EFFECT OF WASTEWATER STOICHIOMETRY AND MEAN CELL RESIDENCE TIME ON PHOSPHOROUS REMOVAL IN THE ACTIVATED SLUDGE PROCESS

By

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CHAPTER I

INTRODUCTION

The concept of nutrient removal as an objective of wastewater treatment is relatively recent. An efficient primary and secondary biological treatment plant has been thought capable of producing an acceptable effluent having a low pollutional effect. However, as man has placed greater demands upon his limited water supplies, it has become apparent that further treatment of his waste discharges are necessary. Recent investigations have shown clearly that nutrient removal, principally nitrogen and phosphorous, should be practiced. However, nutrient removal technology is not far advanced and present methods available are not entirely suitable for general application. Therefore, extensive investigations of the various biological, physical, and chemical methods of nutrient removal are necessary.

Nutrient removal focuses upon two primary elements, nitrogen and phosphorous. Identification of one of these elements as a limiting growth nutrient has received considerable attention. Because of nitrogen fixation by specific microorganisms, phosphorous is generally accepted as being the limiting growth nutrient.

Eutrophication is defined as the natural process of nutrient enrichment of a body of water. The acceleration of the rate of eutrophication by man's waste discharges is a major concern of the water quality field. A very slow natural process, eutrophication can reach

critical levels in a very short period of time when man discharges a nutrient-laden waste into the stream or lake. Having reached a critical level, the process of self-recovery is extremely slow, even if all nutrient flow into the water is stopped (1).

An eutrophied lake possesses many undesirable water quality characteristics. Excessive aquatic plant growth, depleted dissolved oxygen levels, taste and odor problems, and an unbalanced natural life support system are a few of the problems associated with an eutrophied lake. The value of an eutrophied lake as a source of potable water is significantly decreased. Objectionable taste and odor problems resulting from abundant aquatic plant growth and the depleted dissolved oxygen levels require major water treatment operations to eliminate the problem. Furthermore, the aesthetic value of a lake is destroyed. Massive algal blooms reduce boating and swimming activity. Fish kills due to insufficient oxygen are detrimental to sport and commercial fishing. In general, this unbalanced growth system is contrary to the natural balance required in nature, thus, adverse conditions are to be expected. Therefore man, having recognized his dependence upon these limited water supplies, should recognize the need for preventive measures.

Since man's waste discharges are a principal source of phosphorous, it is only logical that removal of phosphorous be accomplished in the wastewater treatment facilities. Phosphorous removal can be accomplished by several methods: 1) biological incorporation, 2) chemical precipitation, 3) electrodialysis, and 4) ion exchange. Chemical precipitation can be accomplished through the use of aluminum salts, iron salts, and lime. Depending upon which chemical is used, the chemical dose can be applied ahead of the primary clarifier, directly into the

aeration tank of the activated sludge process, or to the treated secondary effluent. The latter two processes, electrodialysis and ion exchange, have been considered too expensive for municipal wastewater application. However, continued research and development of these two processes may make it economically feasible to apply this technology to municipal treatment in the near future. Biological incorporation, particularly in the activated sludge process, continues to receive considerable attention. Two reasons are the bases for this interest: 1) economics, and 2) the high removal efficiency reported in several plants (2)(3)(4). Economically, biological incorporation is the cheapest, since it occurs concurrently during oxidation of the soluble organic matter. Removal efficiencies often exceeding 90 percent have been reported. Extensive studies have been directed at determining the operating parameters leading to this high removal efficiency. It was hoped that identification and duplication of these parameters could lead to high removal efficiencies at all plants. However, this approach has not been too successful.

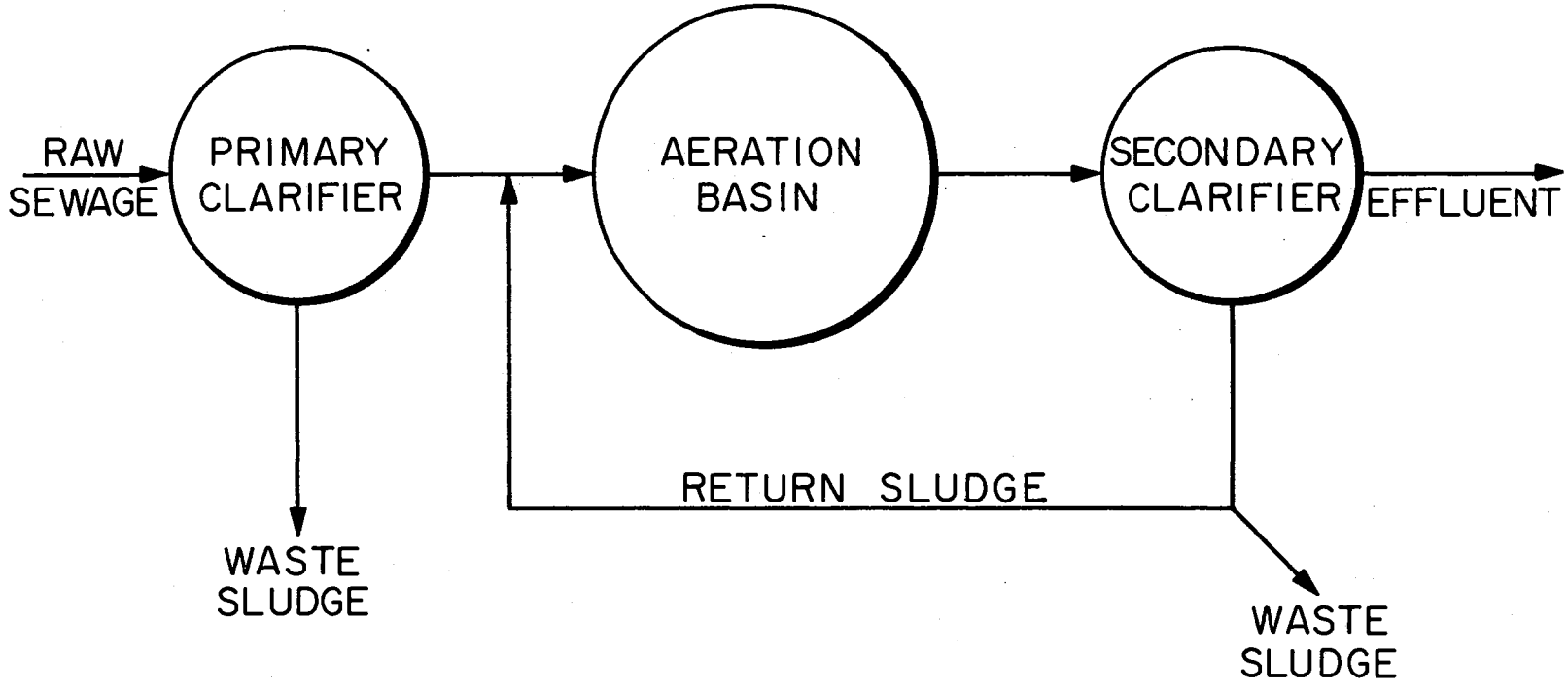
Despite the number of extensive studies reported previously, there is a lack of research in the investigation of the influence of stoichiometric relationships of the wastewater and the mean cell residence time on phosphorous removal. Therefore, the purpose of this investigation is to determine the influence of the wastewater stoiochiometry and mean cell residence time on phosphorous removal in the completely mixed activated sludge process. To accomplish this purpose, a laboratory scale, completely mixed activated sludge reactor, was operated under controlled conditions. Over a period of approximately five months, sufficient data were obtained to indicate the effects of these variables

on the removal of phosphorous.

The activated sludge process has been defined as a fluidized bed biological reactor. As shown in Figure 1, the aeration basin receives settled effluent from the primary clarifier. A heterogeneous microbial population oxidizes the soluble organic material. The microorganisms use a portion of the food for energy and the remaining part for synthesis of new cellular material. Flow from the aeration tank enters the secondary clarifier, where a solids-liquid separation occurs. The supernatant liquid either receives additional treatment or is discharged to a receiving body of water. A portion of the settled sludge is recycled to the aeration basin so that the desired mean cell residence time can be maintained. The remainder of the settled sludge is wasted to sludge handling facilities.

Completely mixed stirred tank reactors with recycle of biological solids using the mean cell residence time as an operating parameter are becoming increasingly popular. Typically, activated sludge units have been classified as either low rate or high rate processes. Low rate units are identified with high mean cell residence times--that is, low production of biological solids. High rate units operate at low mean cell residence times, hence high production of biological solids. The high rate process is typified by such characteristics as 1) high sludge production, 2) high food-to-microorganism ratio, 3) high nutrient removal, 4) lower stability to shock loadings, and 5) general difficulty of operation. Likewise, the low rate unit is characterized by 1) low sludge production, 2) low food-to-microorganism ratio, 3) low nutrient removal, 4) greater stability to shock loadings, and 5) greater ease of operation (5). Therefore, from these general characteristics,

Figure 1. Typical Flow Diagram of the Activated Sludge Process


RAW
SEWAGE
PRIMARY
CLARIFIER
AERATION
BASIN
SECONDARY
CLARIFIER
EFFLUENT
RETURN SLUDGE
WASTE
SLUDGE
WASTE
SLUDGE

one would expect the mean cell residence time to be an important parameter affecting phosphorous removal efficiency.

The remaining chapters of this study will be devoted to a detailed presentation and analysis of factors affecting phosphorous removal efficiency. In Chapter II, a review of pertinent literature will be presented. This chapter will focus upon the theory of luxury uptake and the influence of the mean cell residence time and stoichiometry on the removal of phosphorous. A detailed description of the materials and methods used in performing the research is presented in Chapter III. A presentation of the results and a discussion of these results form the basis of Chapter IV. The application of these findings to actual design and field operations may be found in Chapter V. Conclusions drawn from the results of this study are outlined in Chapter VI. As a result of the findings of this study, recommendations for future work are proposed and are listed in Chapter VII.

CHAPTER II

LITERATURE REVIEW

A. Introduction

Based on a review of the literature concerning removal of phosphorous from wastewaters, it can be concluded that four principal methods are employed. Phosphorous removal methods include 1) biological incorporation, 2) chemical precipitation, 3) chemical-biological removal, and 4) chemical-physical removal (6). Because this investigation pertains specifically to biological incorporation of phosphorous, the literature review will center around studies on biological removal. However, when pertinent, information obtained from physical and chemical removal studies will be presented.

Before proceeding with an analysis of the literature, it is necessary to note several important factors. First, every investigation cited was performed at a full-scale treatment plant. There are obvious disadvantages with such studies. Due to the ever-changing character of the waste flow, it becomes impossible to obtain strict control of various operating and environmental parameters. Furthermore, these studies had as the principal goal the determination of the operating parameters resulting in the greatest phosphorous removal efficiency. Therefore, investigators were preoccupied with such physical parameters as mixing tank configurations, hydraulic detention time, mixed liquor suspended solids concentration, aeration rate, dissolved oxygen concentration, and

pH. While these are important biological environmental parameters, other parameters such as the mean cell residence time and chemical stoichiometric relationships of the wastewater have been virtually ignored.

It is this lack of information concerning the influence of wastewater stoichiometry and mean cell residence time on phosphorous removal in the activated sludge process that has formed the basis of this investigation. This lack of information is not surprising. The COD-to-phosphorous ratio may be changed; however, this may be a costly practice. Organic matter such as methanol may be added to increase the COD:P ratio. For research purposes, phosphorous may be added so that the COD:P ratio will be lowered. Precipitation of the phosphorous ahead of the biological reactor is another means of increasing the COD:P ratio. Although these methods may not be feasible in some cases, it is apparent that some control of the wastewater stoichiometry is possible. When the importance of wastewater stoichiometry is recognized, the alteration of the COD:P ratio may become standard practice. Furthermore, operators are more familiar with using a constant mixed liquor suspended solids concentration level as an operating parameter rather than using sludge age directly as the operating parameter. Therefore, the mixed liquor suspended solids levels are commonly listed without the additional information required for the computation of the mean cell residence time.

B. Sources of Phosphorous

Human wastes and domestic laundering are the primary sources of phosphorous found in wastewater. Black and Veatch Consulting Engineers (7) in a report for the Environmental Protection Agency, concluded that

human wastes and waste food disposal account for 30 to 50 percent of the phosphorous, while detergents used in laundering account for the remainder. In a "typical" domestic waste, the phosphorous concentration will normally range from 10 - 15 mg/l P.

If a treatment plant receives a combined sewage flow, phosphates from fertilizers used on residential yards could drastically increase the total phosphorous loading on the plant. The effect of industrial waste flows are highly variable. Industrial waste discharges should be analyzed individually to ascertain that particular industry's contribution to the phosphorous load.

Nesbitt (8) concluded that phosphorous enters treatment plants in three forms: 1) organic phosphorous, 2) complex inorganic phosphates, and 3) soluble inorganic phosphates. It is the soluble inorganic phosphates (PO_4^{-3}) that are utilized by biological organisms. The organic and complex inorganic phosphates are converted to inorganic phosphates at some time during the treatment process. Finstein and Hunter as reported by Nesbitt (8) found that the hydrolysis of complex phosphates is performed by the biological flora within the treatment plant.

C. Luxury Uptake Theory

1. General Considerations

Biological removal of phosphorous embraces two theories for the removal mechanism. One theory, luxury uptake, has been used to explain excess phosphorous removal strictly on a biological basis. Luxury uptake as defined by Levin and Shapiro (2) is "the uptake of dissolved orthophosphate by sludge organisms, that is, uptake in the absence of growth." Proponents of this theory (2)(3)(9)(10) stress that

microorganisms are capable of storing phosphorous granules (volutin) within their cell structure. Under ordinary conditions, the cell composition of phosphorous ranges from two to three percent. However, when volutin granules are present, the cell may contain as high as six to eight percent phosphorous on a dry weight basis (2)(4). This apparent capacity to incorporate excess phosphorous provided the incentive to instigate field investigations of treatment plants that experience high phosphorous removal (3)(11)(12)(13)(14).

