ABSTRACT

Margaret K. Banks. An Evaluation of Biological Phosphorus Removal.

(Under the direction of Dr. James C. Lamb).

Biological phosphorus removal (BPR) was examined to determine its feasibility as a phosphorus removal method for municipal wastewater. A literature search was conducted which reviewed previous research of the mechanism of phosphorus removal and the major biological phosphorus removal processes. A BPR experiment performed at the Mason Farm Wastewater Treatment Plant was reviewed and critiqued. The plant-scale experiment did not succeed because of; 1) the presence of dissolved oxygen and nitrates in the anaerobic zone, 2) the low BOD concentration of the influent wastewater, and 3) the small portion of the return activated sludge which was treated anaerobically. A bench-scale BPR experiment was performed using the Mason Farm wastewater. The conclusions from the bench-scale experiment were that; 1) the release of phosphorus is an important step in the removal mechanism, 2) the phosphorus removing organisms may have a minimum requirement for organic carbon, and

3) a BOD concentration of greater than 200 mg/l was needed for good phosphorus removal.

ACKNOWLEDGEMENTS

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INTRODUCTION

Recently, there has been much debate in the media in North Carolina on the issue of phosphorus in our waterways. Phosphorus is the most common limiting nutrient for biomass primary producers (Maki, Porcella, and Wendt, 1984) and high concentrations can create eutrophic conditions. Regulations limiting the amount of phosphorus in wastewater discharges have been adopted in many areas and treatment plants are investigating ways to remove phosphorus economically and efficiently.

There are three ways to remove phosphorus from wastewater. The first and the most widely-used method is chemical precipitation using lime, alum, or ferric salts (Barth, 1982), requiring that chemicals be bought, stored and added to the wastewater. This approach increases the quantity of sludge produced in secondary treatment by 10 - 25% (Barth and Stensel, 1981). Its main disadvantages are in the increased costs for chemicals and problems associated with sludge transportation and disposal.

Another method is being developed in Japan where phosphorus is removed by crystallization in a fluidized bed (Barth and Stensel, 1981, van Dijk and Braakensiek,

1984). Wastewater plant effluent is passed through a fluidized bed containing crystalline hydroxyapatite pellets which encourage new crystal growth by phosphorus present in the wastewater. Then the dense granular pellets are removed by sedimentation and can be reused in the phosphate industry. The advantage of this system is that the phosphorus can be reused, but unfortunately it is still in developmental stages and is not presently available for commercial use.

The third method for removing phosphorus from wastewater is Biological Phosphorus Removal (BPR). Researchers have found that when wastewater is passed through an anaerobic zone, phosphorus often is released from the sludge and when the wastewater subsequently passes through an aerobic zone, phosphorus uptake can occur. More phosphorus is accumulated by organisms in the aerobic zone than was released by them in the anaerobic zone. Subsequent removal of excess sludge from the system completes this phosphorus removal process.

An advantage of BPR systems is that they are generally independent of influent phosphorus concentration. Walsh et al., (1983) conclude that BPR is most cost-competitive where high influent phosphorus levels are anticipated. Another advantage of BPR is that it produces a sludge with excellent settling characteristics (Barth, 1982, Barth and Stensel, 1981).

Also the secondary sludge contains a high phosphorus content which makes it suitable for fertilizer use.

BPR systems have been controversial. The actual mechanism by which phosphorus is removed is unclear. All of the major processes that claim to be able to reduce phosphorus to 1 mg/l or less have had problems in attaining that concentration in practice. This report will address some of the current BPR issues and the state-of-the-art.

OBJECTIVES

The objectives of this report are to;

1) review the theories regarding the mechanisms involved in BPR
2) review the major current BPR processes
3) critique a BPR experiment which was conducted by the Chapel Hill Mason Farm Wastewater Treatment Plant
4) conduct and discuss the results of a bench scale laboratory experiment involving BPR

LITERATURE REVIEW

BASICS OF BPR

The basic theory behind BPR is that if activated sludge is exposed to anaerobic conditions and subsequently exposed to aerobic conditions, phosphorus removal can occur. Phosphorus is released in the anaerobic phase and is removed when exposed to aerobic conditions. The presence of nitrates or oxygen in the anaerobic zone will prevent phosphorus release and subsequent phosphorus removal (Barth, 1982). A persistent problem in operating BPR systems is that it is difficult to keep nitrate and dissolved oxygen from being introduced into the anaerobic zone. Nitrate is introduced into the anaerobic basin in the return activated sludge if denitrification does not occur (Paepcke, 1983). Another problem can occur if the secondary sedimentation basin sludge blanket becomes too thick and the sludge is exposed to anaerobic conditions. This could cause phosphorus to be released into the clarified effluent.

PHOSPHORUS REMOVAL MECHANISM

Precipitation of Phosphorus

Some feel that activated sludge can only remove 2-3% by weight of volatile suspended solids as biologically bound phosphorus. That phosphorus is required by the microorganisms to meet metabolic requirements and is removed from the wastewater when the excess sludge is wasted and disposed of separately. Any additional removal of phosphorus is attributed to chemical precipitation of phosphorus and the subsequent capture of the precipitate in sludge that is wasted (Ferguson and McCarty, 1971, Wells, 1975, Riding, Elliot, and Sherrard, 1979).

Menar and Jenkins (1969) hypothesized that chemical precipitation followed by sorption is the most important mechanism for phosphorus removal. They state that less than 20% of phosphorus removed is due to biological uptake and that the remaining phosphorus is removed by the formation of insoluble calcium phosphate. They conclude, further, that the phosphorus precipitation is induced by an increase in pH caused by stripping of carbon dioxide from the wastewater during aeration.

Other researchers have concluded that in the pH range of 7 to 8, generally found in activated sludge systems, the phosphorus would precipitate as hydroxylapatite rather than calcium phosphate (Mulbarger

et al., 1969).

Walsh et al. (1983) believe that the change in oxidation-reduction potential between anaerobic and aerobic environments contributes to phosphorus removal. They explain that with the low oxidation-reduction potential in the anaerobic phase, calcium, magnesium and iron solubilize, releasing phosphorus. Later, with the high oxidation-reduction potential of the aerobic environment, those ions precipitate inorganic phosphorus in the wastewater.

Other researchers believe that the primary phosphorus removal mechanism is not precipitation but uptake of phosphorus by microorganisms in the activated sludge. Miyamoto-Mills et al. (1983) found no association between the uptake and release of calcium and phosphorus under aerobic and anaerobic conditions. They concluded that calcium phosphate precipitation does not account for the observed phosphate removal.

Gerber and Winter (1984) found no significant variation in calcium concentration when passing wastewater through anaerobic, anoxic, and aerobic process stages. They concluded phosphate release and uptake could not be accounted for by dissolution or precipitation of calcium phosphate compounds.

Biological Removal Mechanism

Other investigators feel that the excess uptake of phosphorus results from a biological mechanism. For example, Levin and Shapiro (1965) concluded that physical adsorption on sludge particles accounts only for the initial phosphorus uptake. They state that biological storage is responsible for any further uptake beyond normal metabolic needs of microorganisms.

Biochemistry of the Biological Mechanism

The biochemistry of phosphorus removal has been the subject of much recent research. Many researchers agree on a basic mechanism of phosphorus removal based on existence of both anaerobic and aerobic phases in the activated sludge (Hong, Kisenbaum, and Fernandez, 1979, Fukase, Shibata, and Miyaji, 1982, Deakyne, Patel, and Krichten, 1983, Manning and Irvine, 1985). During the anaerobic phase, microorganisms in the sludge hydrolyze polyphosphate stored in the cells to simple orthophosphate. This provides energy for the uptake of organic substrates and releases phosphorus to the solution as orthophosphate. This results in rising concentration of phosphorus and a decreasing concentration of the organic substrate during the anaerobic phase, as shown in Figure 1. In the aerobic stage, the remaining organic substrate is oxidized and

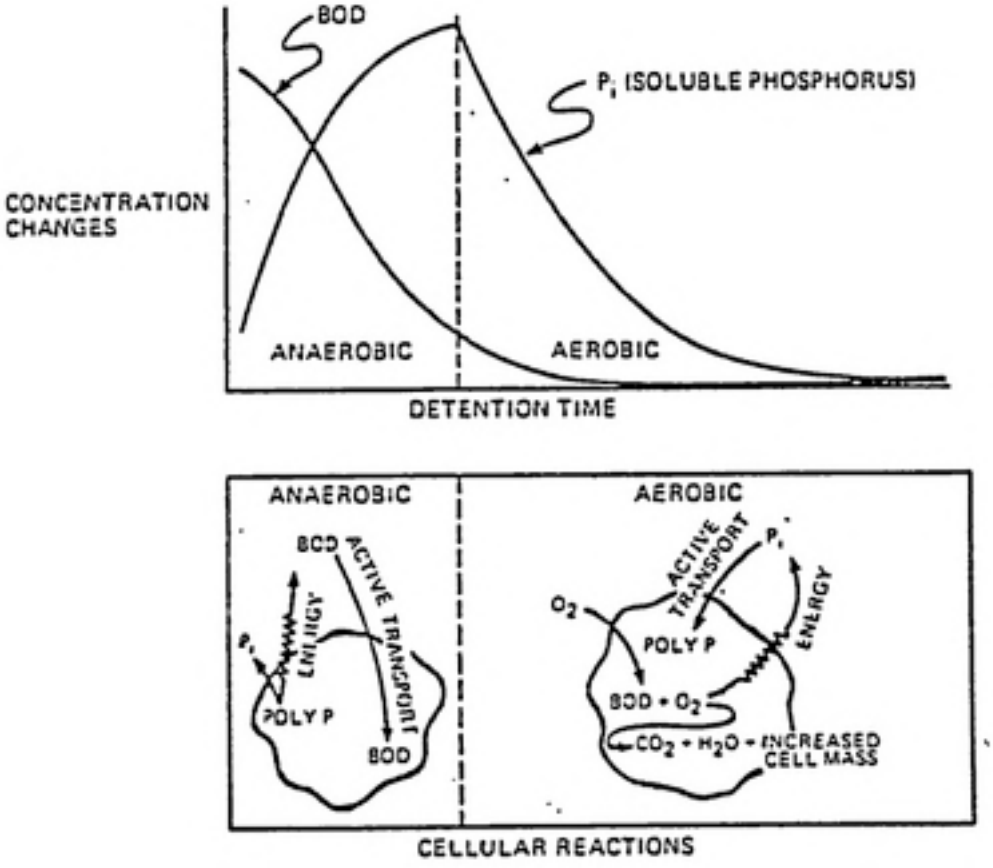


Figure 1

Uptake of Phosphorus by Microorganisms

(from Barth, 1982)

the energy is used for formation of polyphosphate and new cells. This process results in a reduced phosphorus concentration and a low concentration of organic substrate in the liquid (see Figure 1).

