raw municipal wastewater for the combined biological nitrogen-phosphorus removal system was also collected from Oklahoma State University's Environmental Engineering pilot plant building on McElroy Street. This system was operated at different SRT's, which are based on the total volume of all three anaerobic, anoxic, and aerobic reactors. The hydraulic flow rates were carefully controlled, and the reactors were operated by wasting of biological solids from the clarifier to establish desired SRT's, while the temperature of the reactors varied between 22 and 28°C. The temperatures for the 3-day SRT varied between 24 and 34°C because of the high temperature during the summer.

The data collected from this system were presented in the preceding chapter. Generally, BOD/COD:N:P ratios were around 11/30:3:1, except for the 7-day SRT, when they were around 15/38:3.6:1 because of a low influent phosphorus concentration. The external recycle of settled sludge back to the anaerobic reactor was pumped 100 percent (1:1) for SRT's of 25 and 15 days. Then they were reduced to 75, 50, and 31 percent for SRT's of 10, 7, and 3 days, respectively. This reduction in external recycle was basically to maintain a constant level of sludge blanket in the clarifier. This also prevented the water in the clarifier from being pumped back to the anaerobic reactor, due to insufficient sludge in the clarifier bottom.

BOD Removal

The percent BOD_5 removal of 68 percent for the 25-day SRT down to 50 percent for the 3-day SRT was observed in the anaerobic reactor. This anaerobic reactor was purposely subjected to partial removal so that there was enough carbon left for the anoxic reactor for denitrification purposes. Thus the reactor was operated at a very low hydraulic detention time. The biokinetic constants, U_{max} and K_B, for BOD_5 removal were obtained for the anaerobic reactor. The values are 4.00 and 5.60 (Table XXII). The BOD removal percentages in the anoxic reactor based on raw wastewater BOD loading were 29, 34, 40, 39, and 37 percent for SRT's of 25, 15, 10, 7, and 3 days, respectively. The total percent BOD removal through the anoxic reactor (including anaerobic reactor) for SRT's of 25, 15, 10, 7, and 3 days were 97, 96, 93, 92, and 87 percent, respectively. At low SRT's the removal was high compared to 25- and 15-day SRT's for the anoxic (denitrification) reactor. This is due to more availability of carbon for the anoxic reactor at low SRT's from the anaerobic reactor. The biokinetic constants, U_{max} and K_B, for BOD removal in the anoxic reactor are 2.10 and 2.30, respectively. The yield coefficient Y_t (1.0) was calculated for the total system, since the SRT maintained was for the total system, i.e., the sludge was wasted from the total system based on the total volume of all three reactors. High removal percentage and greater kinetic constants for BOD removal were observed for the anaerobic reactor than for the anoxic reactor. This may be due to the rapid removal of easily biodegradable organics in the anaerobic reactor, since it receives the raw wastewater first. The anoxic reactor receives only the remaining organics which are hard to biodegrade. Also, the anoxic reactor receives fewer organics compared to the anaerobic reactor, which reduces the removal rate of organics in the anoxic reactor. Because of these two reasons, there was greater removal of BOD and in turn greater BOD removal of kinetic constants for the anaerobic reactor when compared to the anoxic reactor.

The aerobic (nitrification) reactor removed the remaining BOD that passed through the anoxic reactor. In general, more than 97 percent

BOD removal was achieved in the total system even at the 3-day SRT. So carbonaceous removal is not a problem in this combined nitrogen-phosphorus removal system.

COD Removal

In the anaerobic reactor, for SRT's of 25, 15, 10, 7, and 3 days, the COD removal percentages were observed as 26, 23, 20, 33, and 19 percent, respectively. More removal of 33 percent was observed for the 7-day SRT. This was essentially due to the low COD loading of 278 mg/ℓ, compared to around 310 mg/ℓ for the other conditions. Like the BOD removal, the biokinetic constants U_{max} and K_B are calculated for COD removal also for the anaerobic reactor. The values are 1.66 and 4.93. In Figure 37, F/M versus U, there is more scattering of the data for the F/M value of 8.0 (3-day SRT). This may be due to the very high F/M ratio, in that the reactor was highly stressed. Also, at high growth rates (low SRT's) there would have been many intermediate byproducts produced during new cell synthesis.