The second theory of biological phosphorous removal states that removal is dependent upon net biological growth. Sherrard and Schroeder (15) have suggested that it is possible to predict phosphorous removal knowing the cell composition, sludge age, and the chemical stoichiometry of the wastewater. Shindala (6) concluded as a result of data reported by Stumm and Morgan that the stoichiometrical relationships of the wastewater plays an important role in phosphorous removal efficiency. Data presented by Mulbarger, Shifflett, Murphy, and Huffman (10) from a study of the Greater Manassas Sanitary District activated sludge plant substantiates the theory that phosphorous removal is dependent upon sludge age. Their results indicate maximum phosphorous removal occurred at a mean cell residence time of 3.6 days. Increasing the sludge age lowered the phosphorous removal. This can be attributed to lower sludge production, hence less phosphorous incorporated into the biomass. This is the one point of agreement between the two theories. Phosphorous is removed by incorporation into new cell material and that wastage of this sludge is necessary to remove phosphorous from the waste stream.

2. Reactor Type

As previously stated, studies conducted at full-scale plants have been directed at identifying the parameters which have the greatest influence on phosphorous uptake. The reactor type is one such physical parameter studied. Milbury, McCauley, and Hawthorne (4) noted that all plants which obtain high removal efficiencies are plug flow reactors. In a full scale investigation of the Baltimore Back River plant, these researchers studied the effect of the flow scheme. With the existing plug flow reactor having a theoretical hydraulic detention time of 6.5 hours, phosphorous removal efficiency ranges from 30 to 90 percent. Utilizing a step aeration flow scheme, the removal efficiency dropped to 40 to 50 percent. Further modification to contact stabilization having a 2.5-hour contact time and a 6-hour reaeration time lowered the removal efficiency to the 10 percent range. With a continuous flow, completely-mixed laboratory unit seeded with sludge from the aeration tanks of the plug flow plant, the removal efficiency ranged from 15 to 20 percent. As a result, a plug flow scheme was cited as a requirement for enhanced removal.

Explanations of the apparent need for a plug flow reactor have been proposed (4)(15)(17). Beer (16) suggests that the activated sludge must be taken through a period of intense metabolic activity while under anaerobic conditions to encourage luxury uptake of phosphorous. These conditions exist at the head end of a plug flow tank. The high substrate concentrations and dissolved oxygen levels near zero coupled with the high metabolic activity of the microorganisms thus satisfy the initial growth requirements. Levin and Shapiro (2) also determined that if a sludge was first stripped of its phosphate, it

exhibits greater uptake rate when returned to the aeration tank. In a plug flow tank, a release of phosphorous is detected at the head of the tank (4) followed by a subsequent uptake along the length of the tank. It is at the lower end of the tank where a low food-to-microorganisms ratio exists that phosphorous incorporation takes place. The organisms have passed from the "log growth phase" and into the "endogenous respiration phase." Thus, uptake of dissolved orthophosphate, that is, uptake without growth according to Levin and Shapiro (2), occurs.

The completely mixed flow scheme which maintains cells in a "log growth phase" is reported by investigators at the University of Texas Medical Branch to be ineffective in obtaining enhanced phosphorous removal (17). It was their conclusion that release of phosphorous by "older" cells is encouraged in the complete mix process. Beer (16) also concurs that the luxury uptake phenomenon cannot take place in the complete mix system. The lack of a zone of high substrate concentration prohibits this flow scheme from enhancing phosphorous removal.

3. Hydraulic Detention Time

Hydraulic detention time does not affect phosphorous removal (4). The theoretical detention time of the Baltimore Back River Plant study varied from 2.5 hours to 10 hours without affecting the removal efficiency (4). Reports by Spiegel and Forrest (18) and Convery (19) list acceptable ranges of hydraulic detention times of 1 - 4 hours and 3 - 6 hours, respectively. Therefore, any practical detention time should be satisfactory.

4. Aeration Tank Suspended Solids Concentrations

Aeration tank suspended solids concentrations is another parameter which many investigators believe does not affect phosphorous removal efficiency. In the Baltimore study (4), a range of suspended solids from 1400 - 3800 mg/l was utilized with no effect on removal efficiency. As a result, these researchers concluded that a solids concentration greater than 1400 mg/l could be utilized with equally effective removal. Spiegel and Forrest (18) recommended a mixed liquor suspended solids range of 4000 - 6000 mg/l. Convery (19) in his report to the Environmental Protection Agency recommended the mixed liquor suspended solids range be limited to 2500 - 4000 mg/l.

5. Dissolved Oxygen Level

Luxury uptake proponents strongly stress the importance of dissolved oxygen in the aeration tanks (2)(3)(4)(9)(20). Nesbitt (20) reports that the dissolved oxygen should be at least 2.0 mg/l at the midpoint of the tank, and 5.0 mg/l at the outlet of the tank. Milbury, McCauley, and Hawthorne (4) reported phosphorous releases at the Baltimore Back River plant when the dissolved oxygen dropped from two to three mg/l at the outlet of the aeration basin. Phosphorous leakages as a result of low dissolved oxygen levels were confirmed by Wells (9) and Levin and Shapiro (2). Witherow (14) in his study of the San Antonio treatment plants found that phosphorous removal did not occur in tanks in which a dissolved oxygen concentration from 0.2 to 0.4 mg/l was maintained. However, when the dissolved oxygen level was maintained between 1.5 to 5.3 mg/l, the removal efficiency increased to 70 percent. Convery (19) reported that dissolved oxygen levels greater than 2.0 mg/l

were necessary for luxury uptake. Spiegel and Forrest (18) determined the limiting dissolved oxygen concentrations ranged from 0.4 to 1.9 mg/l. However, it must be pointed out that the importance of dissolved oxygen is related to the leakage of phosphorous from the cell.

6. Rate of Air Application

The rate of phosphorous uptake has been reported to be strongly affected by the rate of air supplied to the mixed liquor (2)(3)(4)(9). Using laboratory batch units, Levin and Shapiro (2) demonstrated that the rate of aeration markedly influenced the rate of dissolved orthophosphate uptake. A range of flowrates, 0, 5, 16, 24, 35, and 50 ml/sec, were studied. At the end of three hours of aeration, the 5 ml/sec flowrate resulted in a 70 percent removal of the dissolved orthophosphate. A flowrate of 17 ml/sec increased the removal efficiency to 80 percent. Flowrates of 24, 35, and 50 ml/sec only slightly increased the removal. Therefore, increasing air flowrates result in increased rates of phosphorous uptake. However, there apparently exists a limiting flowrate which, if exceeded, results in only slightly increased rates of removal. Levin and Shapiro (2) further investigated the effects of pure oxygen versus compressed air on uptake rates. Flowrates of 0.7 ml pure oxygen/second and 3.4 ml air/second were selected to provide equal amounts of oxygen. Fifteen hundred ml of raw activated sludge were aerated over a period of five hours with samples being tested hourly. The experiment showed that aeration with pure oxygen resulted in a greater rate of phosphorous uptake. Connell and Vacker (3) also concluded that the rate of aeration was one of the two principal factors affecting luxury uptake.

7. pH

In batch studies, Levin and Shapiro (2) determined that the mixed liquor pH significantly affects phosphorous uptake. The greatest uptake occurred at a pH range of 7.0 - 8.0. A pH of 9.0 resulted in a noticeable decrease in uptake. Furthermore, at pH values of 5.0 and 6.0, a rapid release of orthophosphate by the microorganisms was detected. This release of phosphate under acidic conditions plays a vital role in enhancing removal rates by phosphorous stripped microorganisms (2). Utilized in this manner, phosphorous stripping can be an effective tool in biological removal. However, if such release occurs unchecked, for instance in anaerobic digestion, a concentrated phosphorous stream could negate an otherwise effective removal program.

D. Stoichiometric Relationship

The stoichiometric relationships of the wastewater play a vital role in the phosphorous removal efficiency of the system (6)(15)(21). Randall, Marshall, and King (21) point out that the stoichiometric relationships of the biological cells as compared to the stoichiometric relationships of the wastewater prevents significant cellular incorporation of phosphorous, i.e., carbon as the limiting growth factor. Shindala attributes the low removal efficiency usually found in the activated sludge process directly to the unfavorable stoichiometric relationship of domestic wastewater and the microorganisms. Stumm and Morgan, as reported by Shindala (6), determined that a mean carbon: nitrogen:phosphorous (C:N:P) ratio of 70:17:1 for a domestic wastewater and a C:N:P ratio of 106:16:1 for the biological sludge commonly exists at treatment plants. Thus, total incorporation of phosphorous

is prohibited by an insufficient quantity of carbon. Sherrard and Schroeder (15) have written stoichiometric equations describing the biological growth process. A cellular composition was assumed in the writing of equations. Also, the net solids production was known. From an analysis of the equations, it is apparent that for a given net solids production, a fixed quantity of phosphorous can be removed. Therefore, the removal efficiency for that one instance is directly dependent upon the quantity of phosphorous supplied to the system. Furthermore, an increase in solids production results in an increase of phosphorous incorporation. Therefore, maximum biological removal of phosphorous corresponds to the maximum production of solids. It is apparent that effective solid-liquid separation is a requirement for effective biological removal.

E. Mean Cell Residence Time

The effect of solids production on nutrient removal, particularly phosphorous removal, is currently being studied in both laboratory and full scale investigations (3)(10). Sherrard and Schroeder (15), as mentioned previously, have demonstrated through the use of stoichiometric equations, the importance of solids production in biological removal. For a given cell and carbon source, phosphorous incorporation increases as the solids production increases. This increase in solids production is a direct result of a decrease of the mean cell residence time (15). Therefore, by decreasing the sludge age of the system, sludge production is increased.

In a study of the Manassas Sanitary District's 1 MGD activated sludge plant, Mulbarger, et al. (10) studied the influence of mean cell

residence time on phosphorous removal. Their report found that maximum removal efficiency occurred at a mean cell residence time of approximately 3.6 days. Decreased removal efficiencies occurred at lower mean cell residence times due to the increase in effluent biological solids. The decreased removal efficiencies for high mean cell residence times were directly attributed to decreased sludge production. A report by the Sewage Commission of the City of Milwaukee adds further evidence of the dependence of phosphorous removal on sludge production (22). During normal operations, the Jones Island treatment plant achieves approximately 80 percent removal of phosphorous. However, during a period of decreased sludge production, the removal efficiency decreased significantly to 60 - 70 percent. The bacterial sludge phosphorous content remained constant at 2.35 percent. However, when sludge production was allowed to increase to the original levels, the phosphorous removal efficiency again increased to the former 80 percent or greater. As a result, it was concluded that if suitable environmental parameters are maintained in the system, phosphorous removal varies directly with sludge production.

Further evidence of the importance of the stoichiometry of the wastewater and sludge production as it is related to the phosphorous removal efficiency may be found in the Sewerage Commission report. In this report, an extensive investigation of the biological removal of phosphorous occurring in the Jones Island treatment facilities was performed. During the study, a shutdown of a brewery industry occurred. The BOD loading contributed by the breweries was found to be approximately 22 percent of the average BOD loading. During normal operations, the average raw sewage BOD at the Jones Island East Plant was

230 mg/l and the average soluble orthophosphorous concentration was 2.1 mg/l. This resulted in a BOD:P ratio of 109.5:1. During the period of the brewery shutdown, the influent BOD dropped to 182 mg/l while the soluble orthophosphorous concentration remained at 2.1 mg/l. The BOD:P ratio of 86.7 indicates the influence of the brewery waste on the plant operation. During normal operations, the East plant averaged 86 percent removal of the soluble orthophosphorous and 91 percent of the total phosphorous. However, during the brewery shutdown, the soluble orthophosphorous removal efficiency decreased to 12.5 percent, while the total phosphorous removal efficiency decreased to 65 percent. The sludge production also decreased significantly from approximately 1600 tons per week to 1100 tons per week.

The phosphorous content of the sludge was monitored continuously. It was determined that phosphorous remained constant throughout the study. Therefore, it can be seen that for decreasing sludge production and decreasing BOD:P ratios, the phosphorous removal efficiency will decrease.

F. Summary

From the preceding discussion, it is apparent that in earlier investigations, emphasis was placed upon identifying the environmental parameters associated with plants achieving abnormally high removal efficiencies. The general reasoning behind such investigations is apparent; if we can identify and duplicate these parameters in other plants, the same removal results can be expected. However, recent trends indicate that biological removal mechanisms are now being recognized as fundamentally important in the understanding of phosphorous

removal. In the presence of suitable environmental conditions, growth rate and wastewater stoichiometry exert a profound influence upon observed removal efficiency. Therefore, an understanding of the effects of these two variables is necessary if the bioengineer is to make reasonable predictions of plant performance.

CHAPTER III

MATERIALS AND METHODS

To study the influence of mean cell residence time and stoichiometric relationships on phosphorous removal in the activated sludge system, a bench scale unit was operated under closely controlled conditions.