Phosphorus taken up by the microorganisms is believed by some researchers to be stored within the cell as volutin granules (Levin and Shapiro, 1965, Nicholls and Osborn, 1979, Barth, 1983). This phenomenon was explored by Miyamoto-Mills et al. (1983). They found that activated sludge contained large quanities of the volutin granules. They observed that after passing through an anaerobic zone, the sludge contained smaller amounts of the volutin granules, and concluded that the phosphorus release and uptake appeared to be associated with the volutin inclusions.

It also has been shown that the amount of phosphorus removed is a function of the influent BOD concentration (Scalf et al., 1969, Sutton and Jank, 1980, Barth and Stensel, 1981, Fukase, Shibata, and Miyaji, 1984). If the BOD is higher than 200 mg/l, a larger percentage of phosphorus will be removed than with lower BOD. Manning and Irvine (1985) attribute this phenomenon to the phosphorus-removing microorganism's inability to compete well with others in activated sludge. A high BOD is needed to provide sufficient organic substrate for both.

Microbiology of the Biological Mechanism

The type of microorganism that removes phosphorus has not been identified conclusively. Mino, Kaocrkami, and Matsuo (1984) observed that the predominant microorganisms are those that can use the organic substrate under both anaerobic and aerobic conditions. Watanabe, Miya, Matsuo (1984) found that organisms in biological phosphorus removal systems were grouped into large cell clusters and were covered with slimy material. They contained large quantities of magnesium and potassium as well as phosphorus.

Marais, Loewanthal, and Siebrite (1983) found PHB (poly-hydroxy butyrate) in phosphorus removing organisms and they concluded that ability to form PHB allows them to thrive in an anaerobic-aerobic environment. They suggest that the presence of PHB's can be used as indicators of phosphorus-removing organisms.

The Water Research Commission (1984) explains that phosphorus-removing microorganisms contain excess phosphorus bound in poly-phosphate chains. The polyphosphate bonds are broken by organisms in the anaerobic zone to release energy for the use of the organic substrate. They observe that microorganisms that contain no polyphosphate cannot utilize the substrate and therefore cannot survive in the anaerobic zone.

Fukase, Shibata, and Miyaji (1984) do not agree that

polyphosphate must be present in phosphorus-removing organisms, but contend they can absorb BOD and synthesize PHB without polyphosphates. They also hypothesize that polyphosphate containing microorganisms have no competitive advantage over the other microorganisms present in the anaerobic phase.

Certain specific organisms have been identified as potential phosphorus removers. In 1975, Fuhs and Chen suggested that the obligate aerobe, Acinetobacter. was responsible for phosphorus removal in many wastewater treatment plants which were using BPR. Matsch and Drnevich (1978) observed that Acinetobacter formed volutin granules during the aerobic phase and was the organism principally responsible for removing phosphorus. Manning and Irvine (1985) also contend that Acinetobacter is one of the microorganisms responsible for phosphorus removal.

Some believe that organisms other than Acinetobacter are capable of phosphorus removal. Osborn and Nicholls (1978) observed phosphorus removal using glucose as a substrate, but Acinetobacter is not able to assimilate glucose. They conclude accordingly that other facultative bacteria must be capable of biological phosphorus uptake.

Brodisch and Joyner (1983) found that there was not any single type of organism which dominated in any stage

in activated sludge plants with anaerobic-aerobic units. Since phosphorus removal was occurring, they concluded that Acinetobacter was not the only organism capable of phosphorus removal. They also found Aeromonas and Pseudomonas in the activated sludge and hypothesize that these two groups also may contribute to BPR.

Alternative Mechanisms

Several researchers contend that there is an interrelationship between the biological and precipitation mechanisms in BPR (Lan, Benefield, and Randall, 1983, Fukase, Shibata, and Miyaji, 1984). They contend that both calcium phosphate precipitation and enhanced biological uptake are phosphorus removal mechanisms. They conclude that precipitation accounts for 15-27% of the total phosphorus removed and that the larger fraction of phosphorus removal is by biological uptake.

BIOLOGICAL PHOSPHORUS REMOVAL PROCESSES

The A/O Process

The A/O process, developed by Air Products and Chemicals, Inc., is an activated sludge system designed to remove phosphorus biologically (See Figure 2). It consists of an anaerobic stage followed immediately by an

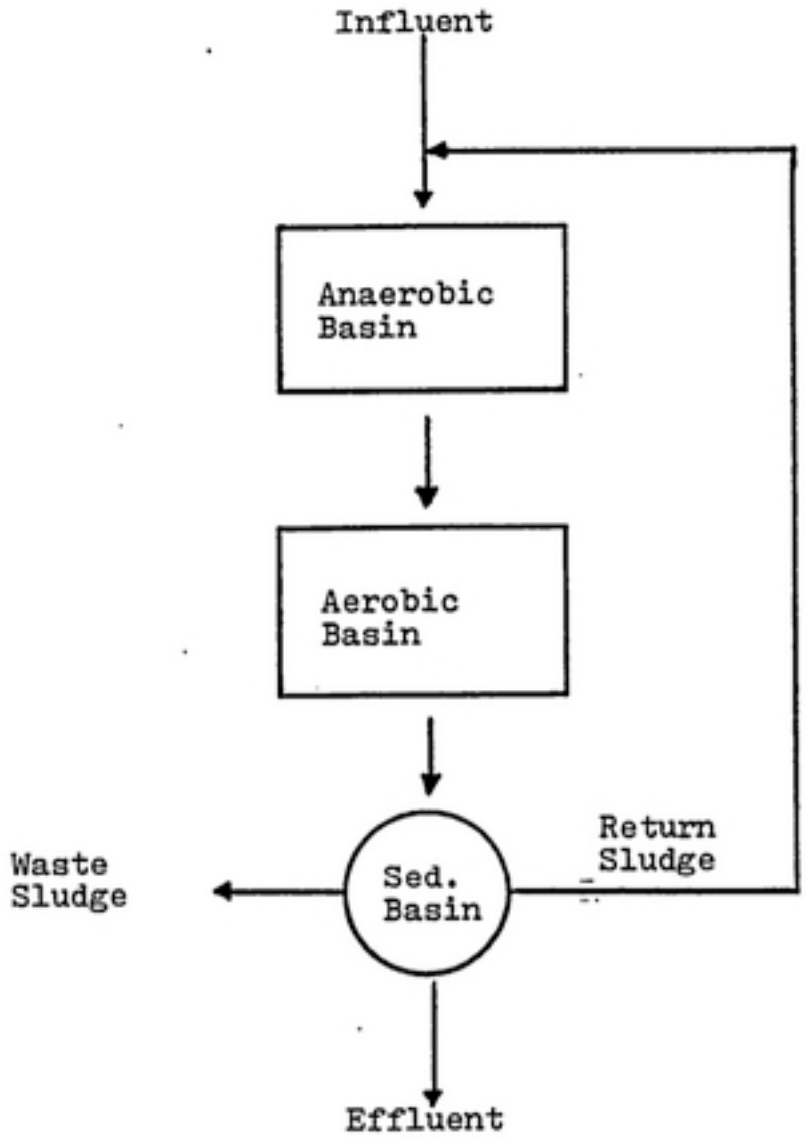


Figure 2

The A/O Process

aerobic stage. Sludge is recycled from the secondary clarifer and mixed with wastewater in the anaerobic zone to produce the high BOD conditions needed for the removal of oxygen and oxidized nitogen from the recycled sludge (Air Products, 1983). The aerobic stage is aerated with either air or oxygen. Figure 2 is a flow sheet of a typical A/O system.

The A/O process operates best when the ratio of soluble BOD to phosphorus is equal to or greater than 10 to 1 (Barth, 1982). The process has had problems with release of nitrogen gas bubbles by denitrification in the secondary clarifier which were solved by maintaining the sludge blanket at a thickness less than 35 inches (Walsh et al., 1983). Some advantages of the A/O process include a short detention time and the production of a sludge with a high fertilizer value (Walsh et al., 1983). Many existing conventional activated sludge plants can be easily modified to include this process. The A/O process can be modified by adding an anoxic zone to include denitrification. There is a full scale A/O plant in Largo, Florida and there are 4 or 5 pilot plants around the United States (Air Products, 1983). Walsh et al. (1983) found the average effluent concentration of phosphorus to be 1.5 - 2.0 mg/l if the effluent was not filtered.

The Bardenpho Process

The Bardenpho process was developed by James Barnard and is marketed in the United States by the Eimco Division of Envirotech Corporation. The Bardenpho system was initially designed to remove nitrogen by including an anoxic stage in an activated sludge system, as shown in Figure 3. The first aeration basin allows nitrification to occur. The nitrogen is removed through denitrification and the release of nitrogen gas. Nitrate containing liquor is recycled from the aeration basin to an anoxic zone located in front of the aeration basin. Also, raw wastewater or primary effluent wastewater is directed into the first anoxic zone to serve as hydrogen donors for the denitrification of the nitrates (Barnard, 1978). Effluent from the aeration basin that is not recycled passes to the second anoxic basin where the remaining nitrogen is removed through denitrification. The wastewater then passes through a second aeration basin to dissolve oxygen in the water.