The percent COD removals in the anoxic reactor were higher than in the anaerobic reactor. They were 61.0, 63.5, 64.0, 56.0, and 62.0 percent for SRT's of 25, 15, 10, 7, and 3 days. This may be due to the removal of easily biodegradable organics (in terms of COD) in the anaerobic reactor, which is less in the total COD. This leaves more COD to the anoxic reactor, in which the microorganisms must use the available organics for denitrification and cell synthesis even though the organics were hard to biodegrade. This might be the reason why more COD removal was observed in the anoxic reactor. The COD removal biokinetic constants U_{max} and K_B obtained for the anoxic reactor are also high at 18.5 and 21.7, respectively. The biokinetic constants for BOD and COD removal were close in the anaerobic reactor, which shows that only easily biodegradable organics were removed in the anaerobic reactor, which is the same in BOD and COD measurements. That is why the constant K_B, which indicates the biodegradability of the waste, is almost the same (5.60 and 4.93) for both BOD and COD removal in the anaerobic reactor. Less U_{max} for COD removal compared to BOD removal was due to the low percentage removal based on COD, i.e., the fraction of organics removed was the same for both BOD and COD, but the influent COD was almost 2.5 times greater than the influent BOD. Therefore, the removal rate U_{max} for COD is almost one-half (1.66) of the BOD removal rate (4.0). Since most of the COD was removed only in the anoxic reactor for the reasons discussed earlier, the COD removal biokinetic constants are also high in the anoxic reactor, which in turn gave the high COD removal percentage for the anoxic reactor. The remaining COD that passed through the anoxic reactor was removed in the aerobic (nitrification) reactor. The sludge production (yield) coefficient, Y_t, for COD removal was 0.40, with the decay coefficient (K_d) of -0.02.

Ammonia-Nitrogen Removal

Figures 42 through 51 show the time in days versus NH_3-N concentration and mass NH_3-N loading for SRT's of 25, 15, 10, 7, and 3 days. Like phosphorus, the mass loading of NH_3-N on the anaerobic reactor was based on influent TKN and NH_3-N loading due to external recycle. Thereafter the NH_3-N loading was calculated based on the NH_3-N concentration in the reactor, for the reasons discussed earlier for phosphorus loading. In all time versus mass NH_3-N plots, there was an increase in mass NH_3-N in the anaerobic reactor with respect to mass influent TKN. This may be due to the release of NH_3-N from the cells into the liquid under the anaerobic condition. In time versus NH_3-N concentration plots, the NH_3-N concentration in the anaerobic reactor is less than the influent TKN concentration due to the dilution by the external recycle of sludge into the anaerobic reactor. The release of NH_3-N in the anaerobic reactor was more for the 15-day SRT than for the 25-day SRT. From the 10-day SRT down to the 3-day SRT, the release started reducing and reached 20 percent for the 3-day SRT, as shown in Figure 52. This reduction in release may be due to the reduced anaerobic microorganism in the reactor that produces acetate at low SRT's because of higher growth rates. The production of acetate enhances the release of NH_3-N or phosphorus in the anaerobic reactor. Another explanation may be due to the reduced population of NH_3-N uptake-release microorganisms in the system at higher growth rates. Moreover, there may have been a predominant change of microorganisms in the system at lower SRT's which might have affected the capacity to uptake and release the NH_3-N into the liquid. The organisms which cause the NH_3-N uptake and release may be the same organisms which cause the phosphorus uptake and release.

More than 98 percent of the NH_3-N was removed at SRT's of 7 days and higher. For the SRT of 3 days, the removal was reduced to 83 percent due to a decrease in nitrification in the aerobic (nitrification) reactor. The decrease in nitrification was essentially due to the reduced population of nitrifying microorganisms at lower SRT's or, in other words, at higher growth rates. These were discussed in detail earlier for one- and three-stage nitrifying systems. The NH_3-N removal biokinetic constants U_{max} and K_B using NH_3-N as substrate were calculated for the aerobic reactor, which were 1.00 and 0.97, respectively. The yield coefficient, Y_t, on the total system is 5.12, with the decay coefficient K_d of -0.05 in terms of NH_3-N.

Nitrate-Nitrogen Removal

The nitrate-nitrogen formed in the aerobic (nitrification) reactor was recycled at the rate of 5:1 to 6:1 back to the anoxic reactor for denitrification. The quantification of NO_3-N was not possible because of instantaneous nitrification and denitrification due to internal recycle between these two reactors. Nevertheless, complete denitrification was achieved in the anoxic reactor even at the 3-day SRT. There was zero NO_3-N in the anoxic reactor. Here the organic carbon in the wastewater itself acts as the electron donor for the denitrification process. So there was no need for external carbon source for this system, unlike the three-stage nitrifying-denitrifying system. Complete denitrification was achieved even at a very low hydraulic detention time (around 25 minutes). Thus denitrification is not critical in the design of the combined nitrogen-phosphorus removal system. The average NO_3-N concentration observed in the final effluent from the aerobic reactor was around 0.8 mg/ℓ throughout the study of this combined nitrogen-phosphorus removal system.