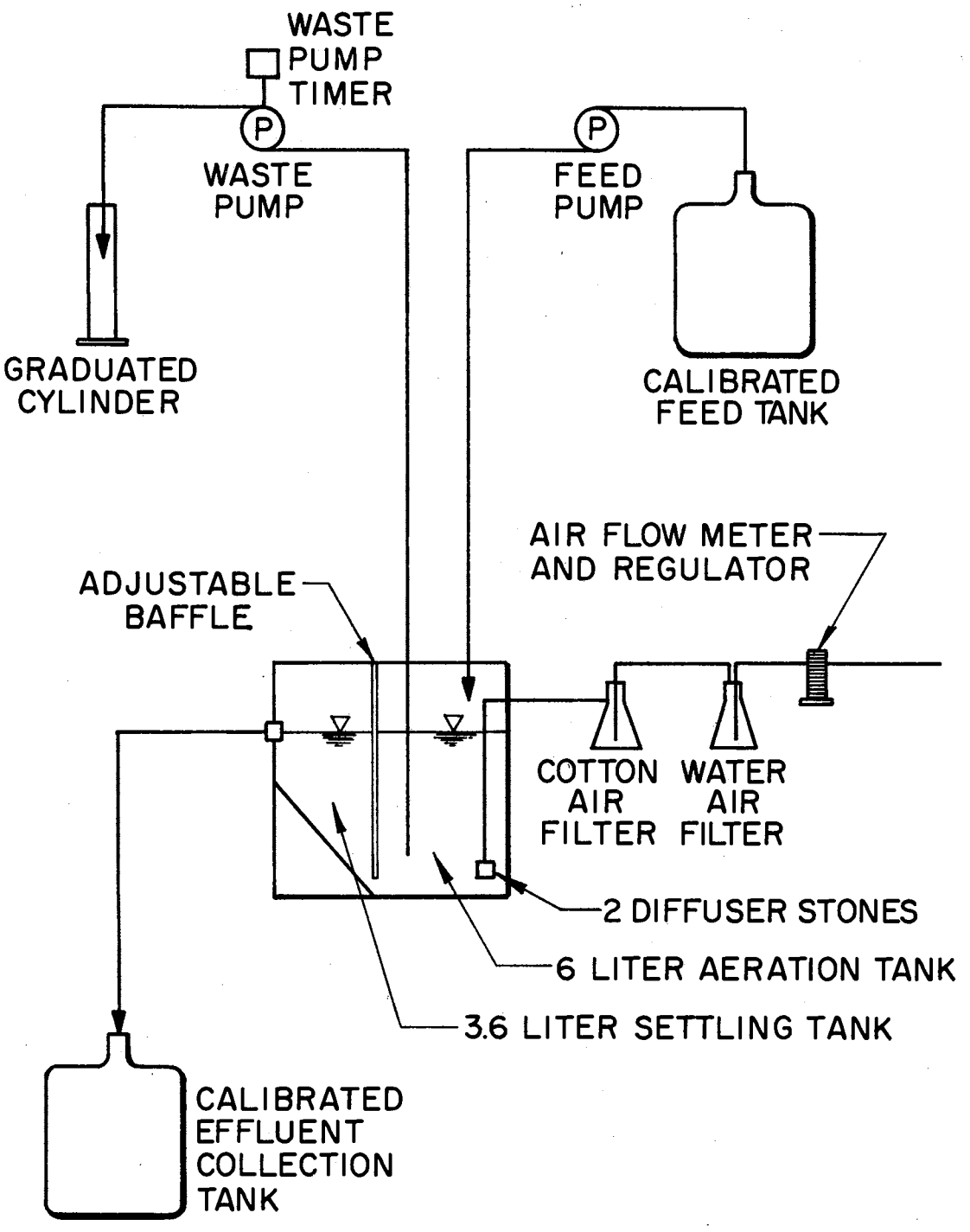
For ease of presentation, a description of the laboratory apparatus, the feed solution, initial startup, daily protocol, analytical procedures, and methods of data analysis used to carry out the objectives of this study are presented separately.

A. Laboratory Apparatus

A schematic diagram of the laboratory apparatus used in the experimental investigation is shown in Figure 2. A 9.6-liter plexiglass reactor with internal recycle of bacterial cells served as the aeration chamber and secondary clarifier. An adjustable plexiglass baffle separated each of these compartments. The aeration chamber and the clarifier volume were six liters and 3.6 liters, respectively. A feed rate of 18 liters per day provided a hydraulic detention time of 8.0 hours in the aeration chamber and 4.8 hours in the clarifier.

Air was supplied through two porous diffuser stones at an airflow rate of 4.0 liters per minute, which was adequate to provide good mixing and also supply sufficient oxygen for the microorganisms. The

Figure 2. Experimental Activated Sludge Unit with Internal Sludge Recycle


WASTE
PUMP
TIMER
P
WASTE
PUMP
P
FEED
PUMP
GRADUATED
CYLINDER
CALIBRATED
FEED TANK
AIR FLOW METER
AND REGULATOR
ADJUSTABLE
BAFFLE
COTTON
AIR
FILTER
WATER
AIR
FILTER
2 DIFFUSER STONES
6 LITER AERATION TANK
3.6 LITER SETTLING TANK
CALIBRATED
EFFLUENT
COLLECTION
TANK

air flow rate was monitored through a Gelman air flow meter. To protect the biological system from oil contamination from the compressed air system, two filters were placed ahead of the diffuser stones. A cotton filter followed by a water filter eliminated the possibility of oil entering the aeration chamber.

A Miltoy-Roy dual, positive displacement pump (Mini-pump, Model MM2-b-96R) was used to provide a continuous flow of wastewater to the treatment unit. Latex tubing was used on the suction side of the pump. Tygon tubing was placed on the discharge side of the pump. Feed lines were disinfected by pumping a one-percent solution of Clorox and distilled water for a period of one day followed by pumping tap water for a period of twenty minutes to cleanse the lines of the disinfectant. Thus, while one line was pumping feed, the second line was being disinfected. Pumping rates were checked periodically by means of a graduated cylinder and timer.

Wasting of biological solids was accomplished from the aeration chamber. A glass tube extended into the center of the aeration chamber through which the solids were removed. The waste sludge system consisted of a timer, a Sigmamotor (Model T-8) "finger" pump, and a graduated cylinder which was used to measure the volume of mixed liquor wasted daily. The timer actuated the finger pump on cycles of 30 seconds per 30 minutes, 60 seconds per 30 minutes, and 120 seconds per 30 minutes to maintain mean cell residence times of approximately 12.0, 8.5, and 4.0 days. The Sigmamotor pump was calibrated to pump flowrates of 320, 600, and 1400 ml per day, thereby maintaining the desired mean cell residence times.

B. Feed Solution

Listed in Table I is the chemical composition of the wastewater used in this study. Bacto-peptone served as the carbon and energy source. The wastewater was designed to have a nominal chemical oxygen demand (COD) of 325 milligrams per liter (mg/l). Other required nutrients were provided in the concentrations as shown in Table I. Sodium phosphate monobasic ($NaH_2PO_4 \cdot H_2O$) was used to supply phosphorous for the system. When varying the COD:P ratio of the feed, the COD was held constant and the phosphorous concentration changed. Phosphorous concentrations of 10, 5, and 2.5 mg/l PO_4-P were selected. A 0.3 M carbonate buffer system controlled the pH of the system. The feed pH was maintained at approximately 7.2. Distilled water was used to dilute the concentrated stock solutions to the final volume of 18 liters.

The feed solution was carefully designed so that iron and calcium precipitation of phosphorous would not occur. The Fe^{3+} and Ca^{2+} feed concentrations of 0.05 mg/l and 1.35 mg/l, respectively, are much too low to result in precipitation of the phosphorous. If the total amount of Fe^{+3} was precipitated as $FePO_4$, the quantity of precipitated PO_4^{-3} ion would be a 0.12 mg/l. From solubility product calculation, the maximum solubility of PO_4^{-3} in the presence of the Ca^{+2} would be 65.1 mg/l. The maximum PO_4^{-3} concentration attained was 42.4 mg/l. Therefore, it is evident that chemical precipitation of PO_4^{-3} was not significant. Optimum pH values for phosphorous precipitation are 4.5 - 5.0 for the Fe^{3+} precipitate and >9.0 for the Ca^{2+} precipitate. The feed solution pH of 7.2 lies outside of these optimum ranges. Furthermore, considerable care was exercised in the mixing of the feed solution. Thirteen liters of distilled water was first placed in the

20-liter carboy. Following this, the stock solutions of Bacto-peptone, magnesium and manganese sulfate, ferric chloride, calcium chloride, sodium phosphate, sodium bicarbonate and sodium carbonate, in that order, were mixed thoroughly in the original 13 liters of water. The feed solution was then diluted to the final volume of 18 liters. The procedure was used daily so that phosphorous precipitation was avoided.

TABLE I

COMPOSITION OF WASTEWATER

	Stock Concentration per 2 ℓ (grams)	Quantity used per 18 ℓ (ml)	Final Concentration per 18 ℓ (mg/l)
Bacto-peptone*	129.00	80.0	287.00
$MgSO_4 \cdot 7H_2O$	20.00	90.0	50.00
$MnSO_4 \cdot H_2O$	2.00	90.0	5.00
$FeCl_3 \cdot 6H_2O$	0.10	90.0	0.25
$CaCl_2$	1.50	90.0	3.75
$(NH_4)_2SO_4$	200.00	45.0	250.00
$NaH_2PO_4 \cdot H_2O$**	17.78	**	**
Na_2CO_3 ***		90.0	
$NaHCO_3$		90.0	

* Nominal COD of waste = 325 mg/l
** Dependent upon COD:P ratio utilized
*** 0.3 M buffer solution

C. Initial Startup

The original seed of microorganisms was taken from a well-operating experimental activated sludge system similar to the one previously described. The unit was operated on a batch basis until the solids concentration had built up to approximately 1500 mg/l. During this period of time, the microorganisms were acclimated to the Bacto-peptone solution.

When the solids concentration reached approximately 1500 mg/l, the unit was switched to continuous flow operating conditions. Wasting of mixed liquor was postponed until the solids concentration had built up to the desired value and the effluent solids reduced to an appropriate level. Having achieved these conditions, wasting of mixed liquor at a previously determined rate was begun. Monitoring of the parameters noted in Table II was initiated.

D. Daily Protocol

A daily operating procedure was developed to aid in efficient and accurate data collection. Table II shows the parameters which were monitored daily.

The wastewater was prepared daily according to the proportions shown in Table I. A 20-ml sample of the fresh feed was removed for the chemical oxygen demand determination. A second 20-ml sample was placed in a glass vial and frozen for later total feed phosphorous concentration analysis. The pH of the feed solution completed the parameters monitored on the feed. Following these operations, the feed supply was connected to the clean feed lines.

TABLE II

PARAMETERS MONITORED DAILY

I.	Feed
	A. Chemical oxygen demand
	B. Total PO_4-P concentration
	C. pH
II.	Filtered Effluent
	A. Chemical oxygen demand
	B. Soluble PO_4-P concentration
III.	Unfiltered Effluent
	A. Total PO_4-P concentration
	B. pH
	C. Suspended solids concentration
IV.	Biological Reactor
	A. Aeration basin microorganism concentration
	B. Total system microorganism concentration
	C. Temperature
	D. pH

A 100-ml effluent sample was collected in a graduated cylinder. From this sample, 50 ml of the volume were filtered through 0.45 μ filter pads for the determination of the effluent solids concentration. A 20-ml sample of the unfiltered effluent was placed in a glass vial

and frozen for the total phosphorous test. The remaining 30 ml of effluent were checked for pH. Twenty ml of the filtrate was used in the COD analysis, and a second 20-ml sample used for the soluble orthophosphate test.

A 25-ml sample of the aeration basin mixed liquor was filtered for determination of the mixed liquor suspended solids. The effluent line was plugged, the baffle removed, and the contents mixed thoroughly. A 25-ml sample was removed and filtered. This sample provided data for the total system suspended solids concentration. The baffle was then replaced, the solids allowed to settle, and the plug removed. The unit was then back on continuous flow operation.

E. Analytical Procedures

To provide the necessary data for this investigation, the chemical oxygen demand, phosphorous concentration, biological solids concentration, pH, and temperature were monitored daily. The following is a brief description of the methods and equipment used to measure these parameters.

Feed COD determinations were made in accordance with Standard Methods (23). Effluent COD determinations utilized the dilute COD method as given in Standard Methods (23).

Biological solids concentrations were performed by filtering the appropriate volume through membrane filters (0.45 μ pore size, Millipore Filter Corp., Bedford, Mass.). The filter pads were placed in aluminum tare pans and dried at 103°C. for two hours. Following cooling to room temperature in a desiccator, the pans were tared to determine the initial weights. All weights were obtained by using a Mettler

Instrument Corporation balance (No. 1-910). After filtration of a known volume of sample, the pans were replaced in the drying oven for two hours at 103°C., cooled in the desiccator, and weighed to obtain the final weights.

Phosphorous determinations were made in accordance with Standard Methods (23). For the total phosphorous determination, the persulfate digestion method followed by the stannous chloride method was utilized. For soluble orthophosphate determination, the stannous chloride was used. Color measurement was obtained by using a Bausch and Lomb Spectronic 20 at a wavelength of 650 mμ.

The pH was determined by use of a Beckman Expandomatic SS-2 pH meter. Periodic standardization of the meter at pH values of 4.0, 7.0, and 10.0 ensured accuracy of the readings.

Temperature of the system was made by use of a Sargent-Welch thermometer having a range of -20 to 110°C.

F. Methods of Data Analysis

The mathematical relationships for the completely mixed activated sludge process as presented by Sherrard, Schroeder, and Lawrence (24) were utilized for data analysis.

Treatment purification or COD removal efficiency was calculated according to the expression

$$E = \frac{100\ (C_o - C)}{C_o} \qquad (1)$$

where

E = COD removal efficiency, percent

C_o = Influent substrate concentration, mg/l

C = Effluent substrate concentration, mg/l.

Phosphorous removal efficiency was calculated by using the following equation:

$$E_p = \frac{100\ (P_o - P)}{P_o} \tag{2}$$

where

E_p = Phosphorous removal efficiency, percent

P_o = Influent PO_4-P concentration, mg/l

P = Effluent PO_4-P concentration, mg/l.

Mean cell residence time or sludge age was determined by the relationship:

$$\theta_c = \frac{VX}{Q_w X + Q_{eff} X_{eff}} \tag{3}$$

where

θ_c = Mean cell residence time, days

V = Volume of aeration basin, liters

Q_w = Wasted liquid flow rate, liters per day

Q_{eff} = Effluent liquid flow rate, liters per day

X = Aeration basin and waste line microorganism concentration, mg/l

X_{eff} = Effluent liquid microorganism concentration, mg/l.

Based on an analysis of equation (3), the mean cell residence time is based upon the aeration basin contents. However, for this study, the mean cell residence time was calculated for both the aeration chamber and the total reactor, i.e., aeration chamber plus settling chamber. Therefore, when based upon the total reactor, the denominator of the above equation remained unchanged. The numerator variables, however, were modified appropriately to

V = Volume of total reactor, liters

X = Total reactor microorganism concentration, mg/l.