The process was later changed to enhance phosphorus removal, if needed, by adding an anaerobic zone before the first anoxic zone, as shown in Figure 4. The denitrified sludge is recycled from the secondary clarifier to the anaerobic zone where it is mixed with the raw wastewater or primary effluent.

Barnard, 1983 modified his phosphorus removing

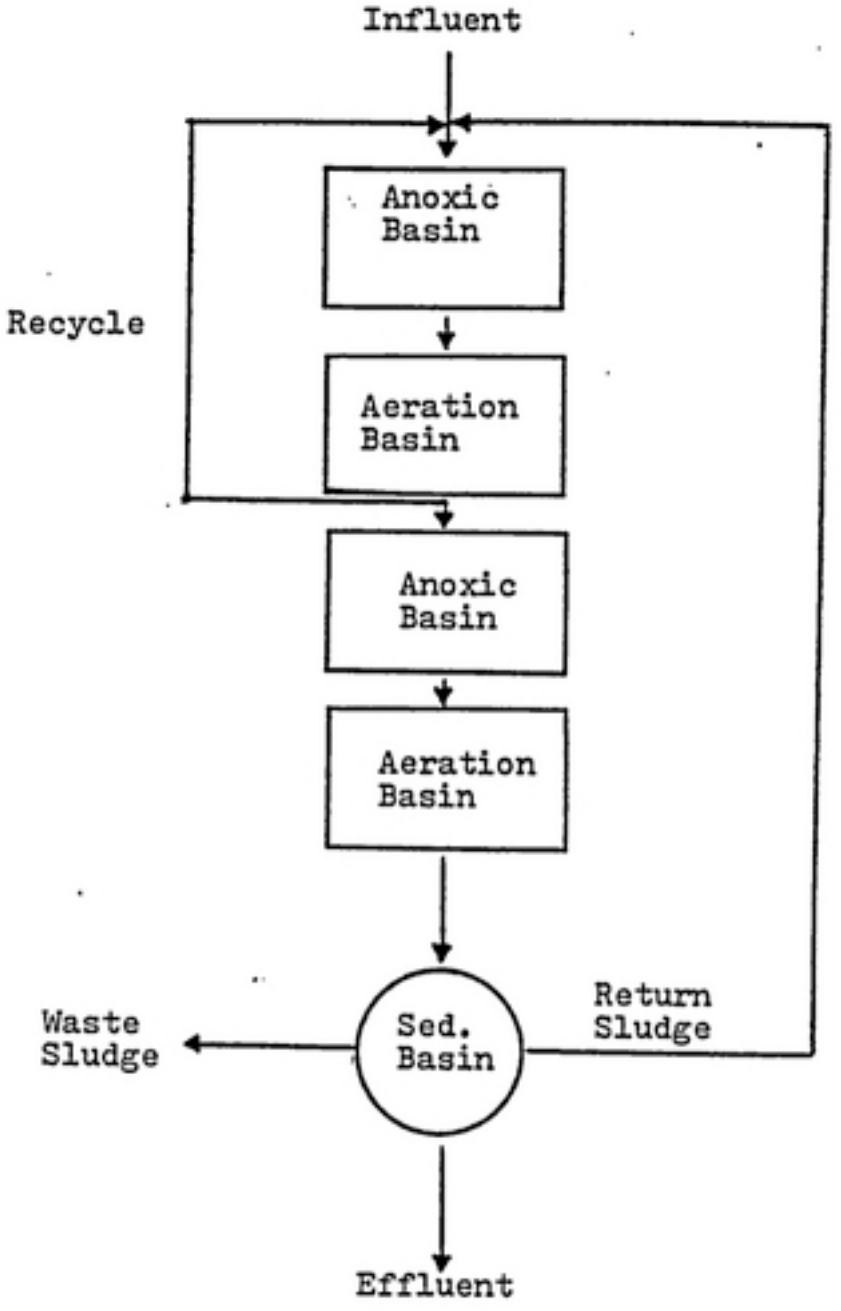


Figure 3

The Bardenpho Process

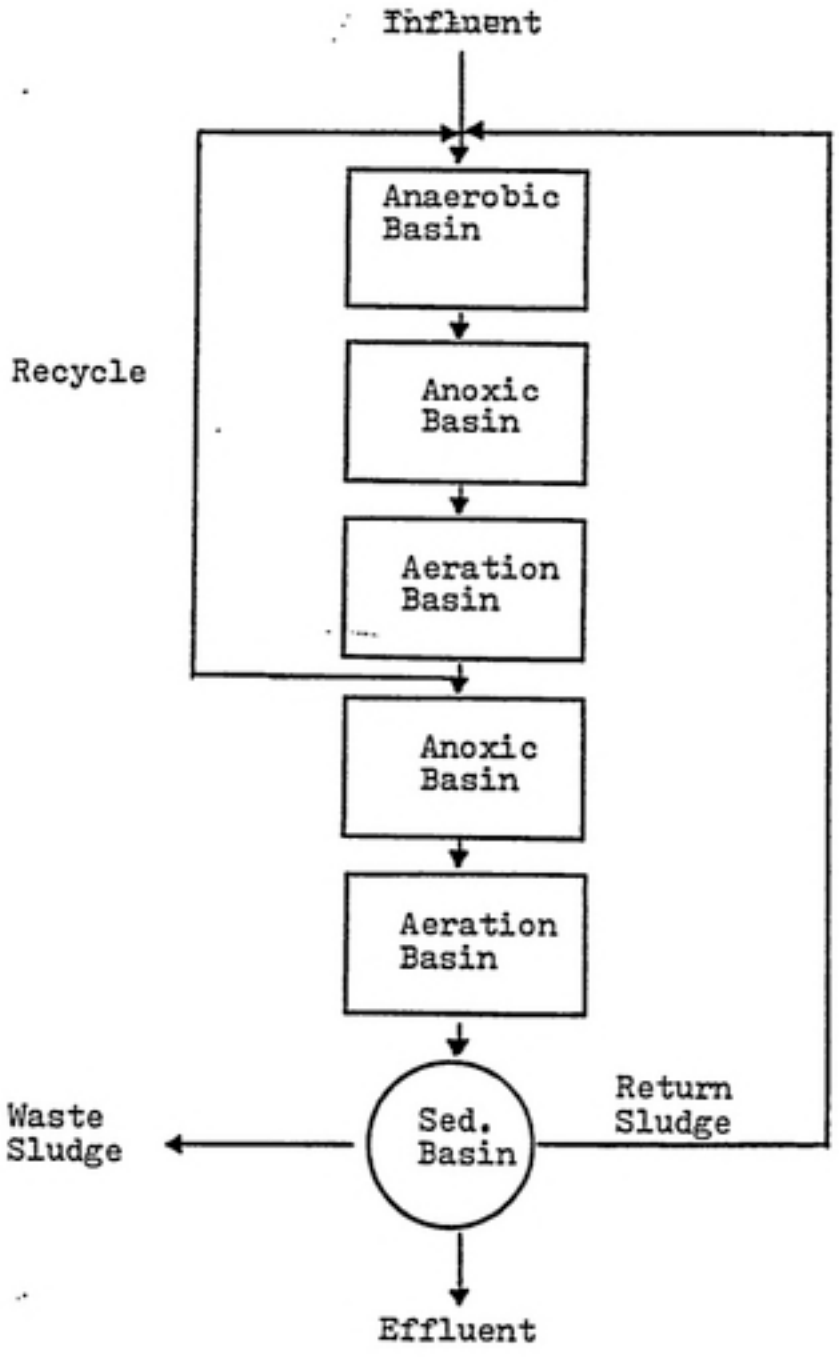


Figure 4

The Bardenpho Process with Phosphorus Removal

process (See Figure 5). The mixed liquor recyle was moved from discharging into the anaerobic zone to discharging in front of the anoxic basins. This was done to reduce the nitrate and oxygen supply to the anaerobic unit. Also a mixing basin was added in front of the anaerobic zone to provide interaction between the return sludge and the influent wastewater so that anaerobic conditions would surely exist. The Modified Bardenpho Process is shown in Figure 5.

The Bardenpho system has the advantage of removing nitrogen from the wastewater. Also less lime is required for controlling pH because some of the alkalinity lost during nitrification is recovered in the first anoxic tank during denitrification (Barnard, 1978). This process operates best with a BOD:P ratio of 20:1 or greater (Barth, 1982). A disadvantage of the process is that the reactor volume needed is larger than required in the A/O process (Walsh et al., 1983). Walsh et al. (1983) reported 40 Bardenpho systems worldwide, one in Palmetto, Florida. Most of the Bardenpho systems are located in South Africa. Walsh et al. (1983) found that the average effluent concentration of phosphorus from this process was 1.0 mg/l.