Phosphorus Removal

Barnard (119) from pilot scale studies on the Bardenpho process reported that excess biological P removal is induced if at some point in the process configuration the organism mass is stressed by subjecting it to an "anaerobic" state (i.e., a state in which neither oxygen nor nitrate is present) such that phosphorus is released by the sludge mass to the bulk liquid. This can be achieved efficiently by including an anaerobic reactor ahead of the anoxic reactor. This reactor receives the influent flow and the underflow recycle from the final clarifier. The data collected from this combined nitrogen-phosphorus removal system were presented in detail in the preceding chapter.

Figures 57 through 66 show the time in days versus phosphorus concentration and mass phosphorus in each reactor for SRT's of 25, 15, 10, 7, and 3 days. In all of these plots, there was an increase in phosphorus in the anaerobic reactor. As discussed earlier, this is due to the release of phosphorus in the liquid. But the amount of release varied for the different SRT's. This can be clearly seen in Figure 67. The maximum release of 182 percent was achieved for the SRT of 15 days. This condition appears to be the optimum condition for the maximum release of phosphorus in the anaerobic reactor for the specific wastewater used in this research.

There are a number of theories relating to the ability of bacteria to take up phosphorus under aerobic conditions and releasing the same under anaerobic conditions into the liquid. The bacteria called Acinetobacter has been frequently found in biological phosphorus removal systems and is known to store polyphosphates. Some theories held that bacteria that have been starved of phosphorus for a certain period will take up vast surpluses of phosphorus when exposed afterward to liquid containing phosphorus under aeration. It was also determined that bacteria will store the surplus phosphate as volutinstaining polyphosphate in the cells. Harold (128) describes the mechanism as being a shunt that occurs when no energy is available for the conversion of ADP to ATP. Under these conditions the phosphate is stored as polyphosphate in the cell by the action of enzyme kinase. Under conditions of phosphate starvation with energy available, the cell will use phosphates from its stored pool. Under conditions of fermentation the cell will release phosphates from the surplus storage.

According to Fuhs and Chen (110), the polyphosphate granules within the cell provides phosphorus to form ATP from ADP through the catalysis of the polyphosphate enzyme. The further conversion of ATP to ADP results in the release of phosphorus from the cell as well as providing a source of energy. Further, the fact that the addition of acetate increases the rate of phosphorus release by these Acinetobacter organisms suggests an interaction between these organisms and the facultative microbes present in activated sludge systems. Under anaerobic conditions the facultative aerobes produce acetates which enhance the rate of phosphorus release by the obligate aerobes (Acinetobacter). When the sludge leaves the anaerobic environment and enters aerobic conditions, the ATP content within the cell is low because the reaction of $ATP \rightarrow ADP + P$ is a high rate reaction relative to the formation of ATP from polyphosphates.

Under aerobic conditions the strict aerobes oxidize stored metabolites and other available substrates to provide energy to increase the ATP content of the cell. After a very short period of time, the ATP content in the cell exceeds the normal level and triggers the reversible polyphosphate kinase enzyme. This results in the formation of polyphosphate granules which are stable storage products while the cells are maintained in the aerobic environment. Thus optimum operational conditions are required to achieve the phosphorus release and uptake, which appears to be a 15-day SRT from the author's research.

For the 25-day SRT, the release dropped to 140 percent. This may be due to the less readily biodegradable organics in the anaerobic reactor surrounding the organisms, since at low growth rates or higher SRT's, the organisms' population in the system was high. This is supported by Siebritz, Ekama, and Marais (121). Another possible explanation may be due to the presence of higher forms of organisms at higher SRT's or low growth rates. There may be a competition for the available substrate among these different types of organisms.

For the 10-day SRT, the P release was observed as 114 percent; then the release started reducing with decreases in SRT and reached only 16 percent for the SRT of 3 days. This may be due to the reduced concentration of sludge mass going through the anaerobic reactor. This occurs when the SRT starts reducing. So there was not sufficient population of these organisms to uptake phosphorus under the aerobic condition and to release the same in the anaerobic reactor at the low SRT's. This trend can be clearly seen in Figure 67. Figure 68 also shows the same trend, but in terms of mass P applied (P/M). Another possible explanation may be due to the slow growing nature of the phosphorus release-uptake bacteria (Acinetobacter). At higher growth rates, i.e., at lower SRT's, these organisms simply cannot grow fast enough to maintain sufficient population in the system while losing these bacteria by wasting the sludge to maintain the required SRT.