The observed yield coefficient was calculated according to the following expression

$$Y_{obs} = \frac{Q_w X + Q_{eff} X_{eff}}{Q(C_o - C)} \quad (4)$$

where

Y_{obs} = Observed yield coefficient

Q = Influent liquid flowrate, liters per day and all remaining terms are as previously defined.

An estimation of the phosphorous content of the cells was obtained by using the following equation

$$\%P = \frac{(A - B)}{X_{eff}} 100 \quad (5)$$

where

%P = Phosphorous content of cell on a dry weight basis, percent

A = Total phosphorous concentration of the unfiltered effluent sample, mg/l

B = Total phosphorous concentration of the filtrate, mg/l

X_{eff} = Effluent liquid microorganism concentration, mg/l.

Linearization of the observed yield data was accomplished by employing two different methods. The least squares method of statistical analysis was employed in determining the equation of the line of best fit (25).

The first method (26) used a plot of the reciprocal of the observed yield versus the mean cell residence time. The resulting equation took the form of

$$\frac{1}{Y_{obs}} = \frac{1}{Y_{max}} + \frac{b\theta_c}{Y_{max}} \quad (6)$$

where

Y_{max} = The intercept of the line at the vertical axis

b = Maintenance energy coefficient, $days^{-1}$ and all other variables are as previously defined.

The second method used is the one often found in the sanitary engineering literature. From the plot of specific growth rate versus specific utilization rate, the yield constant and the maintenance energy coefficient may be determined. This equation took the form

$$\frac{1}{\theta_c} = YU - b \tag{7}$$

where

Y = A yield constant

U = Specific utilization rate, $days^{-1}$ and all other terms are as previously defined.

CHAPTER IV

RESULTS AND DISCUSSION

The laboratory activated sludge unit was operated under closely controlled conditions for a period of approximately five months. The hydraulic detention time was maintained essentially constant at 8.0 hours. The mean cell residence time was varied from 3.6 days to 14.4 days. "Steady-state" conditions were shown when constant values for the aeration basin microorganism concentration, effluent COD, and effluent PO_4-P were obtained. Tabular raw data for each of the nine experimental runs are found in Appendix A.

The remainder of this chapter shall be devoted to a detailed presentation of the results of this investigation. Following the presentation of results, the significance of these findings will be discussed.

A. Results

1. Results

1. COD:P = 32.6:1. Three experimental runs at mean cell residence times of 4.1, 8.6, and 10.7 days were made. A summary of the "steady-state" data for these three sludge ages may be found in Table III. The nominal COD and PO_4-P concentration of the wastewater were 325 mg/l and 10.0 mg/l for an influent COD:P ratio of 32.5:1. As can be seen from the summary of data, the experimental value deviated slightly from the theoretical values.

TABLE III

SUMMARY OF STEADY-STATE DATA FOR LABORATORY REACTOR
FOR COD:P = 32.6:1
(θ = 8.0 hours)

		Substrate Conc.			PO_4-P Concentration					Biolog. Sol. Conc.					
θ_c (days)	COD:P Ratio	Feed (mg/l)	Effl. (mg/l)	Effic. (%)	Feed (mg/l)	Sol. Effl. (mg/l)	Remov. Effi. (%)	Total Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (mg/l)	Total React. (mg/l)	Effl. (mg/l)	Y_{OBS}	pH	P Conc. Sludge (%)
4.1	33.2	322	17	94.7	9.7	5.5	43.3	6.9	28.9	1143	1063	3.0	0.30	7.4	3.32
8.6	33.6	329	24	92.7	9.8	7.2	26.5	8.3	15.3	1930	1452	7.0	0.23	7.1	2.21
10.7	31.1	311	25	92.0	10.0	8.5	15.0	8.9	11.0	2188	1748	8.0	0.22	6.8	2.85

The COD removal efficiency exceeded 92.0 percent for each of the three runs. Aeration basin microorganism concentrations of 1143, 1930, and 2188 mg/l were obtained for mean cell residence times of 4.1, 8.6, and 10.7 days, respectively. The calculated observed yield of 0.30, 0.23, and 0.22 for sludge ages of 4.1, 8.6, and 10.7 days, respectively, decreased with increasing mean cell residence times. The pH of the unit decreased with increasing cell residence times. This decrease in pH was attributed to the nitrification that was occurring at the higher sludge ages (27).

Phosphorous removal efficiency increased with decreasing mean cell residence times. For soluble orthophosphate, the maximum removal efficiency of 43.3 percent was obtained at 4.1 days. As the mean cell residence was increased to 8.6 and 10.7 days, the corresponding phosphorous removal efficiencies decreased to 26.5 and 15.0 percent. For total phosphorous removal efficiency, the maximum efficiency, 28.9 percent, also occurred at a sludge age of 4.1 days. As with the soluble orthophosphate results, increased cell residence times were accompanied by decreased removal efficiency. Total phosphorous removal efficiencies of 15.3 and 11.0 percent were obtained for sludge ages of 8.6 and 10.7 days. The phosphorous content of the sludge varied slightly for this particular range of mean cell residence times. The maximum phosphorous content (percent on a dry weight basis) was 3.32 percent at a sludge age of 4.1 days. Phosphorous contents of 2.21 and 2.85 percent at sludge ages of 8.6 and 10.7 days, respectively, were found.

2. COD:P = 63.6:1. As with the COD:P = 32.6:1, three experimental runs were also made. Sludge ages of 4.0, 8.5, and 13.1 days were used. The nominal COD of the wastewater was the same as with the previous

COD:P ratio. However, for this ratio a feed phosphorous concentration of 5.0 mg/l P was used, thus yielding an ideal COD:P ratio of 65:1. From the summary of "steady-state" data as shown in Table IV, COD:P ratios of 60.2:1, 64.3:1, and 66.3:1 for mean cell residence times of 4.0, 8.5, and 13.1 days were calculated. For the three data collection periods an average COD:P ratio of 63.6:1 may be calculated.

The COD removal efficiency remained above 92 percent. The maximum COD removal efficiency of 96.5 percent was obtained at a sludge age of 8.5 days. Meanwhile, the minimum removal efficiency of 92.6 percent was observed for a mean cell residence time of 13.1 days.

Aeration basin microorganism concentrations of 1180, 1946, and 2580 mg/l were measured at corresponding sludge ages of 4.0, 8.5, and 13.1 days. Observed yields of 0.34, 0.24, and 0.20 were calculated for the previously listed cell residence times. As with the previous COD:P ratio, the pH decreased with increased mean cell residence times. An average pH of 6.5 was maintained for a cell residence time of 13.1 days.

Soluble orthophosphate removal efficiencies of 82.0, 55.1, and 42.1 percent were obtained at sludge ages of 4.0, 8.5, and 13.1 days. Total phosphorous removal efficiency was less than that of the soluble phosphates. At mean cell residence times of 4.0, 8.5, and 13.1 days, total phosphorous removal efficiencies of 66.0, 46.9, and 26.5 percent were measured.

The phosphorous content of the sludge was also determined for this COD:P ratio. Phosphorous contents of 3.63, 3.35, and 2.84 percent on a dry weight basis at mean cell residence times of 4.0, 8.5, and 13.1 days, respectively, were found.

TABLE IV

SUMMARY OF STEADY-STATE DATA FOR LABORATORY REACTOR
FOR COD:P = 63.6:1
(θ = 8.0 hours)

		Substrate Conc.			PO_4-P Concentration					Biolog. Sol. Conc.					
θ_c (days)	COD:P Ratio	Feed (mg/l	Effl. (mg/l)	Effic. (%)	Feed (mg/l)	Sol. Effl. (mg/l)	Remov. Effi. (%)	Total Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (mg/l)	Total React. (mg/l)	Effl. (mg/l)	Y_{OBS}	pH	P Conc. Sludge (%)
4.0	60.2	301	22	92.7	5.0	0.9	82.0	1.7	66.0	1180	1102	4.0	0.34	7.5	3.63
8.5	64.3	315	11	96.5	4.9	2.2	55.4	2.6	46.9	1946	1587	7.0	0.24	7.0	3.35
13.1	66.3	325	24	92.6	4.9	2.8	42.1	3.6	26.5	2580	1925	15.0	0.20	6.5	2.84

3. COD:P = 126.51. For a COD:P = 126.5:1, a feed phosphorous concentration of 2.5 mg/l P was used. The nominal COD:P ratio was 130:1. However, slight deviations from this ideal value were calculated as shown in Table V. The average COD:P ratio for the three experimental data collection periods was 126.5:1.

Phosphorous removal efficiencies for this low phosphorous feed concentrations were found to be exceedingly high. At mean cell residence times of 3.6, 8.5, and 14.4 days, soluble orthophosphate removal efficiencies of 97.5, 96.1, and 69.2 percent were achieved. Total phosphorous removal efficiencies of 68.8, 72.9, and 42.3 percent for the same sludge ages were obtained. The lower total removal efficiency at the sludge age of 3.6 days was attributed to the higher (13.0 mg/l) effluent microorganism concentration. As the data indicate, the system was phosphorous-limited when the sludge age was 3.6 days.

As with the preceding two COD:P ratios, the phosphorous content of the sludge for each mean cell residence time was determined. For this particular COD:P ratio, mean cell residence times of 3.6, 8.5, and 14.4 yielded phosphorous content of 2.31, 2.87, and 2.21 percent, respectively.

The COD removal efficiency was affected by this phosphorous limitation. At the low sludge age, the removal efficiency dropped to 81.1 percent. At the higher sludge ages of 8.8 and 14.4 days, the removal efficiency increased to the normal range, that is, greater than 92.0 percent.

The aeration basin biological solids concentration at a sludge age of 3.6 days was 939 mg/l. Biological solids concentrations of 1941 mg/l and 2816 mg/l maintained mean cell residence times of 8.5 and 14.4 days. Observed yields of 0.34, 0.25, and 0.19 for sludge ages

TABLE V

SUMMARY OF STEADY-STATE DATA FOR LABORATORY REACTOR
FOR COD:P = 126.5:1
(θ = 8.0 hours)

		Substrate Conc.			PO_4-P Concentration					Biolog. Sol. Conc.					
θ_c (days)	COD:P Ratio	Feed (mg/l)	Effl. (mg/l)	Effic. (%)	Feed (mg/l)	Sol. Effl. (mg/l)	Remov. Effi. (%)	Total Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (mg/l)	Total React. (mg/l)	Effl. (mg/l)	Y_{OBS}	pH	P Conc. Sludge (%)
3.6	127.9	307	58	81.1	2.4	0.06	97.5	0.75	68.8	939	901	13.0	0.34	7.5	2.31
8.5	128.8	309	24	92.2	2.4	0.09	96.1	0.65	72.9	1941	1590	7.0	0.25	7.0	2.87
14.4	122.7	319	16	95.0	2.6	0.80	69.2	1.50	42.3	2816	2076	9.0	0.19	6.7	2.21

of 3.6, 8.5, and 14.4 days were calculated. As with the previous two COD:P ratios, the pH decreased with increasing mean cell residence times.

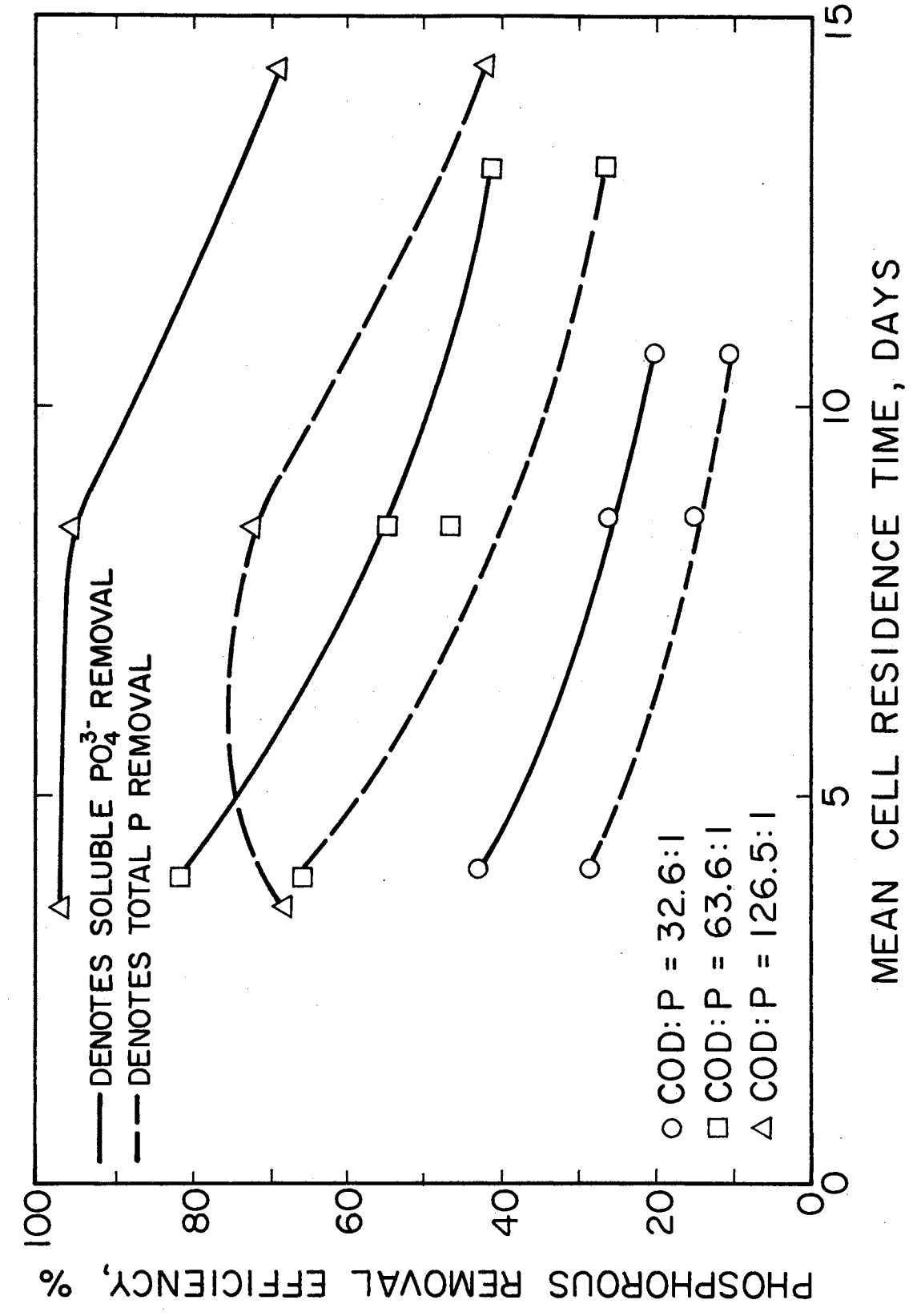
B. Discussion

1. Phosphorous Removal

By combining the data from the three stoichiometric ratios, the influence of the mean cell residence time and stoichiometry of the wastewater is apparent as shown in Figure 3. From the graph, two general conclusions may be drawn. First, lowering the mean cell residence time increases the phosphorous removal efficiency. Secondly, increasing the stoichiometric COD:P ratio also increases the phosphorous removal efficiency. It is also apparent that at sufficiently high COD:P ratios and low sludge ages, the removal efficiency curve flattens out and only slight increases in efficiency are detected at lower cell residence times. For this case, phosphorous has become the limiting nutrient. Furthermore, it is obvious that the effective removal efficiency, that is, the total removal efficiency, is dependent greatly upon an effective solids-liquid separation in the clarifier. In other words, high solids carryover in the effluent greatly reduces the effective removal of phosphorous.