The Phostrip Process

The Phostrip Process was developed by Gilbert Levin

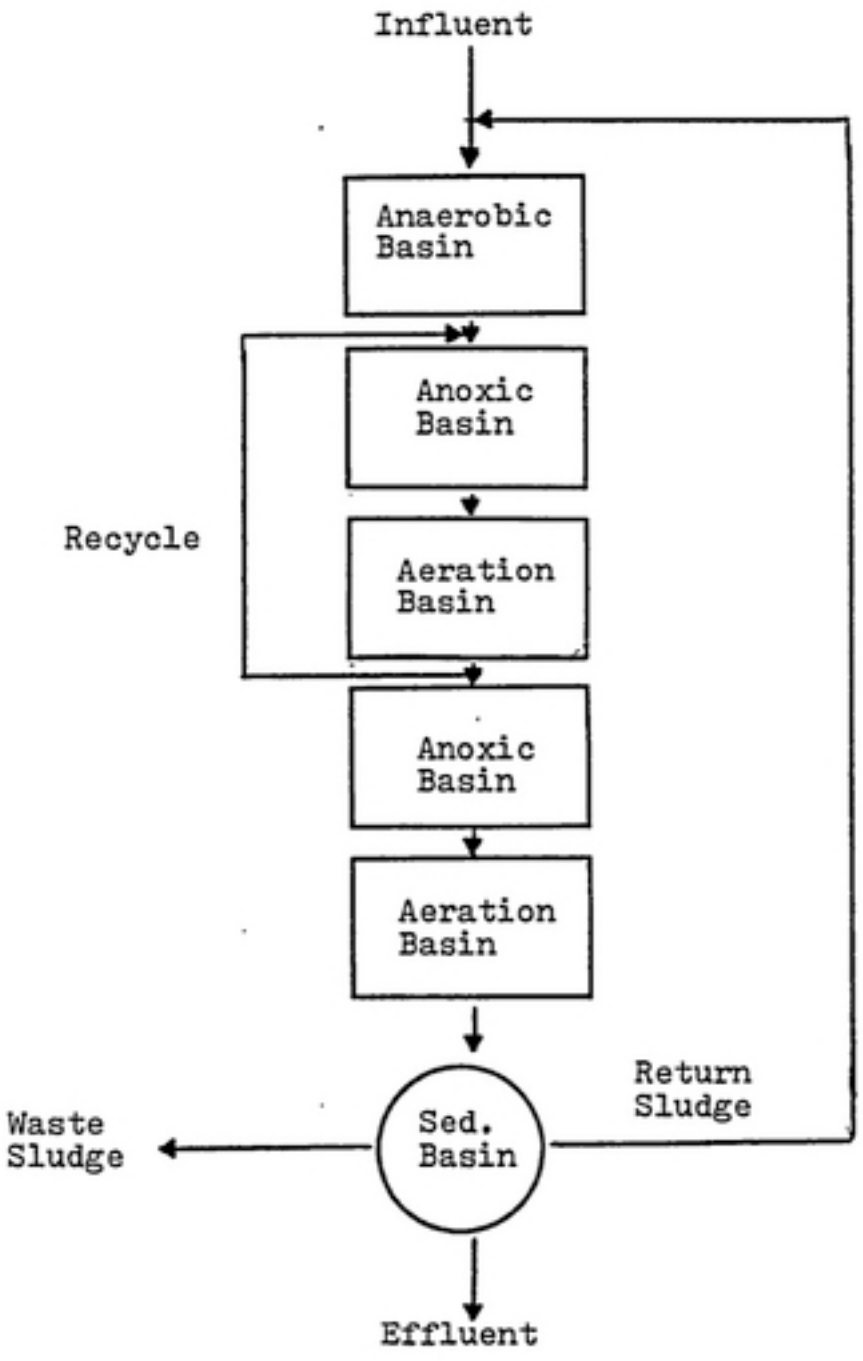


Figure 5

The Modified Bardenpho Process

and is marketed by Biospherics, Inc. It is a combined biological-chemical process for the removal of phosphorus from wastewater. This process differs from the other biological phosphorus removal systems because the anaerobic zone lies outside the activated sludge system. All or part of the return sludge is exposed to anaerobic conditions in a stripper tank. The sludge settles and releases phosphorus while in the stripper tank and the supernantant passes out of the tank into a chemical reactor where lime is added for chemical precipitation of calcium phosphate. The return sludge then proceeds to the aeration basin where phosphorus is removed from the wastewater. If the mainstream plant is nitrifying the wastewater, the stripper tank is proceeded by a denitrifying tank to ensure that anaerobic conditions occur (Miyamoto-Mills et al., 1983). The Phostrip system is shown in Figure 6.

Peirano, (1977) found that the Phostrip process' major control parameters are the quantity of biomass routed through the stripper tanks, the detention time of this biomass in the stripper tank, and the rate of withdrawal of the supernatant liquid from the surface of the stripping tank. He also suggests that the sludge blanket level in the secondary sedimentation basin be kept as low as possible to prevent anaerobic conditions from occurring and causing a release of phosphorus.

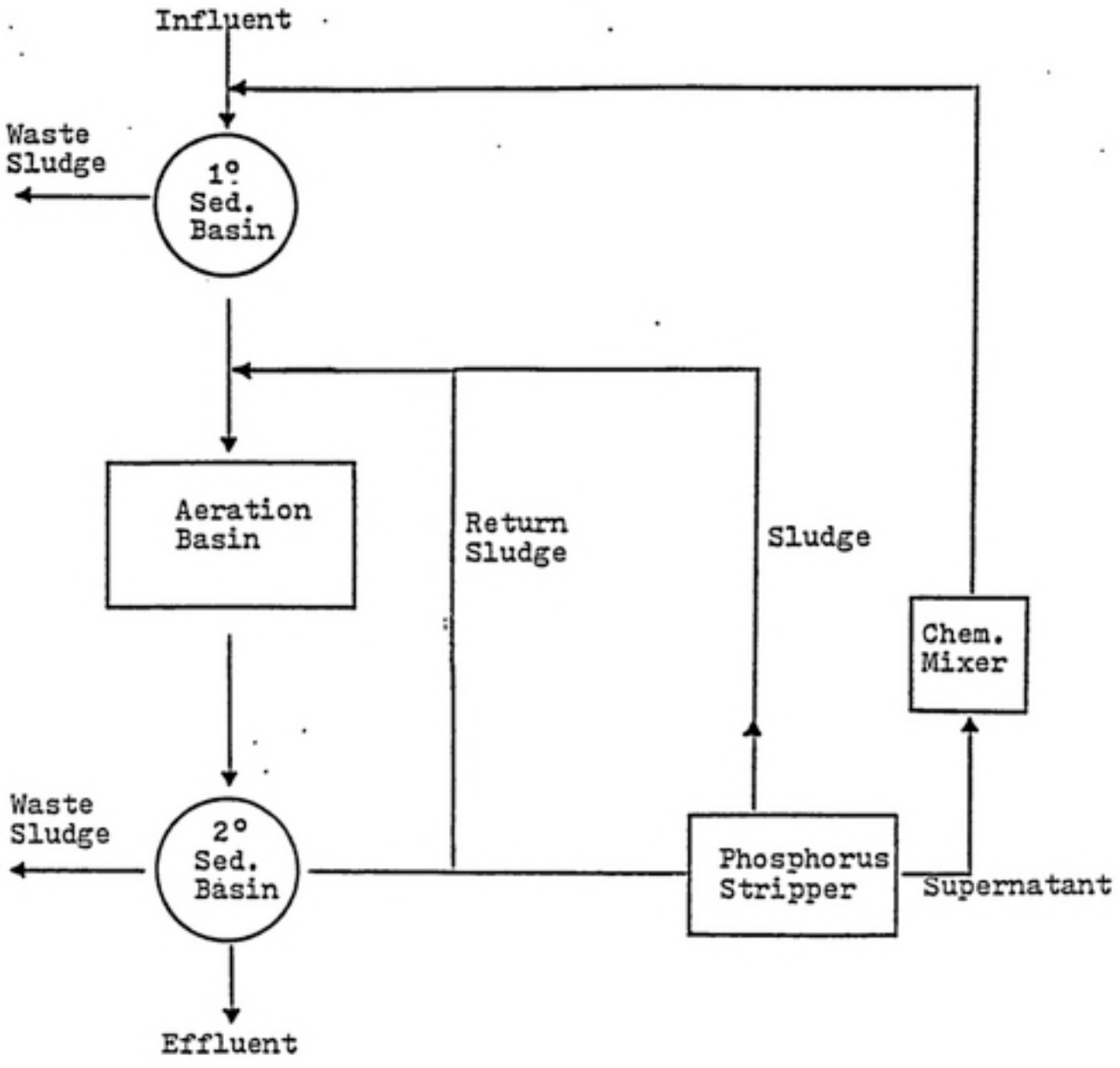


Figure 6

The Phostrip Process

Phostrip processes can operate with either plug or mixed flow reactors and do not depend on a high ratio of BOD to phosphorus in the raw wastewater (Barth, 1982). The reactor volumes for A/O and Bardenpho are much greater than those required for the Phostrip system. A disadvantage of Phostrip is that it requires chemical additions to the supernatant to precipitate the phosphorus, which produces a chemical sludge requiring disposal. Walsh et al. (1983) found that there were 10 Phostrip plants in the United States. They also found the average effluent concentration of phosphorus in this system to be 1.5 mg/l if not filtered.

MASON FARM WASTEWATER TREATMENT PLANT'S BPR EXPERIMENT

The Mason Farm Plant was notified in June, 1983 by the North Carolina Department of Environmental Management that the Environmental Management Commission had recently classified Jordan Lake as Nutrient Sensitive. The Commission was also debating a 1.0 mg/l or lower limit on phosphorus for all wastewater treatment plants discharging into Jordan Lake or its tributaries. The plant's staff initiated studies of ways to remove phosphorus cheaply and efficiently and conducted a preliminary plant scale trial of BPR (Gottschalk, 1985). The experiment began in October, 1983 and continued until August, 1984.