For P/M values of 0.83 (3-day SRT) in terms of phosphorus, there was a slightly higher P release than for the P/M value of 0.10 (7-day

SRT). This was mainly due to the high P loading for the SRT of 3 days and the low P loading for the SRT of 7 days (Table XVIII and XIX).

From Figures 61 and 62, it can be seen that for three days (days 11, 12, and 13) the P release and uptake were minimum. This occurred during rainy days, so the municipal wastewater was diluted during these days, which gave very low concentrations of carbon, nitrogen, and phosphorus. However, the carbon source was added in the influent wastewater to enhance the phosphorus release-uptake mechanism. Even then the phosphorus release-uptake mechanism was not triggered. This may be due to the low concentration of the phosphorus in the wastewater, in which case there is a need for minimum phosphorus loading on the system to enhance the release-uptake mechanism. This is also supported by Figure 71, in which phosphorus removal does not start until the P/M value of 0.02 in terms of phosphorus on the aerobic reactor. Another explanation may be due to some inhibitory substances from the rainwater washout into the sewage which could have inhibited the phosphorus removal organisms.

Figure 69 shows the plot of average percent P content of the sludge from the aerobic reactor for different SRT's. The maximum sludge P content of 8.5 percent was observed for the SRT of 15 days, when the maximum P release was achieved in the anaerobic reactor for the same SRT. For 25 and 10 days SRT, the sludge P content dropped to 7.0 percent, which corresponds to less release of P for these conditions in the anaerobic reactor. P content of sludge for 7- and 3-day SRT's were 3.1 and 3.5 percent, respectively. As discussed previously, the higher P content of the sludge for the 3-day SRT compared to the 7-day SRT was mainly due to the difference in the mass loading of P into the system.

The initial average P concentration for SRT's of 25, 15, 10, 7, and 3 days were 10.0, 12.0, 11.8, 7.5, and 13.0 mg/ℓ, respectively. The average concentrations of P removed for SRT's of 25, 15, 10, 7, and 3 days were 5.00, 6.65, 6.60, 3.65, and 5.00 mg/ℓ, respectively. Figure 70 shows the average percent mass P removed as a function of SRT. Here also the maximum P removal (66%) was observed in the aerobic reactor for the SRT of 15 days, which corresponds to the high release of P in the anaerobic reactor. Although the sludge P content was the same (7.0%) for SRT's of 25 and 10 days, the removal of P was higher (62%) for the 10-day SRT than for the 25-day SRT (55%). This was mainly due to the higher wastage of sludge from the clarifier for the 10-day SRT than for the 25-day SRT. Then the P removal started decreasing for decreasing SRT, as shown in Figure 70. It is clear that whenever there is more release of P in the anaerobic reactor, more removal of P will be achieved in the aerobic (nitrification) reactor. Therefore, in order to achieve P removal in the aerobic reactor, it is very important to achieve P release in the anaerobic reactor. Figure 71 shows the mass P removal as a function of mass P applied. From this curve, it can be seen that the maximum P removal was achieved for the P/M value (P applied) of 0.062. The P/M value was calculated based on the phosphorus coming out of the anaerobic reactor.

From the above results and discussion, the optimum condition for the maximum phosphorus release and removal was found to be a 15-day SRT (P/M value of 0.062) for this study. This condition may vary for different municipal wastewaters depending upon their BOD/COD:TKN:TP ratio and the biodegradability of the organic matter.

Figures 72 and 73 show the settling characteristics of the aerobic sludge for the combined nitrogen-phosphorus removal system. Zone settling velocities of the sludge mass from the aerobic reactor increased with decreasing SRT's, as shown in Figure 73. Thus a decrease in zone settling velocity was observed at higher SRT's of 25, 15, and 10 days, when the system was removing phosphorus. Normally zone settling velocity decreases with an increase in SRT.

Comparison of Ammonia-Nitrogen Removal

Similar NH_3-N removal percentages were observed for both the one-stage nitrifying system and the three-stage nitrifying-denitrifying system even at lower SRT's. This might be due to the low BOD/COD:NH_3-N ratio of the wastewater. So for the high ratio (i.e., high BOD or COD), the three-stage nitrifying-denitrifying system may be more efficient for the removal of NH_3-N than the one-stage nitrifying system, since the one-stage system has to remove both carbon and NH_3-N in a single reactor.