Operating the laboratory activated sludge unit at lower sludge ages resulted in higher phosphorous removal efficiencies. This increase in removal efficiency may be attributed to increased sludge production and thus removal of the incorporated phosphorous by means of the waste sludge system. Over the range of mean cell residence times used for this investigation, this generalization was found to be applicable for the soluble orthophosphate removal. This conclusion may also be applied

Figure 3. Phosphorous Removal Efficiency versus Mean Cell Residence Time


PHOSPHOROUS REMOVAL EFFICIENCY, %
100
80
60
40
20
0
0
5
10
15
MEAN CELL RESIDENCE TIME, DAYS
—DENOTES SOLUBLE PO_4^{3-} REMOVAL
– – DENOTES TOTAL P REMOVAL
○ COD:P = 32.6:1
□ COD:P = 63.6:1
△ COD:P = 126.5:1

for the total phosphorous removal efficiency at COD:P ratios of 32.6:1 and 63.6:1. Had the effluent microorganism concentration remained low at a θ_c = 3.6 days and a COD:P = 126.5:1, this conclusion would also be valid. However, the excess solids carryover in the effluent resulted in a slightly lower overall efficiency at the lower sludge age. Regardless of this one exception, high rate operation with its larger production of sludge results in larger phosphorous removal efficiencies.

The stoichiometry of the wastewater strongly influences the removal efficiency. At a given mean cell residence time, the larger the COD:P ratio, the larger the removal efficiency. The increase in removal efficiency is not due to an increase in the amount of phosphorous incorporated into cellular material. Rather, the amount of phosphorous incorporated remains constant while the influent concentration is reduced. Thus, on the basis of the definition of removal efficiency, the calculated efficiency increases. Thus, removal efficiency is a vague and ambiguous term since it is strongly influenced by the influent concentration.

As previously mentioned, effective phosphorous removal is dependent upon efficient separation of the biological solids from the effluent liquid. The potential advantages obtained from biological incorporation are lost when the microorganisms are discharged with the effluent. This is readily apparent from the graph. A removal efficiency greater than 80 or 90 percent should have been obtained at the mean cell residence time of 3.6 days. However, the increase of biological solids in the effluent reduced this efficiency to 68.8 percent. Therefore, effective solids-liquid separation must be insured to obtain the full benefits of biological incorporation of phosphorous.

The phosphorous content of sludge varied from 2.21 percent to a maximum of 3.63 percent, as shown in Figure 4. The phosphorous content of the sludge seems relatively unaffected by changes in sludge age or stoichiometry of the wastewater. Although there appears to be a slight decrease in the phosphorous content of the sludge with increasing mean cell residence times, the significance of this decrease cannot be ascertained. In this study, the bacterial cells did not seem to store phosphorous within their structure as would be indicated by high (6 - 8 percent) phosphorous contents. The phosphorous content range determined in this study agrees closely with other published data. The lack of phosphorous storage is one plausible explanation for the relatively low phosphorous removal efficiencies encountered for the low COD:P ratio (10 mg/l P). If the phosphorous content of the bacterial cells had doubled, i.e., phosphorous content of about 6.6 percent, a removal efficiency of approximately 80 percent may have been obtained. This type of removal efficiency compares favorably with those plants exhibiting "luxury uptake."

2. COD Removal Efficiency

Over the range of mean cell residence times used in this investigation, the COD removal efficiency remained virtually unaffected, as shown in Figure 5. However, the COD removal efficiency was significantly influenced by the phosphorous limitation which occurred at a sludge age of 3.6 days and a COD:P ratio of 126.5:1. The COD removal efficiency which had been exceeding 92.0 percent at all previous runs, dropped to 81.1 percent. This decrease in efficiency is attributed to unmetabolized substrate remaining in the effluent. This excess

Figure 4. Phosphorous Content of Sludge versus Mean Cell Residence Time

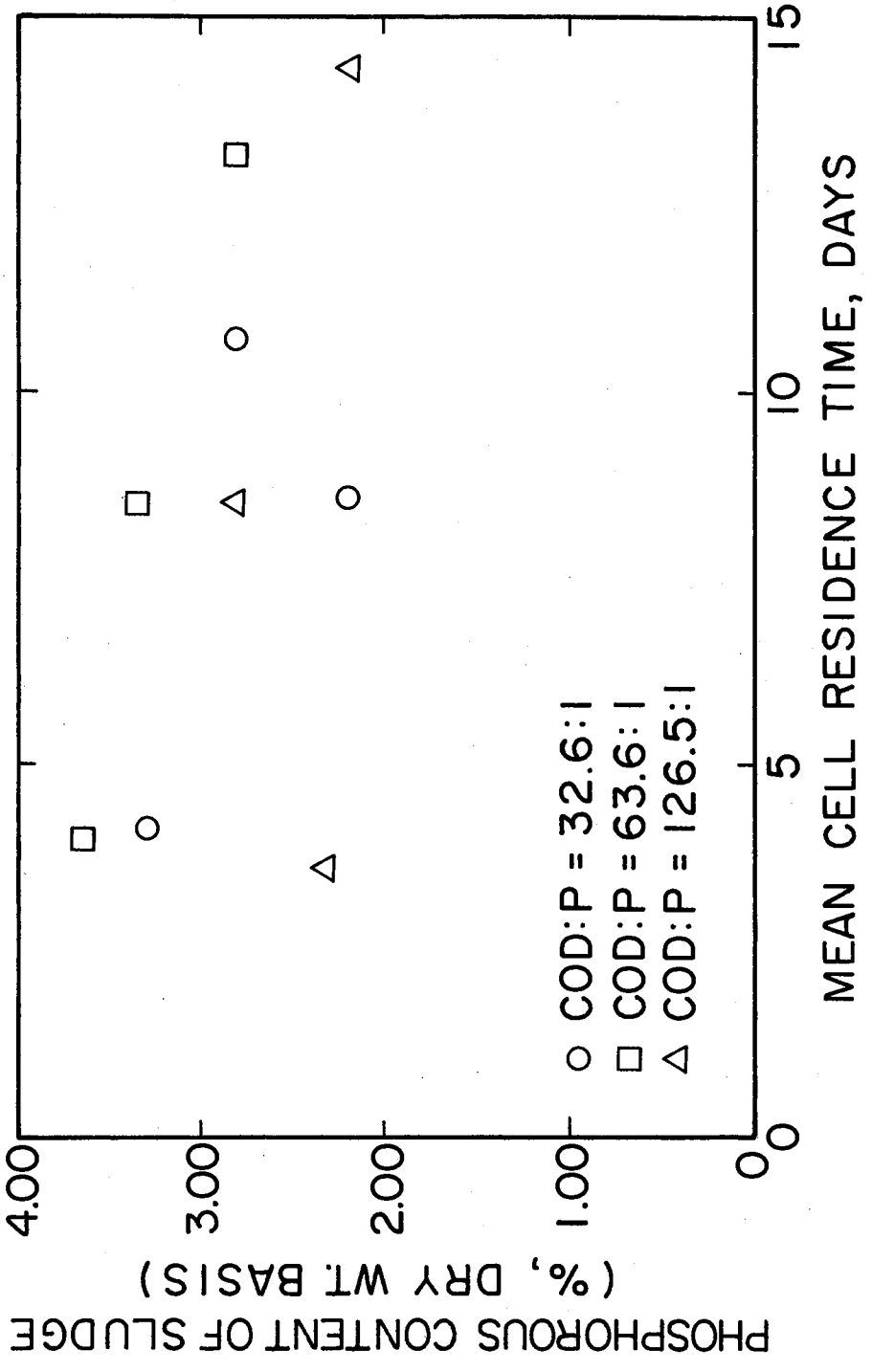
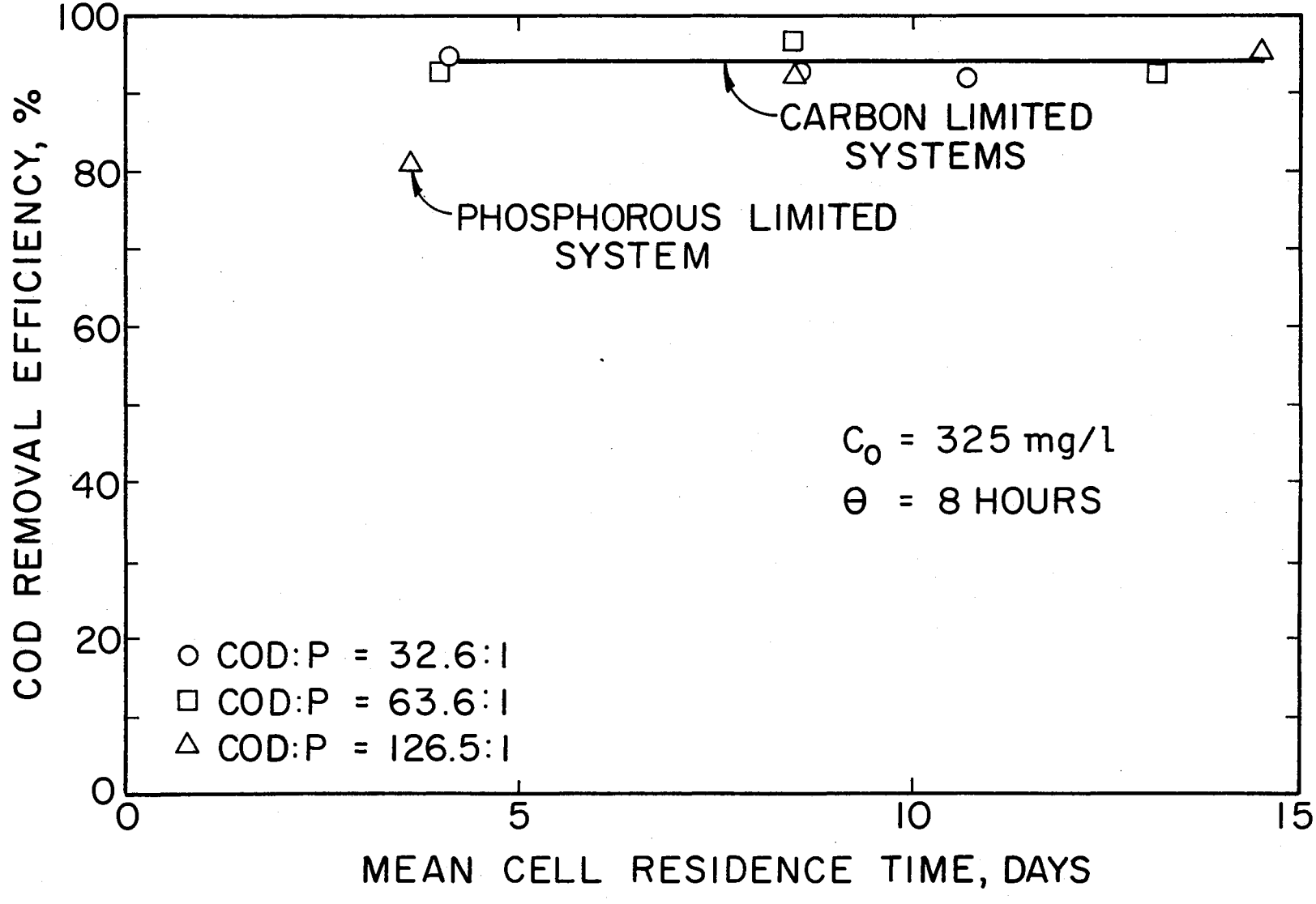

PHOSPHOROUS CONTENT OF SLUDGE
(%, DRY WT. BASIS)
4.00
3.00
2.00
1.00
0.0
0
5
10
15
MEAN CELL RESIDENCE TIME, DAYS
○ COD:P = 32.6:1
□ COD:P = 63.6:1
△ COD:P = 126.5:1

Figure 5. COD Removal Efficiency versus Mean Cell Residence Time


100
80
60
40
20
0
0
5
10
15
COD REMOVAL EFFICIENCY, %
MEAN CELL RESIDENCE TIME, DAYS
CARBON LIMITED SYSTEMS
PHOSPHOROUS LIMITED SYSTEM
C_o = 325 mg/l
θ = 8 HOURS
○ COD:P = 32.6:1
□ COD:P = 63.6:1
△ COD:P = 126.5:1

substrate constitutes that portion of substrate which would have been metabolized if sufficient phosphorous had been available.