EXPERIMENTAL DESIGN

The Mason Farm Plant's activated sludge plant consists of eight basins, each of which contains both aerators and mixers. The aeration was turned off in October, 1983 in three of the eight basins but the mixing continued. The other five basins were kept aerobic (See Figure 7). The initial design called for four basins to be anaerobic but mechanical problems resulted in air being present in the fourth basin leaving only three anaerobic ones. The detention time in each basin was 1.7 hours, without recycle, making the anaerobic period 5.1 hours and the aerobic peroid 8.5 hours. One-half of the

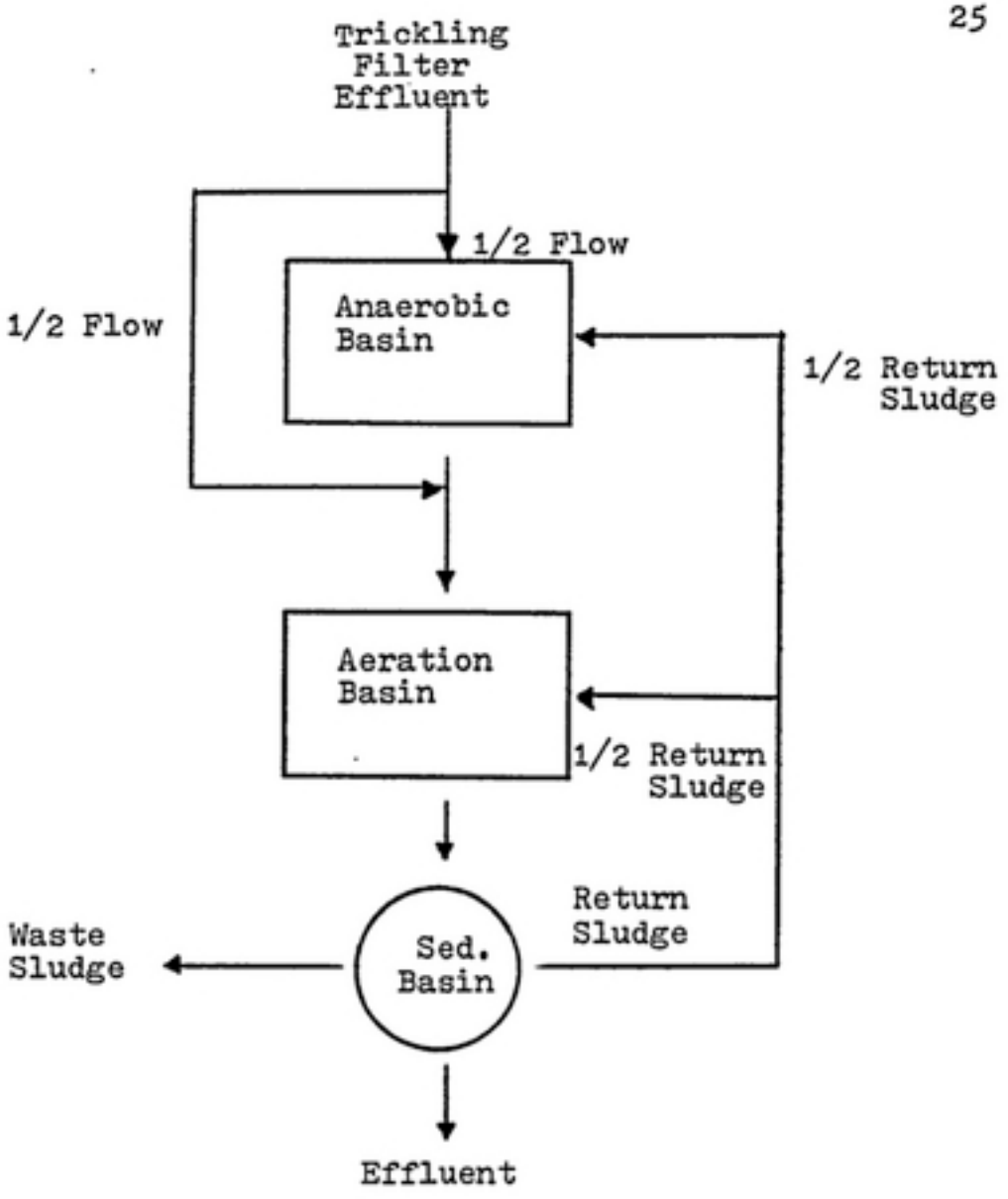


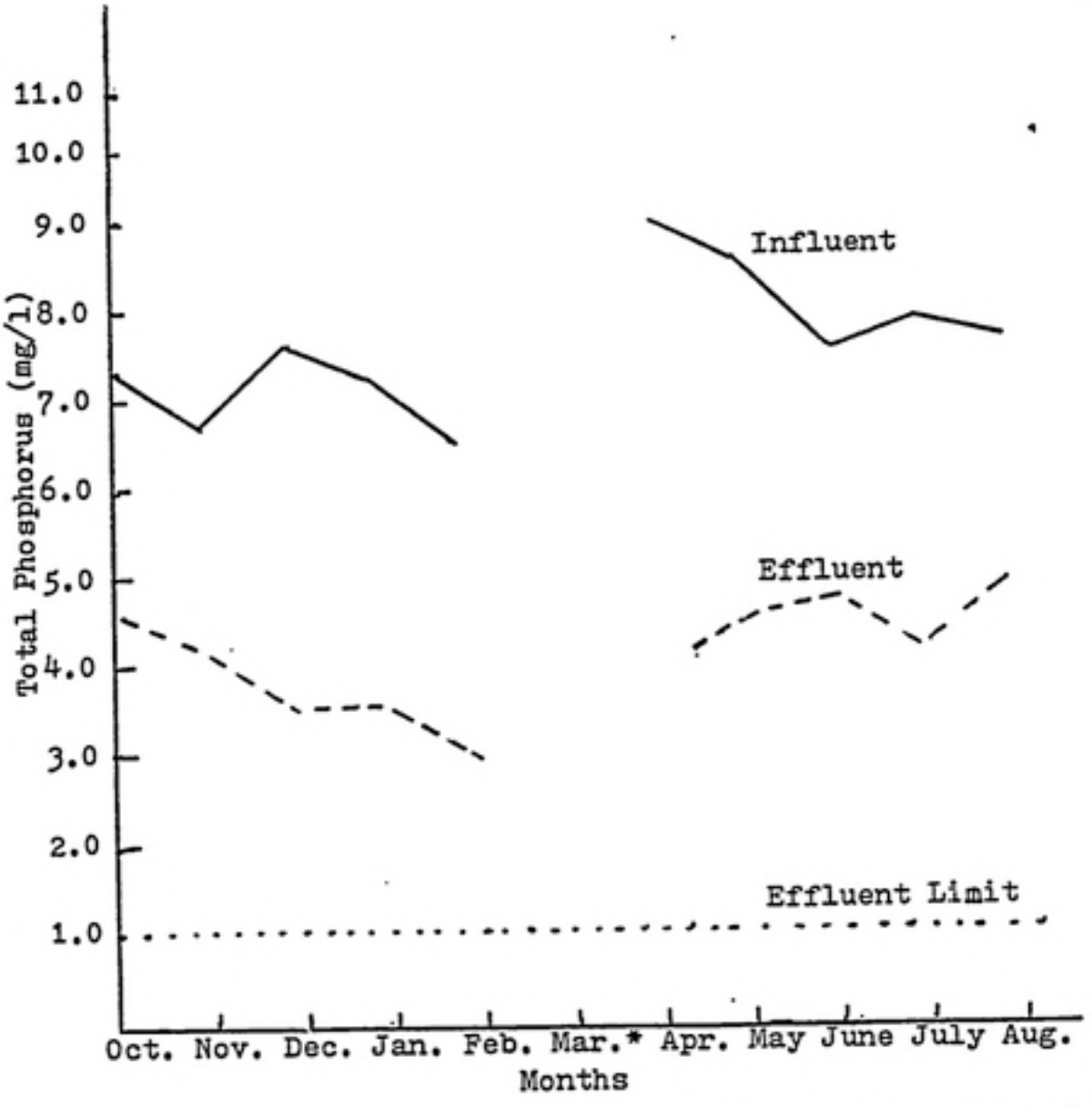
Figure 7

Mason Farm Plant's BPR Process

plant's wastewater flow and one-half of the return activated sludge were put through the anaerobic stage. The other half of the wastewater and return activated sludge were directed into the aerobic zone. This was done because the plant operator feared that if the sludge reacted poorly to anaerobic conditions, effluent limits might be exceeded. The return activated sludge came from the secondary clarifiers. The influent wastewater had previously been treated by primary sedimentation and trickling filters. The average BOD of the tricking filter effluent was 88 mg/l.

RESULTS

The data was collected by the Mason Farm Plant's employees. The reported influent and effluent phosphorus concentrations were the plant influent and effluent, respectively. As shown in Figure 8, the phosphorus level in the effluent never got below the 1 mg/l limit. The experiment was discontinued in August, 1984 because the limit was not being reached. Review of the data collected by the Mason Farm Plant's staff (Appendix A), shows that even though there was no aeration, dissolved oxygen and nitrates were still present in the anaerobic zone most of the time.



*No Results reported

Figure 8

Mason Farm Plant's BPR Results

DISCUSSION

There were problems with this experiment which caused minimal phosphorus removal. To attain good phosphorus removal, the anaerobic zone must be devoid of all dissolved oxygen and nitrates. The anaerobic zone in this experiment was never devoid of dissolved oxygen for more than a few days consecutively and often there were also nitrates in that anaerobic zone because they were present in the return sludge flow. Also, BOD of the influent wastewater was very low, only averaging 88 mg/l and a high BOD concentration has been shown to be essential for good phosphorus removal (Scalf et al., 1969, Sutton and Jank, 1980, Barth and Stensel, 1981, Fukase, Shibata, and Miyaji, 1984).

A major problem was that only one-half of the return activated sludge and flow were put though the anaerobic stage, but all went through the aerobic stage. Accordingly, if phosphorus removal occurred, its effect was partially obscured by dilution with that flow not exposed to the anaerobic phase. Further, the phosphorus removing sludge and the non-phosphorus removing sludge were mixed perhaps negating some biochemical process effectiveness when the wastewater was treated by the mixture. The full potential of the effect of anaerobic conditions on the sludge cannot be realized unless all of the sludge has been rigorously exposed to alternating

aerobic and anaerobic conditions.

The Mason Farm Plant's experiment did not succeed because : 1) anaerobic conditions of sufficient duration were never reached, 2) the BOD concentration was too low to produce fully anaerobic conditions and efficient phosphorus removal, and 3) only a portion of the return activated sludge and wastewater flow were treated anaerobically.