The combined nitrogen-phosphorus removal system also removed NH_3-N equal to the other two systems at low SRT's. This system can be closely compared to the three-stage nitrifying-denitrifying system for the removal of NH_3-N. There is no need for the addition of external carbon source for this system, since it uses the raw wastewater organics itself as a carbon source. So there is no need for the calculation of an exact amount of external carbon source, which is required for the three-stage nitrifying-denitrifying system. If more external carbon source is added than required for denitrification, there will be a leakage of carbon in the effluent. Conversely, if less external carbon source is added, there will be a leakage of nitrate-nitrogen in the effluent of the three-stage nitrifying-denitrifying system. Therefore, the combined biological nitrogen-phosphorus removal system solves this problem in addition to the removal of phosphorus. The NH_3-N removal biokinetic constants U_{max}, K_B, Y_t, and K_d cannot be compared with any of these three systems because of differences in the physical mode of operation and competing biological mechanisms involved. The effluent quality was good in all three systems for NH_3-N.

Comparison of Phosphorus Removal

There was no phosphorus removal observed in the one-stage nitrifying system. A small amount of P removal was observed in the three-stage nitrifying-denitrifying system. This might be due to the phosphorus used for cell synthesis in all three reactors. The phosphorus removal was only achieved in the combined biological nitrogen-phosphorus removal system. The average phosphorus concentration removed (approximately 7.0 mg/ℓ) at an optimum condition of a 15-day SRT may be increased if the raw wastewater easily biodegradable organics increase.

Comparison of Effluent Quality

The suspended solids in the final effluent of all three systems were very low for all operated conditions. The BOD, COD, and NH_3-N removal was also very good (more than 98%) for these systems. Since phosphorus removal was achieved only in the combined biological nitrogen-phosphorus removal system, the effluent phosphorus concentration was high for the one-stage nitrifying and the three-stage nitrifying-denitrifying systems. The phosphorus from these two effluents can be removed by the addition of chemicals. Even in the combined biological nitrogen-phosphorus removal system there was around 5.0 mg/ℓ of phosphorus observed in the effluent. This can be removed by adding small amounts of chemicals such as alum, lime, etc.

CHAPTER VI

CONCLUSIONS

The results of this investigation support the following conclusions:

1. It was found that SRT is not the criteria for nitrification to occur. Instead, the food to microorganisms ratio (F/M) in terms of BOD or COD appears to be the important criteria in defining nitrification in one-stage nitrifying systems. This agrees with results obtained by Lan (21), indicating that nitrifying organisms can be heterotrophic.

2. The Kincannon and Stover model shows promise as an alternate approach for evaluating and designing one-stage nitrifying systems (in terms of specific BOD/COD:NH_3-N ratios and specific wastewater treatability characteristics.

3. The Kincannon and Stover model seems to give similar biokinetic constants for the same COD:NH_3-N ratio, with similar wastewater characteristics for the one-stage nitrifying system.

4. Almost the same level of nitrification was achieved in both the one-stage nitrifying system and the three-stage nitrifying-denitrifying system for the BOD/COD:NH_3-N ratio of 110/275:30.

5. Nitrate-nitrogen removal (denitrification) was very good even at the F/M value of 1.0 (2 day SRT's) in terms of nitrate-nitrogen in the temperature range of 24 to 35°C.

6. High percentage COD removal was observed in the anoxic (deni-

trification) reactor of the combined biological nitrogen-phosphorus removal system.

7. The Kincannon and Stover model appears to be useful in evaluating combined biological nitrogen-phosphorus removal systems for the particular BOD/COD:NH_3-N:P ratio with similar wastewater characteristics.

8. Ammonia-nitrogen release was observed in the anaerobic reactor of the combined biological N-P removal system, and the release reached the maximum amount for the total system SRT of 15 days.

9. Complete denitrification was achieved in the anoxic reactor of the combined biological N-P removal system for the total system SRT of 3 days and above.

10. The maximum phosphorus removal was obtained at the total system SRT of 15 days, in the combined biological N-P removal system, for the specific municipal wastewater used in the author's research.

11. It was found there may be a minimum phosphorus loading required for the combined N-P removal system in order to enhance the phosphorus release-uptake mechanism.

12. In the combined biological nitrogen-phosphorus removal system, the optimum condition for NH_3-N and phosphorus removal was found to be 15 days SRT based on the total system, for the specific wastewater used in this research.

13. Many researchers have theoretically expected an increase in phosphorus removal for the decrease in SRT, but a decrease in phosphorus removal was observed for the decrease in SRT's in this research for a combined biological nitrogen-phosphorus removal system.

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