3. Aeration Basin Microorganism Concentration

As predicted by the mathematical model (24), the aeration basin microorganism concentration decreased with lower mean cell residence times. A plot of aeration basin biological solids concentration as a function of the mean cell residence time is shown in Figure 6. The biological solids concentration was also affected by the phosphorous-limiting condition. As shown on the graph, the solids concentration shows a drop occurring at the sludge age of 3.6 days. The observed biological solids concentration of 939 mg/l is apparently less than what might have been predicted. Coupled with the observed influence on COD removal efficiency, the microorganisms were apparently unable to produce a sufficient quantity of new cells to replace those being wasted. Thus, the biological solids decreased to a new equilibrium level such that the amount produced equalled the amount wasted daily.

4. Observed Yield

The observed yield coefficient increased as the mean cell residence time decreased, as shown in Figure 7. This graph demonstrates that the observed yield increases rapidly at lower sludge ages and tends to flatten out at higher cell residence times.

When the observed yield data was linearized by using an equation of the form

$$\frac{1}{Y_{obs}} = \frac{1}{Y_{max}} + \frac{b\theta_c}{Y_{max}} \qquad (8)$$

Figure 6. Aeration Basin Microorganism Concentration versus Mean Cell Residence Time

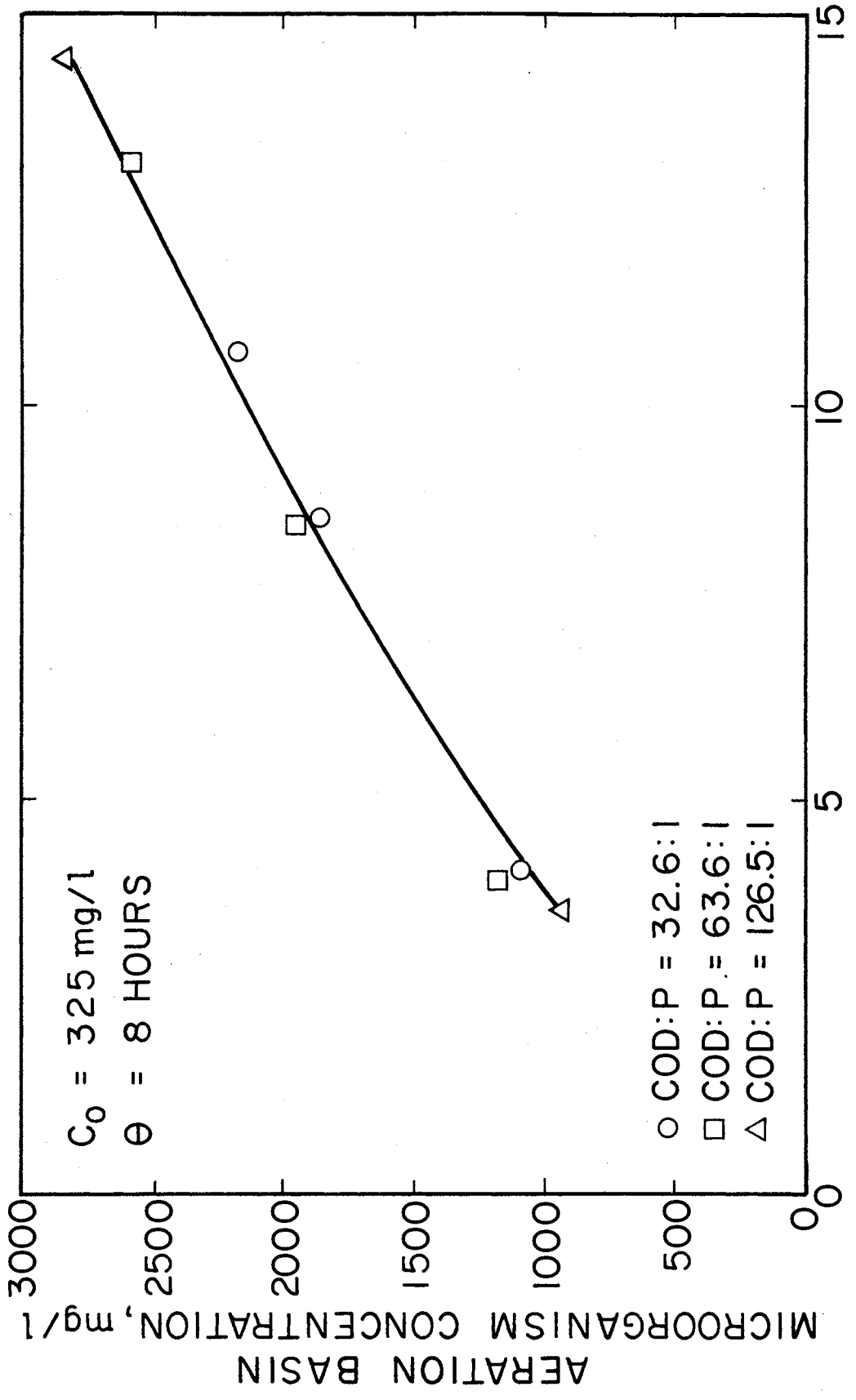
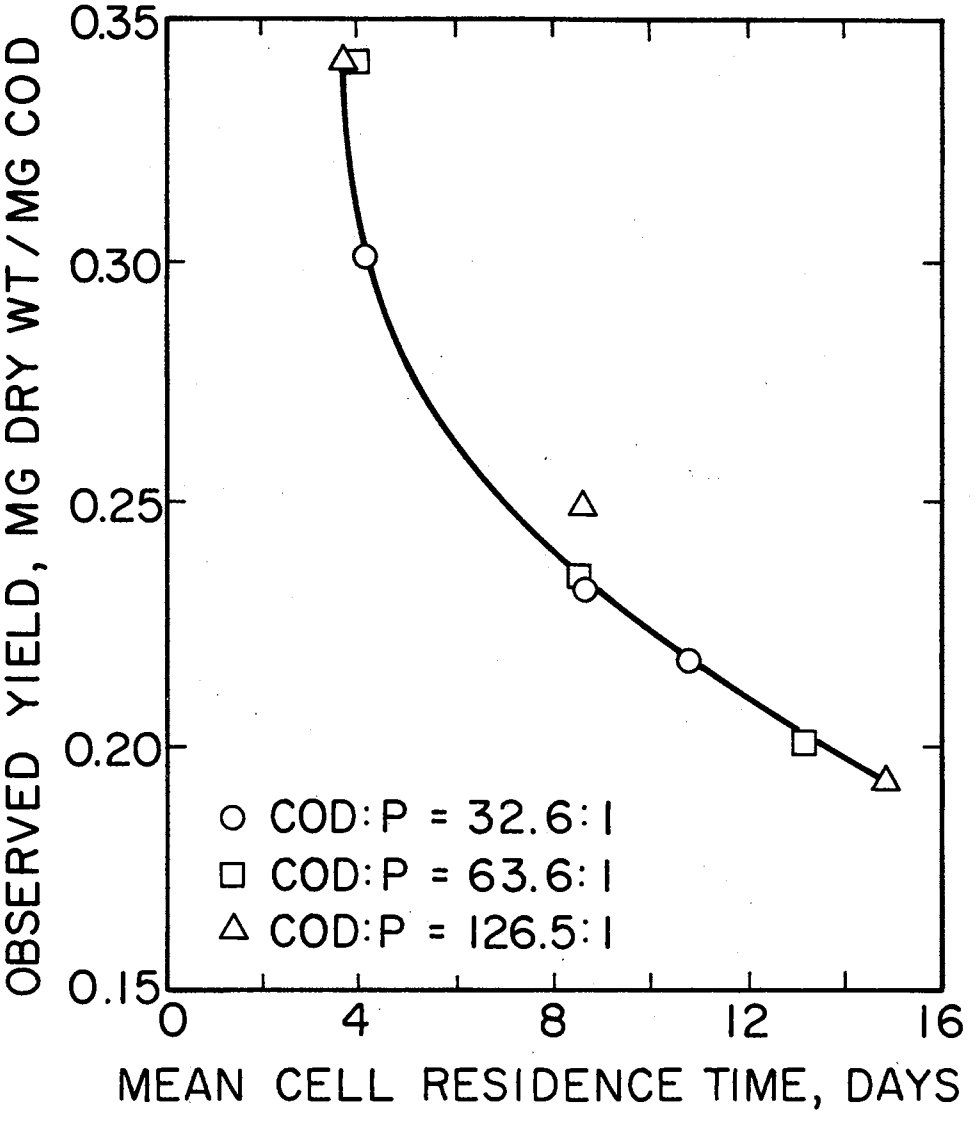

AERATION BASIN
MICROORGANISM CONCENTRATION, mg/l
3000
2500
2000
1500
1000
500
0
0
5
10
15
MEAN CELL RESIDENCE TIME, DAYS
C_o = 325 mg/l
Θ = 8 HOURS
○ COD:P = 32.6:1
□ COD:P = 63.6:1
△ COD:P = 126.5:1

Figure 7. Observed Yield versus Mean Cell Residence Time


0.35
0.30
0.25
0.20
0.15
OBSERVED YIELD, MG DRY WT / MG COD
0
4
8
12
16
MEAN CELL RESIDENCE TIME, DAYS
○ COD:P = 32.6:1
□ COD:P = 63.6:1
△ COD:P = 126.5:1

this resulting equation

$$\frac{1}{Y_{obs}} = \frac{1}{.433} + \frac{0.090\theta_c}{.433} \qquad (9)$$

was obtained. From a solution of Equation (8), Y_{max} = 0.433 and b = 0.090 days^{-1} was obtained. The linearized data is plotted with $\frac{1}{Y_{obs}}$ as a function of θ_c in Figure 8.

The data were also linearized according to an equation of the form

$$\frac{1}{\theta_c} = YU + b \qquad (10)$$

The following equation

$$\frac{1}{\theta_c} = 0.446U - 0.096 \qquad (11)$$

describes the linear relationship of the data. From Equation (10), Y_{max} = 0.446 and b = 0.096 days^{-1} may be obtained. The correlation coefficient for Equation (11) is 0.99. Graphical results of these data are shown in Figure 9. The specific growth rate as a function of the specific utilization is plotted.

Although the values obtained for Y_{max} and b differ slightly, this difference is considered to be negligible. Correlation coefficients of 0.99 and 1.00 suggest that the derived equations are significant.

5. pH Control

Considerable difficulty was encountered in maintaining the pH near 7.0. At mean cell residence times of 8.5 days or longer, periodic adjustment of the pH with 1.0 N NaOH was necessary. A high degree of nitrification was identified as the source of the pH control problem (27). Having achieved "steady-state" conditions at a mean cell residence time of approximately 4.0 days, the addition of 1.0 N NaOH was

Figure 8. Reciprocal of Observed Yield versus Mean Cell Residence Time

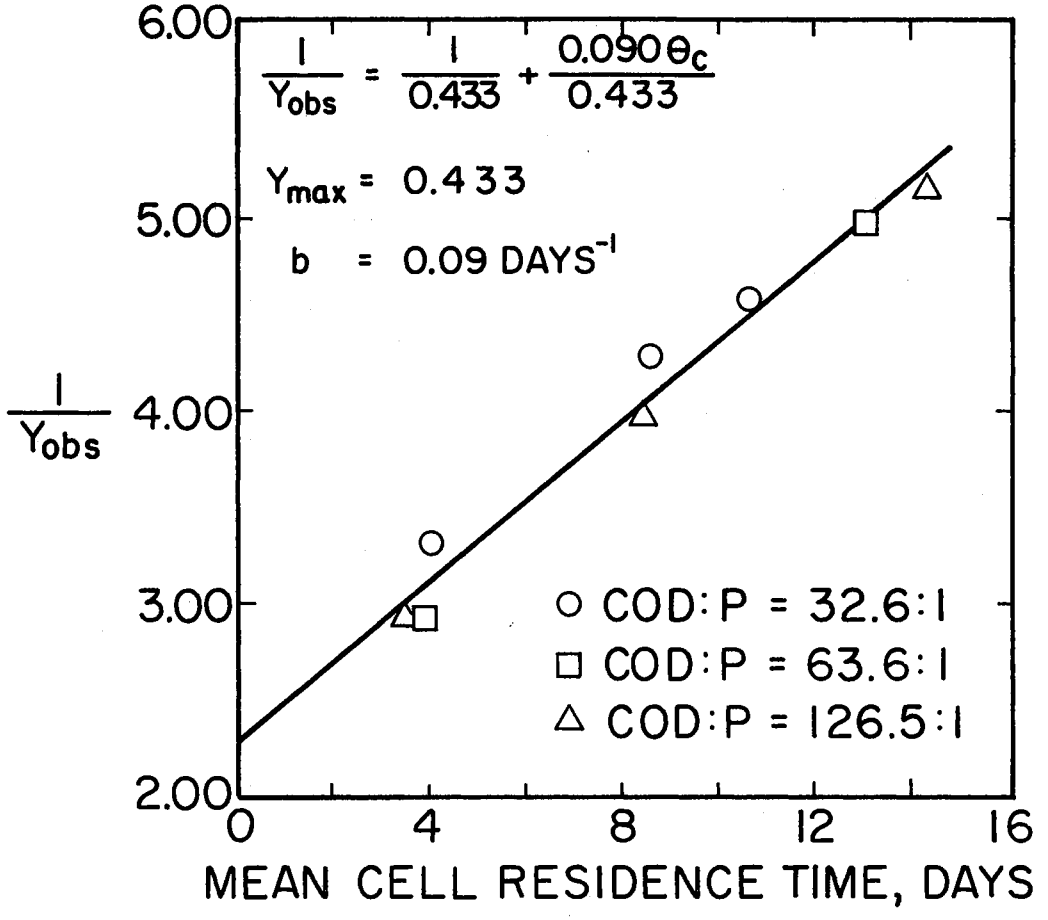
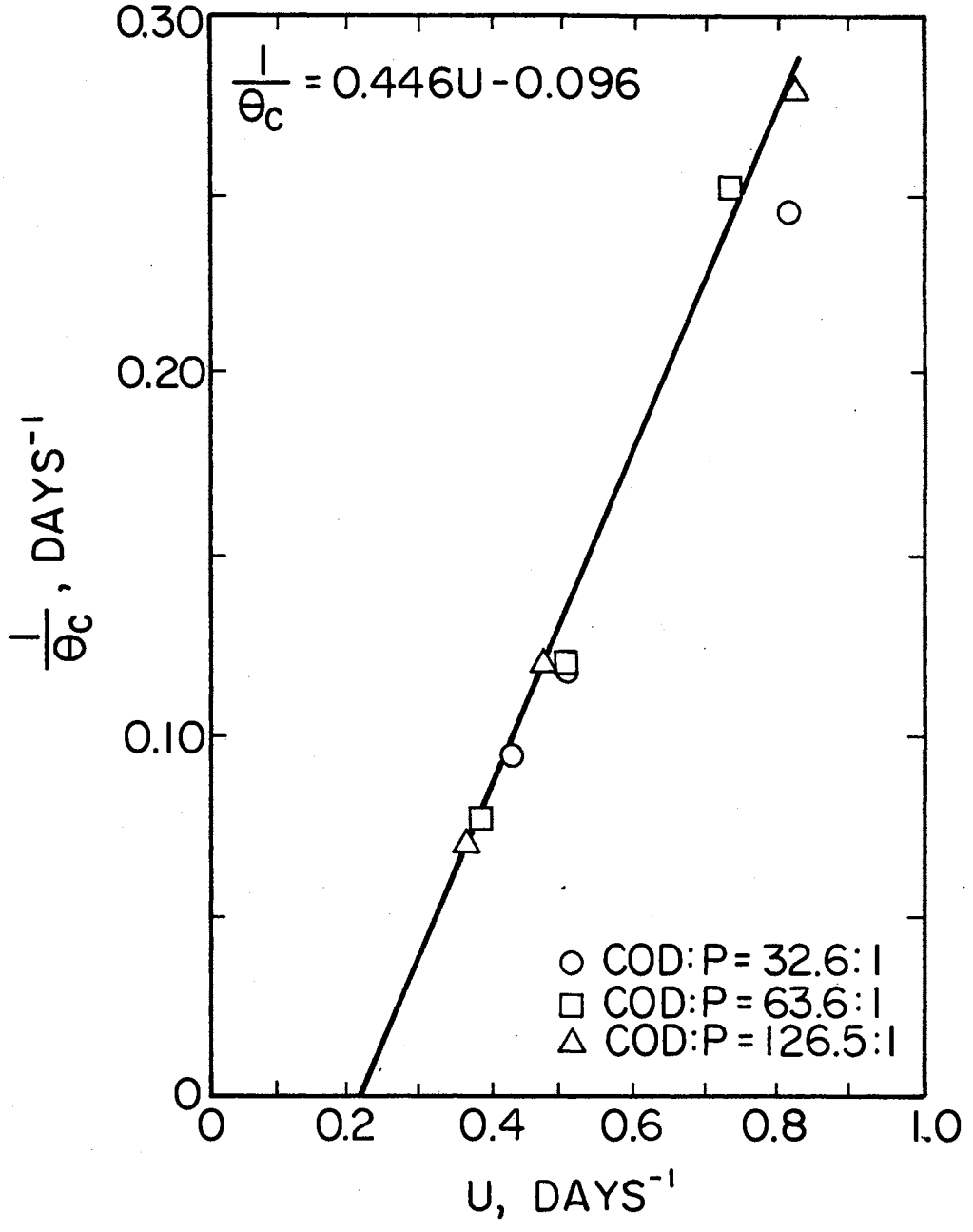