RECOMMENDATIONS

If this experiment is to be repeated, there should be some changes. First, sludge from the secondary clarifier should be treated to eliminate nitrates. Second, the low BOD trickling filter effluent should not be used. The trickling filter should be bypassed and the primary clarifier effluent (or raw wastewater) should be used as the influent wastewater. Third, the total return activated sludge and wastewater should be treated anaerobically. Possibly, if these changes are made, phosphorus removal could occur.

EXPERIMENTAL METHODS

APPROACH

A batch-type experiment was conducted to determine if significant BPR could occur with Chapel Hill's wastewater and sludge. If BPR did not occur, the reactors were to be used to determine under what conditions BPR would occur using the local wastewater and sludge. The experiment was proposed as an initial study to be followed by more extensive work based on the results.

Two reactors were used. One was a control unit, which was aerated constantly, as it would be in a typical activated sludge plant. The other reactor was operated to include an anaerobic phase of 8 hours followed by an aerobic phase of 16 hours. Other conditions of the reactors were kept as similar as possible.

APPARATUS

Two 2 liter graduated cylinders were used as the reactors. A styrofoam cover coated in plastic was used to keep the air from contacting the solution in the experimental reactor while it was in the anaerobic phase. Both reactors were mixed continuously by a magnetic mixer. Aeration was accomplished by an air pump with hoses leading into each reactor. Figure 9 is a diagram of the reactors.

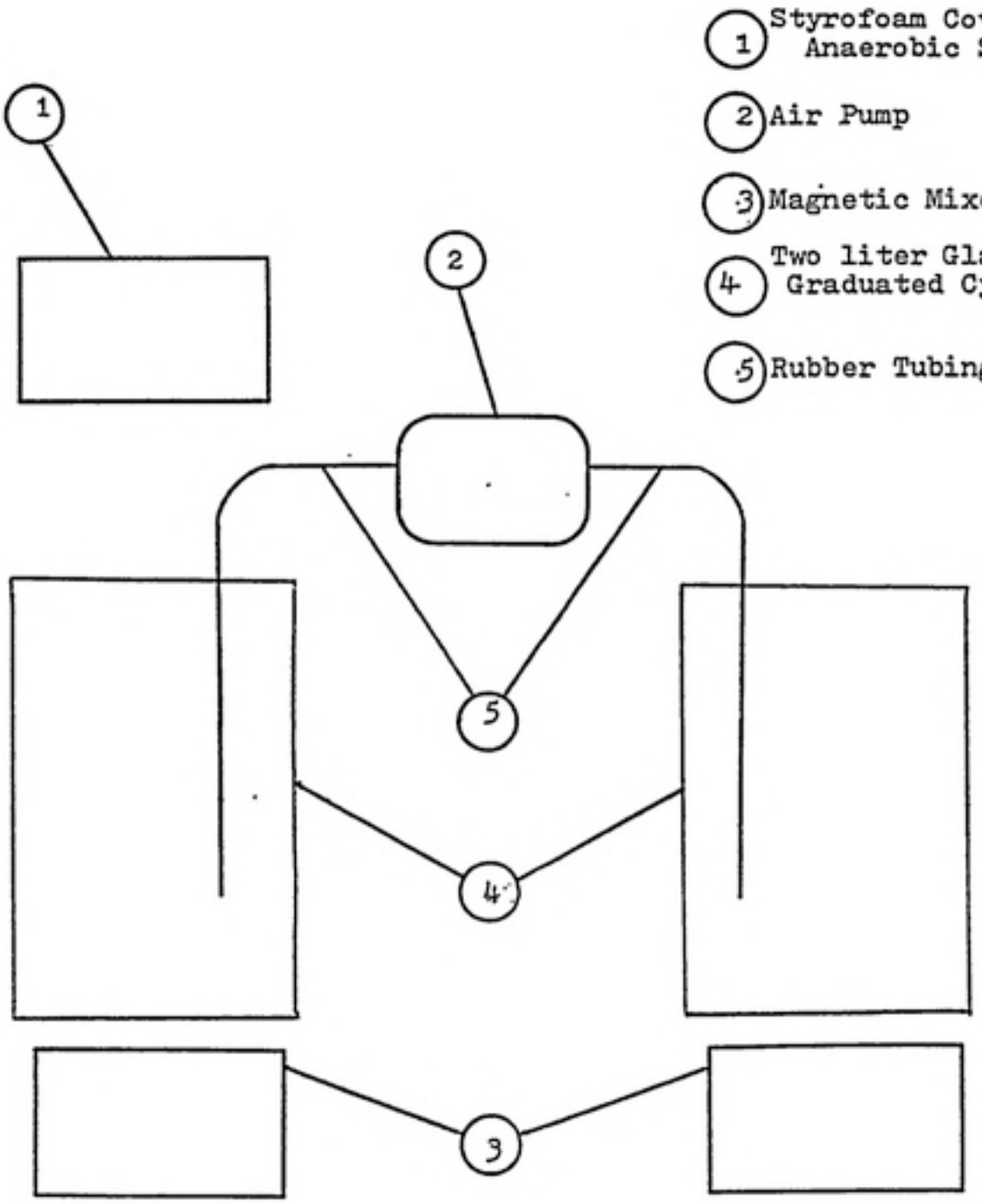


Figure 9

Reactor Apparatus

The reactors were kept out of direct sunlight to prevent algal growth. Dissolved oxygen was measured using a Weston and Stack Dissolved Oxygen Analyzer - Model # 330. The pH was measured with a digital Fisher Accumet pH meter - Model 610. The phosphorus and nitrogen content of the samples were measured colorimetrically by using a Perkin-Elmer Lambda 3 UV/VIS spectrophotometer.

EXPERIMENTAL DESIGN

Initial Set-up

Initially, both reactors were filled with 600 ml of return activated sludge (30%) and 1400 ml of grit chamber effluent (70%) from the Mason Farm Plant. The grit chamber effluent was grab sampled from the influent end of the primary settling tank and the return activated sludge was taken from the return outlet in the activated sludge basin. The reactor units contained a solution with a concentration of 3000 mg/l mixed liquor suspended solids. The reactors were mixed well prior to the start of the experimental procedure.

Daily Procedure

The reactors were operated on a 24 hour cycle. Grit chamber effluent was collected daily on non-peak hours, 7 a.m. and 3 p.m., to increase the BOD concentration of the

wastewater. The effluent was then refrigerated until used. When the effluent was used, it was first mixed and warmed to room temperature.

At the beginning of each cycle, hour 0, 1400 ml of grit chamber effluent was added to sludge remaining in each reactor. The control reactor was then aerated and mixed for 24 hours. The experimental reactor was covered with the styrofoam cover and mixed for 8 hours; creating anaerobic conditons. After 8 hours, the experimental reactor was uncovered, aerated, and mixed for the next 16 hours. At the end of the cycle, hour 24, the mixers and air for both reactors were turned off and the solutions were allowed to settle. After 30-45 minutes, 1400 ml of the supernatant was removed, sampled, and discarded.

Samples

Samples were taken at various points in the experimental cycle. The first sample was taken at the beginning of the cycle, directly from the grit chamber effluent when it was being added to the reactors. A second sample of mixed liquor was taken from each reactor after 8 hours at the end of the experimental reactor's anaerobic stage. The third sample was taken from each at the end of the cycle as reactor supernatant. The pH and dissolved oxygen were measured and then the samples were frozen until the other analyses were conducted.

The samples were first tested for pH and dissolved oxygen. An initial pH reading was taken of the mixed liquor after influent sewage had been added to the sludge and mixed. The digital meter on which the pH was measured was calibrated daily.

The dissolved oxygen was measured by pouring 300 ml of the mixed liquor into a clean 300 ml BOD bottle, avoiding aeration of the solution. The dissolved oxygen was then checked on the Weston and Stack Dissolved Oxygen meter which was calibrated before each measurement. The mixed liquor then was returned to the reactors.

Initially both filtered and unfiltered samples were used to determine phosphorus concentrations. The filtered samples were passed through a Gelman GN-6 0.45 um filter to remove most of the particulate matter. Both filtered and unfiltered samples were then tested for reactive (PO4) and total phosphorus. The reactive phosphorus was measured by using the Hach Amino Acid Method with the Perkin-Elmer Lambda 3 UV/VIS spectrophotometer. The total phosphorus was measured by first using the Hach's Hydrolysis to Orthophosphate Method and then proceeding with the Hach's Amino Acid Method.

The filtered samples were also used to determine the amount of nitrate in the solution. This test was done, like the dissolved oxygen test, to insure anaerobic

conditions in the experimental reactor. For anaerobic conditions to exist, both must be essentially at zero. The nitrate concentration was measured by the Hach Cadmium Reduction Method using the Perkin-Elmer Lambda 3 UV/VIS spectrophotometer.

After the first four weeks, the phosphorus testing was reduced to testing only for reactive filtered phosphorus. The unfiltered samples were discontinued since they have phosphorus containing particles which settle and would indicate phosphorus removal in the results when none occurred. The total filtered phosphorus and the reactive filtered phosphorus were compared using a paired sample T test (Kleinbaum and Kupper, 1978) and the test showed that there was no significant difference between the two ($T=0.104$, $p=0.919$). Thereafter, the reactive soluble phosphorus measurement was used because it was much simpler than measuring the total soluble phosphorus. Another reason for reducing the phosphorus measurements to include only reactive soluble phosphorus was that additional measurements were time-consuming and, due to the preliminary nature of this experiment, were deemed unnecessary.

The dissolved oxygen test was eliminated after 5 weeks. The data (see Table B-1, Appendix B) consistently had showed near zero dissolved oxygen concentrations after the 8 hours of non-aeration in the experimental

reactor and had shown near saturation values in both the aerated experimental and control reactors. The testing was stopped due to a Dissolved Oxygen Meter malfunction. Since the data to that point had shown zero dissolved oxygen concentrations existing in the experimental reactor, the nitrate analysis was assumed to be sufficient for checking anaerobic conditions.

Variations in the Experiment

There were three major parts of this experiment. Phase I was the initial period consisting of days 1-18. After 18 days with no apparent phosphorus removal (See Discussion Section), additional sludge was added to the reactors. This sludge was added to try to circumvent the reported acclimation period (Manning and Irvine, 1985). Three sources of sludge were added to the reactors which contained the initial Mason Farm activated sludge. Sludge from two of these sources had previously been exposed to anaerobic conditions. The reason for this addition was that the new sludge may contain significant numbers of the microorganisms which are responsible for phosphorus removal. Therefore, the acclimation period in which the phosphorus removing organisms thrive and grow would be shortened.

On day 18, 300 mg/l of the Mason Farm Plant's primary sludge, 300 mg/l of Durham's Northside Plant's

return activated sludge, and 300 mg/l of the supernatant from the Northside Plant's anaerobic digesters were added to the reactors. Days 18-57 will be referred to as Phase II. The Mason Farm Plant's primary sludge was used because it was Chapel Hill sludge which had not been exposed to aeration and contained more BOD. The Northside Plant's activated sludge was added because the anaerobic supernatant is discharged back into the activated sludge basins. Also, the aeration system is such that some of the mixed liquor is anaerobic at times, as well as being exposed to aerobic conditions in the activated sludge process.

After the addition of sludge on day 18, no significant phosphorus removal occurred. The average BOD concentration of the grit chamber effluent was approximately 200 mg/l. A high BOD concentration has been found essential for significant phosphorus removal (Scalf et al., 1969, Sutton and Jank, 1980, Barth and Stensel, 1981, Fukase, Shibata, and Miyaji, 1984). A/O process researchers recommend glucose be used as an additional BOD source to initially start the reactors removing phosphorus. They also suggest that after the reactors had been removing phosphorus for a few weeks, additional glucose would not be needed for phosphorus removal. Barnard, 1978 suggests that sodium acetate be added to BPR systems as a source of BOD to accelerate the

initial phosphorus removing process.

On days 57-67, 100 mg/l of sodium acetate and 100 mg/l of glucose were added to each of the reactors daily along with the 1400 ml of grit chamber effluent. These additions increased the BOD of the influent wastewater by 103 mg/l as 5-day BOD (Stream Sanitation Committee RA58, 1966).

To determine whether even higher BOD levels would increase the phosphorus removal, on days 67-75, an additional 200 mg/l of sodium acetate (or 64 mg/l as BOD) was added daily to the reactors. The sodium acetate was used due to a shortage of glucose.

RESULTS AND DISCUSSION

CONTROL PARAMETERS

Dissolved Oxygen

Dissolved oxygen was measured intermittently in both reactors for the first 40 days of the experiment. These values can be found in the Table B-1 (Appendix B). The first four days of the dissolved oxygen measurements showed high dissolved oxygen levels in the anaerobic stage. The most probable cause was the absence of an air-tight cover. Such a cover was constructed and used starting on the fifth day of the experiment. Dissolved oxygen anaerobic phase measurements taken after the installation of the cover showed near zero dissolved oxygen conditions. The slight amount of oxygen found could be explained by measurement error since the sample was handled in a way that permitted some aeration to occur. The dissolved oxygen present in the aerated phases was always satisfactorily near saturation values.

Nitrate

The nitrate level was measured to assure the existence of anaerobic conditions in the experimental unit. The nitrate measurements can be found in Table 1. Since the organisms which require oxygen use dissolved oxygen before using nitrates, the absence of nitrates

Table 1

Results from the Experimental and Control Reactors

Experimental Reactor

		pH			NO3 (mg/l)			PO4 (mg/l)		
Hours		0	8	24	0	8	24	0	8	24
Days	Avg. BOD									
1	156	*	*	*	0.00	4.02	24.20	10.71	10.90	5.75
2	*	*	*	*	0.00	17.59	23.79	1.33	1.05	0.66
3	*	*	*	*	0.00	1.80	17.48	4.66	1.87	1.65
4	240	*	*	*	0.00	8.70	20.65	4.20	1.79	3.49
5	126	*	*	*	0.00	0.00	2.71	6.17	2.22	6.69
9	*	6.52	6.25	6.15	0.00	0.00	2.71	6.60	7.98	6.69
12	173	6.90	7.00	6.50	0.00	0.00	13.79	7.32	5.36	4.83
24	*	7.25	7.05	7.85	0.00	0.00	7.43	1.37	3.97	3.25
26	196	7.25	7.05	7.65	0.00	0.00	0.90	7.46	6.57	4.71
31	*	7.40	7.15	7.55	0.00	0.00	3.79	6.24	7.98	5.53
33	205	7.20	7.00	7.20	0.00	0.00	5.29	8.59	9.95	6.92
38	*	6.85	7.00	6.90	0.00	0.00	19.71	4.91	7.03	5.78
40	233	6.90	7.05	7.00	0.00	0.00	14.12	8.06	9.67	6.01
43	188	6.65	6.75	6.15	0.00	0.00	24.07	5.40	6.97	6.21
48	172	6.70	6.75	6.25	0.00	0.00	14.64	4.91	6.76	2.78
57	215	6.65	6.30	7.00	0.00	0.00	20.68	3.63	3.82	1.87
59	*	7.10	6.75	7.05	0.00	0.00	15.10	3.18	5.44	0.62
64	168	7.05	6.40	6.85	0.00	0.00	14.30	3.66	10.18	0.27
66	*	7.05	6.55	6.65	0.00	0.00	18.21	4.60	13.30	0.65
69	238	7.00	6.30	6.90	0.00	0.00	11.30	4.51	13.00	0.95
71	173	6.90	6.30	7.20	0.00	0.00	8.21	4.46	13.67	0.10
73	*	7.10	6.20	6.60	0.00	0.00	10.91	2.40	10.19	0.36
75	188	7.20	6.55	7.30	0.00	0.00	10.60	1.01	5.02	0.22

Hours

0 - Influent

8 - Anaerobic/Aerobic Mixed Liquor

24 - Effluent

Table 1 cont.

Results from the Experimental and Control Reactors

Control Reactor

		pH			NO_3 (mg/l)			PO_4 (mg/l)		
Hours		0	8	24	0	8	24	0	8	24
Days	Avg. BOD									
1	156	*	*	*	0.00	5.14	20.62	10.71	6.99	6.92
2	*	*	*	*	0.00	19.90	26.75	1.33	0.71	0.66
3	*	*	*	*	0.00	14.06	22.97	4.66	1.06	1.10
4	240	*	*	*	0.00	22.00	23.63	4.20	2.05	2.97
5	126	*	*	*	0.00	1.21	8.98	6.17	1.79	8.17
9	*	6.78	6.88	6.80	0.00	4.17	8.98	6.60	6.69	8.17
12	173	6.70	7.10	5.60	0.00	3.16	19.33	7.32	6.10	5.87
24	*	7.25	7.40	7.50	0.00	15.13	10.16	1.37	1.21	1.63
26	196	7.20	7.65	7.80	0.00	0.60	1.76	7.46	4.64	4.66
31	*	7.40	7.35	7.20	0.00	12.70	18.20	6.24	6.13	6.38
33	205	7.05	7.00	7.33	0.00	11.32	30.50	8.59	8.59	7.35
38	*	6.75	6.70	6.90	0.00	7.93	15.35	4.91	4.36	6.26
40	233	6.90	6.85	7.00	0.00	8.19	27.22	8.06	8.22	8.24
43	188	6.65	6.80	5.35	0.00	6.67	32.32	5.40	6.55	7.05
48	172	6.80	7.00	5.30	0.00	7.50	14.64	4.91	3.81	2.81
57	215	6.75	6.95	7.00	0.00	5.79	18.49	3.63	2.80	3.80
59	*	7.15	7.10	7.10	0.00	6.22	20.10	3.18	2.40	3.14
64	168	7.00	6.85	6.85	0.00	9.47	16.80	3.66	2.82	2.56
66	*	7.05	6.85	6.75	0.00	6.36	20.33	4.60	3.73	3.47
69	238	6.90	6.85	6.80	0.00	3.90	14.74	4.51	3.96	3.63
71	173	6.95	7.10	7.25	0.00	2.09	11.20	4.46	2.82	2.10
73	*	7.15	7.20	6.40	0.00	4.58	18.76	2.40	2.43	1.60
75	188	7.20	7.15	7.30	0.00	2.05	18.77	1.01	1.19	1.00

Hours

0 - Influent

8 - Anaerobic/Aerobic Mixed Liquor

24 - Effluent

indicates anaerobic conditions. The presence of nitrates in the aerated phases indicates sufficient aeration for nitrification.

The nitrate measurements for the raw sewage were consistently zero, as expected. The first four days of the experimental unit's anaerobic phase showed high nitrate content. This was attributable to inadequate denitrification possibly due to the presence of oxygen. The subsequent nitrate measurements found no nitrates present. The aerated samples all showed significant nitrate levels, which meant sufficient aeration to allow nitrification, except for day 26. The low nitrate levels in the aerated samples on day 26 can be explained by a malfunction in the air pump which was immediately corrected.

STATISTICAL ANALYSES OF PH AND REACTIVE PHOSPHORUS DATA

In order to determine whether pH may have initiated chemical precipitation of phosphorus and whether significant phosphorus removal occurred in any of the experimental phases, analyses of variance (ANOVA) were conducted (Kleinbaum and Kupper, 1978). The pH was used for the statistical analyses since, at the reported range, the magnitude of the difference between the means of hydrogen ion concentration and pH was insignificant (less than 4%). The pH and the phosphorus levels

measured in each reactor at 0,8 and 24 hours were used as the dependent variable. Three independent variables were used in the initial ANOVAs for each of the dependent variables. Reactor was a two-level variable which represented the experimental and control reactors. A three-level variable named Hour was used to represent the three sampling points each day. Phase was a three-level variable which described the three variations in the experimental method discussed earlier. All possible interactions among these three variables were also included.