6.00
5.00
4.00
3.00
2.00
1/Yobs
1/Yobs = 1/0.433 + 0.090θc/0.433
Ymax = 0.433
b = 0.09 DAYS-1
○ COD:P = 32.6:1
□ COD:P = 63.6:1
△ COD:P = 126.5:1
0
4
8
12
16
MEAN CELL RESIDENCE TIME, DAYS

Figure 9. Specific Growth Rate versus Specific Utilization Rate


0.30
0.20
0.10
0
0
0.2
0.4
0.6
0.8
1.0
$\frac{1}{\theta_c} = 0.446U - 0.096$
$\frac{1}{\theta_c}$, DAYS^{-1}
U, DAYS^{-1}
○ COD:P = 32.6:1
□ COD:P = 63.6:1
△ COD:P = 126.5:1

discontinued. The 0.3 M carbonate buffer system maintained the pH at approximately 7.5. Experimental analysis indicated that the NO_3^- concentration in the effluent had decreased to almost zero; i.e., that nitrification had ceased (27).

CHAPTER V

ENGINEERING APPLICATION

Having determined the influence of the mean cell residence time and the stoichiometry of the wastewater on phosphorous removal efficiency in a laboratory activated sludge, it is possible to extrapolate these findings to a full-scale treatment plant to assist the design engineer in making a sound decision when confronted with a phosphorous problem.

Domestic wastewaters typically have an influent phosphorous concentration of 10 mg/l P or more. In such systems, carbon is normally the limiting nutrient. Therefore, an unfavorable stoichiometric COD:P exists. For these conditions, there is a maximum removal efficiency that can be achieved. For typical domestic wastewaters, effluent phosphorous concentrations of less than one mg/l cannot be achieved solely by biological incorporation. To consistently obtain such low effluent concentrations, some form (chemical precipitation, ion exchange, etc.) of chemical treatment must be employed.

Operation of the activated sludge process at lower mean cell residence times will increase phosphorous removal efficiency through increased sludge production. However, operation of the plants at low sludge ages has some drawbacks. Sludge production is much greater at the lower cell residence times. As a result, the sludge handling facilities (normally anaerobic digesters) must be sized accordingly.

Typically, to handle this increase in sludge, these facilities will necessarily be enlarged, thus adding considerable cost to the new plant or necessitating expansion in an existing plant. Careful handling of the waste streams from the digesters must be practiced, otherwise the phosphorous incorporated into cellular material may be released during the digestion process and re-introduced into the treatment plant through the returned supernatant.

It is generally agreed that greater operator skill is required for a high-rate process. The operators must understand the process so that they can exercise sound judgment in operational decision-making. Therefore, before deciding to design a plant using the high-rate mode of operation for increased biological incorporation of phosphorous, the design engineer must be certain of the knowledge and capabilities of the plant operators.

Furthermore, the high-rate process is characterized by being less stable than the low-rate process. Therefore, the high-rate process is more susceptible to upset due to shock loads. However, this problem can be eliminated by providing equalization basins ahead of the plant or controlling the discharging of toxic wastes into the sewer system. Therefore, providing flow equalization results in a more uniform waste, thus a more consistent effluent being produced.

Effective clarification must be obtained or the benefits obtained from biological incorporation will be lost. The solids lost in the effluent will ultimately break down in the receiving stream and thus release the phosphorous. Therefore, it may be stated that we are concerned with phosphorous to a different form. Phosphorous discharged in any form will ultimately be converted to the orthophosphate form,

thus it becomes available for aquatic plant use. Therefore, the design engineer must consider the clarification facilities a vital step in an effective phosphorous removal scheme. The plant operator must be provided a system with enough flexibility to meet varying demands. The plant operator must be knowledgeable of the proper operation of the clarifiers.

As previously stated, biological incorporation alone will seldom reduce the phosphorous concentration to the desirable levels. Currently, chemical precipitation is the most reliable and effective method available for supplemental phosphorous removal. However, in using chemical precipitation in combination with biological incorporation, certain concepts must be kept in mind.

First, if chemical precipitation is practiced ahead of the biological reactor, care must be exercised so as not to establish phosphorous limiting conditions. One of the observed consequences of phosphorous limitation of this study was the decrease of COD removal efficiency. As a result, unnecessarily high organic loads may be discharged to the stream. Therefore, when calculating chemical dosages, the operator must be aware of the phosphorous requirements of the biological unit. Ideally, the chemical dose should leave in solution a satisfactory amount of phosphorous for the microorganisms to utilize. As a result, favorable COD:P ratios would be maintained in the flow to the biological reactor so that the biological process would reduce the remaining phosphorous level to the desired level.

In summary, the chemical precipitation process and the biological incorporation process could be matched so that each is used to its full potential, thus resulting in the most efficient and economical treatment

scheme.

Secondly, appropriate chemical addition could aid in maintaining suitable biological environments. For instance, if an acidic waste was to be treated, the addition of lime could achieve two goals. First, the pH of the wastewater could be raised to neutrality and, secondly, the lowering of the phosphorous concentration by forming a calcium precipitate. Furthermore, if nitrification was occurring within the biological reactor and if the waste did not have sufficient buffering capacity, the addition of lime could maintain a suitable pH and precipitate the phosphorous. Thus, the reactor could be operated under highly stable conditions suitable for obtaining nitrification and effective COD removal along with phosphorous removal principally through chemical precipitation.

However, this combined nitrification, COD removal, and phosphorous precipitation scheme may have some drawbacks. There seems to be concern over the long-term detrimental effects of a possible buildup of phosphate precipitate (28). The idea considers the possibility of eventually recycling only inorganic phosphate precipitate rather than activated sludge. Thus, the biological reactor would be void of the activated sludge necessary for oxidation of the organic material. However, the principle of mean cell residence time could be applied to this precipitate. A definite quantity of the precipitate would be wasted daily, thus a buildup of the precipitate should not occur.

Chemical precipitation could also be applied to the secondary effluents. In this case, the residual phosphorous concentration, that is, the phosphorous remaining after biological incorporation, must be removed. However, it is believed that greater chemical dosages will be

required to produce the same effluent phosphorous concentrations (<0.5 mg/l P) for chemical addition following the aeration tank than for chemical addition ahead of the aeration tank. It has been found that lower initial phosphorous concentration requires increased chemical dosages (7). For instance, to precipitate one mg of phosphorous at an initial phosphorous concentration of two mg/l P requires a significantly larger chemical dosage than that to precipitate one mg of phosphorous within the initial phosphorous concentration is 15 mg/l. In other words, the chemical dosage becomes less effective at smaller initial phosphorous concentrations. Therefore, it is believed that the most efficient system could be achieved by chemical addition ahead of the aeration tank to take advantage of the chemicals' increased effectiveness at higher phosphorous concentration and then allow the microorganisms to act as "scavengers" to reduce the effluent phosphorous concentration to the required level.

Minton and Carlson (29) have found that clearer effluents are produced when alum and ferric chloride are added between the aeration tank and final clarifier. These researchers suggest the floc particles were destroyed in the aeration tank due to the violent agitation. Therefore, the place of chemical addition may significantly affect the quality of effluent.

These are but a few of the considerations concerning phosphorous removal techniques. Each waste no doubt has its own distinct features. Therefore, the waste must be carefully analyzed so that the engineer can devise a suitable removal scheme. Stock solutions cannot be given. General concepts are thus important and the ability to apply these general concepts to specific problems must be possessed.

CHAPTER VI

CONCLUSIONS

The operation of a continuous flow activated sludge unit using the mean cell residence time as a principal operational parameter has led to the following conclusions:

1. Lower mean cell residence times result in higher phosphorous removal efficiencies.

2. At a given mean cell residence time, larger COD:P ratios result in higher phosphorous removal efficiencies.

3. For this experimental reactor, the phosphorous content of the sludge varied over the range of 2.21 percent to 3.63 percent on a dry weight basis.

4. Phosphorous removal efficiency is directly related to sludge production.

5. Solids carryover in the effluent significantly reduces the effective phosphorous removal efficiency.

6. Close prediction of biological phosphorous removal can be made if the cellular phorphorous content and the sludge production is reasonably estimated.

7. With the high COD:P ratios and low sludge ages, phosphorous may become a limiting nutrient, whereas at a high sludge age COD would be limiting.

8. For the experimental reactor, phosphorous limitation resulted

in decreased COD removal efficiency and decreased aeration basin micro-organism concentrations.

9. Unless suitable COD:P ratios exist, biological incorporation of phosphorous generally will not reduce phosphorous concentrations to below discharge standards (<1 mg/l).

CHAPTER VII

SUGGESTIONS FOR FUTURE STUDY

Based on the findings of this study, the following suggestions are presented for further studies of phosphorous removal in the activated sludge process:

1. Study the effects of chemical precipitation by chemical addition into the aeration tank.

2. Subject a portion of the recycled sludge to a "phosphorous stripping" process to determine if increased removal efficiencies can be obtained.

3. Study the effects of the addition of phosphates in the complex inorganic or organic form rather than only in the soluble orthophosphate form on treatment efficiency.

4. To study more fully the effects of phosphorous limitations on treatment efficiency.

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APPENDIX A

RAW DATA FOR EACH OF THE NINE STEADY-STATE DATA COLLECTION PERIODS

TABLE VI

RAW DATA FOR θ_c = 4.1 DAYS AND COD:P = 33.2:1

	COD			Biological Solids			PO_4-P Concentration					θ_c		
Date	Feed (mg/l)	Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (mg/l)	Total System (mg/l)	Effl. (mg/l)	Feed (mg/l)	Sol. Effl. (mg/l)	Remov. Effic. (%)	Total Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (days)	Total System (days)	pH
(1973)														
8-15	317	15	95.3	1108	1044	2	9.7	5.7	41.2	6.7	30.9	4.1	6.1	7.3
8-16	324	17	94.8	1132	1092	2	10.0	5.5	45.0	6.7	33.0	4.1	6.3	7.4
8-17	328	20	93.9	1116	1036	2	9.4	5.7	39.4	6.5	30.8	4.1	6.0	7.4
8-18	320	15	95.3	1180	1072	4	9.7	5.3	45.4	6.5	33.0	4.0	5.8	7.3
8-19	320	14	95.6	1164	1036	2	9.5	5.4	43.2	7.5	21.1	4.1	5.8	7.4
8-20	324	20	93.8	1160	1096	4	10.0	5.4	46.0	7.5	25.0	4.0	6.0	7.4
Avg.	322	17	94.7	1143	1063	3	9.7	5.5	43.3	6.9	28.9	4.1	6.0	7.4

TABLE VII

RAW DATA FOR θ_c = 8.6 DAYS AND COD:P = 33.6:1

Date (1973)	COD			Biological Solids			PO_4-P Concentration					θ_c		pH
	Feed (mg/l)	Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (mg/l)	Total System (mg/l)	Effl. (mg/l)	Feed (mg/l)	Sol. Effl. (mg/l)	Remov. Effic. (%)	Total Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (days)	Total System (days)	
7-22	329	31	90.6	1904	1388	6	9.8	7.2	26.5	8.2	16.3	8.6	10.0	7.2
7-23	321	29	91.0	1940	1408	10	9.8	7.0	28.6	8.62	12.2	8.2	9.5	7.3
7-24	332	26	92.2	1976	1384	10	10.0	7.4	26.0	8.0	20.0	8.3	9.3	7.1
7-25	329	28	91.5	1908	1368	2	9.8	7.6	22.4	8.7	11.2	9.1	10.4	7.2
7-26	325	22	93.2	1880	1424	6	9.7	7.6	21.6	8.6	11.3	8.6	10.4	7.0
7-27	329	23	93.0	1984	1536	6	10.1	7.4	26.7	7.6	24.8	8.6	10.6	7.2
7-28	329	24	92.7	1944	1500	8	9.8	7.1	27.6	8.2	16.3	8.4	10.3	7.0
7-29	333	19	94.3	1924	1484	6	9.5	7.0	26.3	7.9	16.8	8.6	10.6	7.1
7-30	333	17	94.9	1884	1508	8	9.8	6.9	29.6	8.5	13.3	8.3	10.7	6.8
7-31	329	20	93.9	1952	1516	4	9.7	7.1	26.8	8.2	15.5	8.8	11.0	6.8
Avg.	329	24	92.7	1930	1452	7	9.8	7.2	26.5	8.3	15.3	8.6	10.3	7.1

TABLE VIII

RAW DATA FOR θ_c = 10.7 DAYS AND COD:P = 31.1:1

	COD			Biological Solids			PO_4-P Concentration					θ_c		
Date	Feed (mg/l)	Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (mg/l)	Total System (mg/l)	Effl. (mg/l)	Feed (mg/l)	Sol. Effl. (mg/l	Remov. Effic. (%)	Total Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (days)	Total System (days)	pH
(1973)														
9-11	306	25	91.8	2192	1728	8	9.2	8.2	10.9	8.5	17.6	10.4	13.2	7.0
9-12	309	22	92.9	2196	1744	6	9.8	8.4	14.3	8.7	11.2	11.0	14.2	6.9
9-13	313	28	91.1	2200	1732	8	10.0	8.6	14.0	8.9	11.0	10.7	13.5	6.9
9-14	323	24	92.3	2188	1740	6	9.8	8.5	13.3	8.9	19.2	11.0	14.1	6.7
9-15	327	25	92.4	2192	1736	8	10.6	8.7	17.9	9.2	13.2	10.7	13.6	6.7
9-16	320	27	91.6	2180	1768	8	10.6	8.8	17.0	9.1	14.2	10.7	13.9	6.6
9-17	298	28	90.6	2180	1756	10	19.5	8.1	14.7	8.4	11.6	10.4	13.4	6.8
9-18	298	20	93.3	2196	1772	8	10.3	8.7	15.5	9.2	10.7	10.5	13.6	6.8
9-19	302	26	91.4	2184	1752	8	10.3	8.6	16.5	8.8	14.7	10.7	13.8	7.1
Avg.	311	25	92.0	2188	1748	8	10.0	8.5	15.0	8.9	11.0	10.7	13.7	6.8

TABLE IX

RAW DATA FOR θ_c = 4.0 DAYS AND COD:P = 60.2:1

Date	COD			Biological Solids			PO_4-P Concentration					θ_c		pH
	Feed (mg/l)	Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (mg/l)	Total System (mg/l)	Effl. (mg/l)	Feed (mg/l)	Sol. Effl. (mg/l)	Remov. Effic. (%)	Total Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (days)	Total System (days)	
(1973)														
8-22	303	18	94.1	1176	1128	4	4.9	0.9	81.6	2.0	59.2	4.0	6.1	7.4
8-23	307	17	94.5	1180	1096	4	4.9	1.0	79.6	1.5	69.4	4.0	5.9	7.4
8-24	303	22	92.7	1188	1108	4	5.0	0.9	82.0	1.3	74.0	4.0	6.0	7.4
8-25	299	20	93.3	1196	1080	4	5.0	0.7	86.0	1.5	70.0	4.0	5.8	7.4
8-26	295	35	88.1	1180	1108	2	5.1	0.6	88.2	1.7	66.7	4.1	6.1	7.5
8-27	299	21	93.0	1160	1096	6	5.1	1.0	80.4	2.0	60.8	3.9	5.9	7.6
Avg.	301	22	92.7	1180	1102	4	5.0	0.9	82.0	1.7	66.0	4.0	6.0	7.5

TABLE X

RAW DATA FOR θ_c = 8.5 DAYS AND COD:P = 64.3:1

	COD			Biological Solids			PO_4-P Concentration					θ_c		
Date	Feed (mg/l)	Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (mg/l)	Total System (mg/l)	Effl. (mg/l)	Feed (mg/l)	Sol. Effl. (mg/l)	Remov. Effic. (%)	Total Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (days)	Total System (days)	pH
(1973)														
8- 4	326	18	94.5	1956	1628	8	4.9	2.1	57.1	2.7	42.9	8.4	11.1	6.9
8- 5	303	11	96.4	1976	1584	8	5.0	2.1	58.0	2.3	54.0	8.4	10.8	7.1
8- 6	314	7	97.8	1948	1596	6	5.1	2.1	58.8	2.7	47.0	8.6	11.3	6.9
8- 7	314	12	96.2	1892	1616	6	4.8	2.1	56.3	2.6	45.8	8.6	11.7	7.0
8- 8	314	9	97.1	1932	1584	8	4.9	2.2	55.1	2.8	42.8	8.4	11.0	6.8
8- 9	322	9	97.2	1944	1576	6	4.7	2.3	51.1	2.4	48.9	8.6	11.1	7.0
8-10	318	12	96.2	1952	1528	6	4.7	2.3	51.1	2.4	48.9	8.6	10.8	7.2
8-11	314	12	96.2	1952	1572	8	4.9	2.2	55.1	2.5	49.0	8.4	10.8	7.0
8-12	310	8	97.4	1964	1608	6	4.9	2.3	53.1	2.9	40.8	8.6	11.3	6.9
8-13	314	10	96.8	1944	1580	6	4.9	2.3	53.1	2.5	49.0	8.6	11.2	7.0
Avg.	315	11	96.5	1946	1587	7	4.9	2.2	55.1	2.6	46.9	8.5	11.1	7.0

TABLE XI

RAW DATA FOR θ_c = 13.1 DAYS AND COD:P = 66.3:1

	COD			Biological Solids			PO_4-P Concentration					θc		
Date	Feed (mg/l)	Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (mg/l)	Total System (mg/l)	Effl. (mg/l)	Feed (mg/l)	Sol. Effl. (mg/l)	Remov. Effic. (%)	Total Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (days)	Total Systems (days)	pH
(1973)														
6-20	324	28	91.4	2464	2024	16	4.9	2.9	40.8	3.6	26.5	12.5	16.4	6.8
6-21	320	24	92.5	2532	1828	4	4.8	2.6	45.8	3.2	33.3	15.3	17.7	6.5
6-22	331	24	92.7	2544	1808	10	4.7	2.7	42.6	3.4	27.7	12.7	14.4	6.6
6-23	330	23	93.0	2532	1852	8	4.9	2.4	51.0	3.3	32.7	14.3	16.8	6.6
6-24	334	21	93.7	2604	1988	4	4.8	2.9	39.6	4.0	16.7	15.3	18.7	6.8
6-25	323	20	93.8	2776	2048	28	4.9	2.6	46.9	3.8	22.4	11.1	13.3	6.4
6-26	330	23	93.0	2796	2068	12	5.2	3.2	38.5	3.9	25.0	13.7	16.2	6.3
6-27	315	28	91.1	2652	1992	20	4.9	3.1	36.7	3.9	20.4	12.2	14.5	6.4
6-28	323	24	92.6	2556	1976	24	5.1	2.9	43.1	3.8	25.5	11.3	14.0	6.2
6-29	323	25	92.3	2612	1880	12	4.8	3.0	37.5	3.6	25.0	13.5	15.6	6.6
6-30	322	25	92.2	2424	1832	20	5.0	3.1	38.0	3.8	24.0	11.8	14.2	6.7
7- 1	323	21	93.5	2464	1804	12	5.2	2.9	44.2	3.3	36.5	13.4	15.6	6.3
Avg.	325	24	92.6	2580	1925	15	4.9	2.8	42.1	3.6	26.5	13.1	15.6	6.5

TABLE XII

RAW DATA FOR θ_c = 3.6 DAYS AND COD:P = 127.9:1

	COD			Biological Solids			PO_4-P Concentration					θ_c		
Date	Feed (mg/l)	Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (mg/l)	Total System (mg/l)	Effl. (mg/l)	Feed (mg/l)	Sol. Effl. (mg/l)	Remov. Effic. (%)	Total Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (days)	Total Systems (days)	pH
(1973)														
8-29	305	58	81.0	960	920	6	2.4	0.07	17.1	0.70	70.8	3.9	5.9	7.4
8-30	316	55	82.6	944	914	10	2.3	0.05	97.8	0.75	67.4	3.7	5.7	7.5
8-31	305	59	80.7	952	904	14	2.4	0.08	96.7	1.00	58.3	3.5	5.4	7.4
9- 1	305	59	81.7	924	888	12	2.4	0.03	98.8	0.50	79.2	3.6	5.5	7.5
9- 2	301	59	80.4	932	896	20	2.3	0.09	96.1	0.80	65.2	3.3	5.1	7.4
9- 3	308	59	80.8	920	880	16	2.4	0.04	98.3	0.75	68.8	3.5	5.3	7.5
Avg.	307	58	81.1	939	901	13	2.4	0.06	97.5	0.75	68.8	3.6	5.5	7.5

TABLE XIII

RAW DATA FOR θ_c = 8.5 DAYS AND COD:P = 128.8:1

	COD			Biological Solids			PO_4-P Concentration					θ_c		
Date	Feed (mg/l)	Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (mg/l)	Total System (mg/l)	Effl. (mg/l)	Feed (mg/l)	Sol. Effl. (mg/l)	Remov. Effic. (%)	Total Effl. (mg/l)	Remov. Effic. (mg/l)	Aera. Basin (days)	Total Systems (days)	pH
(1973)														
9- 6	310	25	91.9	1944	1580	10	2.4	0.10	95.8	0.66	72.5	8.2	10.5	7.0
9- 7	306	26	91.5	1948	1616	12	2.4	0.09	96.3	0.64	73.3	8.0	10.6	7.1
9- 8	314	25	92.0	1932	1556	4	2.4	0.10	95.8	0.70	70.8	8.8	11.4	7.1
9- 9	310	24	92.2	1948	1632	6	2.3	0.09	96.3	0.66	71.3	8.6	11.5	7.0
9-10	306	21	91.5	1932	1568	4	2.4	0.09	96.3	0.59	75.4	8.8	11.4	6.9
Avg.	309	24	92.2	1941	1590	7	2.4	0.09	96.1	0.65	72.9	8.5	11.1	7.0

TABLE XIV

RAW DATA FOR θ_c = 14.4 DAYS AND COD:P = 122.7:1

	COD			Biological Solids			PO_4-P Concentration					θ_c		
Date	Feed (mg/l)	Effl. (mg/l)	Remov. Effic. (%)	Aera. Basin (mg/l)	Total System (mg/l)	Effl. (mg/l)	Feed (mg/l)	Sol. Effl. (mg/l)	Remov. Effic. (%)	Total Effl. (mg/l)	Remov. Effic. (mg/l)	Aera. Basin (days)	Total Systems (days)	pH
(1973)														
7- 9	320	15	95.3	2500	2000	6	2.5	0.6	76.0	0.9	64.0	14.7	18.9	6.6
7-10	328	15	95.4	2528	2032	8	2.4	0.7	70.8	1.5	37.5	14.3	18.3	6.6
7-11	305	18	94.1	2680	2096	8	2.5	0.6	76.0	1.1	56.0	14.4	18.0	6.3
7-12	328	19	94.2	2728	2015	10	2.7	0.9	66.7	1.7	37.0	14.0	16.6	6.7
7-13	324	21	93.5	2852	2024	10	2.6	1.0	61.5	1.7	34.6	14.1	16.0	6.7
7-14	315	16	94.9	2932	2056	8	2.6	1.0	61.5	2.0	23.0	14.6	16.4	6.9
7-15	322	12	96.7	2832	2032	12	2.7	1.0	63.0	1.8	33.3	13.7	15.7	6.7
7-16	322	15	95.3	3088	2188	8	2.7	0.8	70.4	1.7	37.0	14.7	16.6	6.7
7-17	319	15	95.3	2824	2096	12	2.7	0.9	66.7	1.1	59.3	13.7	16.3	6.7
7-18	300	12	96.0	3200	2224	4	2.7	0.9	66.7	1.5	44.3	15.6	17.4	6.7
Avg.	319	16	95.0	2816	2076	9	2.6	0.8	69.2	1.5	42.3	14.4	17.0	6.7

APPENDIX B

MASS BALANCES ON PHOSPHOROUS

TABLE XV

MASS BALANCES ON PHOSPHOROUS

COD:P	θ_c (days)	In	Out		
		Feed (mg/day)	Effluent (mg/day)	Waste Sludge (mg/day)	Σ in - Σ out (mg/day)
32.6:1	4.1	174.60	114.54	60.83	-0.77
	8.6	176.40	144.09	31.91	+0.44
	10.7	180.00	157.35	22.67	-0.02
63:6:1	4.0	90.00	28.22	61.23	+0.55
	8.5	88.20	45.74	43.13	-0.07
	13.1	88.20	63.65	24.35	+0.20
126.5:1	3.6	43.20	12.45	30.45	+0.30
	8.5	46.80	11.28	36.71	-0.19
	14.4	46.80	26.52	20.17	+0.11

VITA

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