The assumptions for an ANOVA are 1) all observations are statisically independent of one another; 2) each observation comes from a normally distributed population; and 3) each observation has the same population variance. These assumptions were presumed to be met for this experiment. Days were not considered as a factor in this analysis because each day's pH and phosphorus level were assumed to be a random variable and independent of the previous day's pH and phosphorus level. The results were assumed to be significantly different if the $p < 0.05$. The results were marginally different if the $p < 0.10$.

Analysis of pH Data

As shown in Table 2, the Hour by Reactor interaction

Table 2

ANOVA for pH

R-square = 0.261

F = 1.87

pr > F = 0.030

Dependent Variable - pH

Source	ss	df	F	pr > f
Hour	0.530	2	1.70	0.188
Reactor	0.103	1	0.66	0.419
Reactor * Hour	0.774	2	2.48	0.089
Phase	1.517	2	4.87	0.009
Hour * Phase	1.231	4	1.98	0.105
Reactor * Phase	0.391	2	1.26	0.289
Reactor * Phase * Hour	0.186	4	0.30	0.878
Total	4.963	17		

ss - sum of squares
df - degrees of freedom

was marginally significant (F=2.48, p=0.089) and the Phase was significant (F=4.87, p=0.009). The Hour by Reactor interaction indicates that the pH in the one reactor was different from the pH for the other reactor for at least one level of Hour. The significance of Phase indicates that the pH differed between at least two phases. When an interaction is significant, the main effect cannot be directly interpreted; instead the appropriate cell means must be compared. To further investigate the reported results, two-way ANOVA's were run using the pH observations within each phase. Each of these analyses used pH as the dependent variable and Reactor and Hour along with their interaction as independent variables.

Table 3 shows the ANOVA results for each phase. The ANOVA's for Phases I and II indicate no significant differences in pH for Reactor, Hour or their interaction. Phase III, on the other hand, shows significant differences for Hour (F=9.22, p=0.0005), Reactor (F=10.89, p=0.002), and in the Reactor by Hour interaction (F=10.90, p=0.0002). In order to determine which of these factors contributed to the levels of significance of these effects, the means within each combination of factor levels were compared. The mean pH at the 8 hour level in the experimental reactor was significantally different from the mean pH of the other

Table 3

ANOVA for pH by Phase

	Phase I				Phase II			
	R-square = 0.419				R-square = 0.039			
	F = 0.87				F = 0.34			
	pr > F = 0.552				pr > F = 0.888			
Source	ss	df	F	pr > F	ss	df	F	pr > F
Hour	0.690	2	1.78	0.247	0.091	2	0.17	0.812
Reactor	0.024	1	0.13	0.735	0.042	1	0.16	0.612
Reactor * Hour	0.125	2	0.32	0.735	0.322	2	0.59	0.559
Total	0.840	5			0.444	5		

Phase III

R-square = 0.549

F = 10.23

pr > F = 0.0001

Source	ss	df	F	pr > F
Hour	0.780	2	0.17	0.0003
Reactor	0.460	1	10.89	0.002
Reactor * Hour	0.922	2	10.90	0.0002
Total	2.162	5		

ss - sum of squares
df - degrees of freedom

two levels of Hour in both the experimental and control reactors and also different from the 8 hour level in the control reactor (See Table 4).

Analysis of Phosphorus Data

To determine whether significant phosphorus removal occurred in each of the three phases, another three-way ANOVA was conducted. This analysis used the reactive soluble phosphorus as the dependent variable. The independent variables were the same as those used previously: Hour, Reactor, Phase, and their interactions. As shown in Table 5, the Hour variable ($F=8.06$, $p=0.0005$), the Reactor by Hour interaction ($F=6.99$, $p=0.0015$), and the Phase variable ($F=13.30$, $p=0.0001$) were significant. In addition, the Hour by Phase interaction ($F=2.97$, $p=0.022$) and the Reactor by Hour by Phase interation ($F=2.78$, $p=0.012$) were also significant, while Reactor was marginally significant ($F=3.37$ $p=0.098$). In order to isolate the specific differences in the reactive soluble phosphorus, two-way ANOVA's were again conducted for each phase. As shown in Table 6, there was no significant differences in the phosphorus levels in Phases I and II. In Phase III, however, there were significant differences in the phosphorus concentration among the levels of Hour ($F=22.01$, $p=0.0001$) and the levels of Reactor ($F=7.67$, $p=0.008$).

Table 4

ANOVA for pH - Cell Means Comparison - Phase III

	Hour		
Reactor	0	8	24
Experimental Reactor	7.01	6.45**	6.94
Control Reactor	7.01	7.01	6.93

** $p < 0.01$ - mean is significantly different from other means

Table 5

ANOVA for Reactive Soluble Phosphorus

R-square = 0.439

F = 5.34

pr > F = 0.0001

Dependent Variable - Reactive Soluble Phosphorus

Source	ss	df	F	pr > F
Hour	93.47	2	8.02	0.0005
Reactor	16.09	1	2.78	0.098
Reactor * Hour	80.08	2	6.99	0.0015
Phase	154.28	2	13.30	0.0001
Hour * Phase	68.99	4	2.97	0.0222
Reactor * Phase	11.77	2	1.01	0.365
Reactor * Hour * Phase	78.14	4	3.37	0.012
Total	596.95	17		

ss - sum of squares
df - degrees of freedom

Table 6

ANOVA for Reactive Soluble Phosphorus by Phase

Phase I

R-square = 0.041

F = 0.27

pr > F = 0.926

Phase II

R-square = 0.062

F = 0.056

pr > F = 0.732

Source	ss	df	F	pr > F	ss	df	F	pr > F
Hour	10.94	2	0.57	0.569	4.90	2	0.47	0.626
Reactor	0.08	1	0.01	0.920	2.89	1	0.56	0.459
Reactor * Hour	1.91	2	0.10	0.905	6.64	2	0.64	0.531
Total	12.93	5			14.45	5		

Phase III

R-square = 0.698

F = 19.39

pr > F = 0.0001

Source	ss	df	F	pr > F
Hour	15.69	2	22.01	0.0001
Reactor	27.32	1	7.67	0.0083
Reactor * Hour	161.28	2	22.63	0.0001
Total	345.50	5		

ss - sum of squares
df - degrees of freedom

There was also a Reactor by Hour interaction ($F=22.63$, $p=0.0001$).

To determine the specific significant differences among the means, pairwise comparisons were conducted. Table 7, 8 and 9 shows the means of each of the reactors for the various sampling times. Table 10 shows the pairwise comparison of the means. The results show significant differences between the reactors at hour 8 and hour 24. At hour 8, the phosphorus level in the anaerobic phase experimental reactor is higher than in the control unit. At hour 24, the control unit's phosphorus level is higher than the experimental reactor's phosphorus level. The means for three levels of Hour were significantly different from each other in the experimental reactor, while none of the means of Hour differed significantly in the control reactor.

In Phase III, on day 67, additional BOD in the form of sodium acetate was added to the reactors. A two-way ANOVA was conducted to determine whether the chemical addition had an effect on the release and/or removal of phosphorus. In the ANOVA, reactive soluble phosphorus was used as the dependent variable. The independent variable was a two-level variable called BOD, which represented the two concentrations of BOD. The ANOVA was run for the 8 hour and 24 hour sampling points. There was no significant difference in the phosphorus level

Table 7

ANOVA for Reactive Soluble Phosphorus
Cell Means Comparison

Phase I

	Hours		
Reactor	0	8	24
Experimental Reactor	5.29	5.50	3.87
Control Reactor	5.29	4.80	4.28

Table 8

ANOVA for Reactive Soluble Phosphorus
Cell Means Comparison

Phase II

	Hours		
Reactor	0	8	24
Experimental Reactor	5.94	7.38	6.14
Control Reactor	5.94	5.96	5.69

Table 9

ANOVA for Reactive Soluble Phosphorus
Cell Means Comparison

Phase III

	Hour		
Reactor	0	8	24
Experimental Reactor	3.43	9.32	0.63
Control Reactor	3.43	2.76	2.66

Table 10

Pairwise Comparison of the Means of Reactive Soluble Phosphorus

Phase III

Reactors		Experimental			Control		
	Hours	0	8	24	0	8	24
Experimental	0	-					
	8	**	-				
	24	*	**	-			
Control	0	NS	**	*	-		
	8	NS	**	*	NS	-	
	24	NS	**	*	NS	NS	-

** pr < 0.01

* pr < 0.05

NS - no significance

before and after the BOD addition for either the 8 ($F=0.61$, $p=0.467$) or the 24 ($F=1.25$, $p=0.31$) hour sampling points.

DISCUSSION OF STATISTICAL ANALYSIS

pH

As discussed earlier, significant phosphorus removal only occurred in Phase III when additional BOD was added to the wastewater. Figure 10 shows the mean pH values at the three sampling times for both the experimental and control reactors in Phase III. In the control reactor, the pH stayed fairly constant. In the experimental reactor, the pH dropped when the unit was under anaerobic conditions and the pH returned to near its orginal level after aeration. In the anaerobic stage, the carbon dioxide products were high because of microbiological activity. This may have resulted in the pH after 8 hours being lower than the influent pH. Also, the pH may have been reduced due to the formation of acids by anaerobic bacteria. As the reactor was aerated, the carbon dioxide was stripped and the pH increased (Jenkins and Menar, 1969). The pH dropped approximately 0.5 pH units during the anaerobic peroid.

The pH did change, when phosphorus removal occurred, as anticipated by Jenkins and Menar (1969) but the overall change in pH was not statistically significant in either the control or experimental reactor. Some of the phosphorus

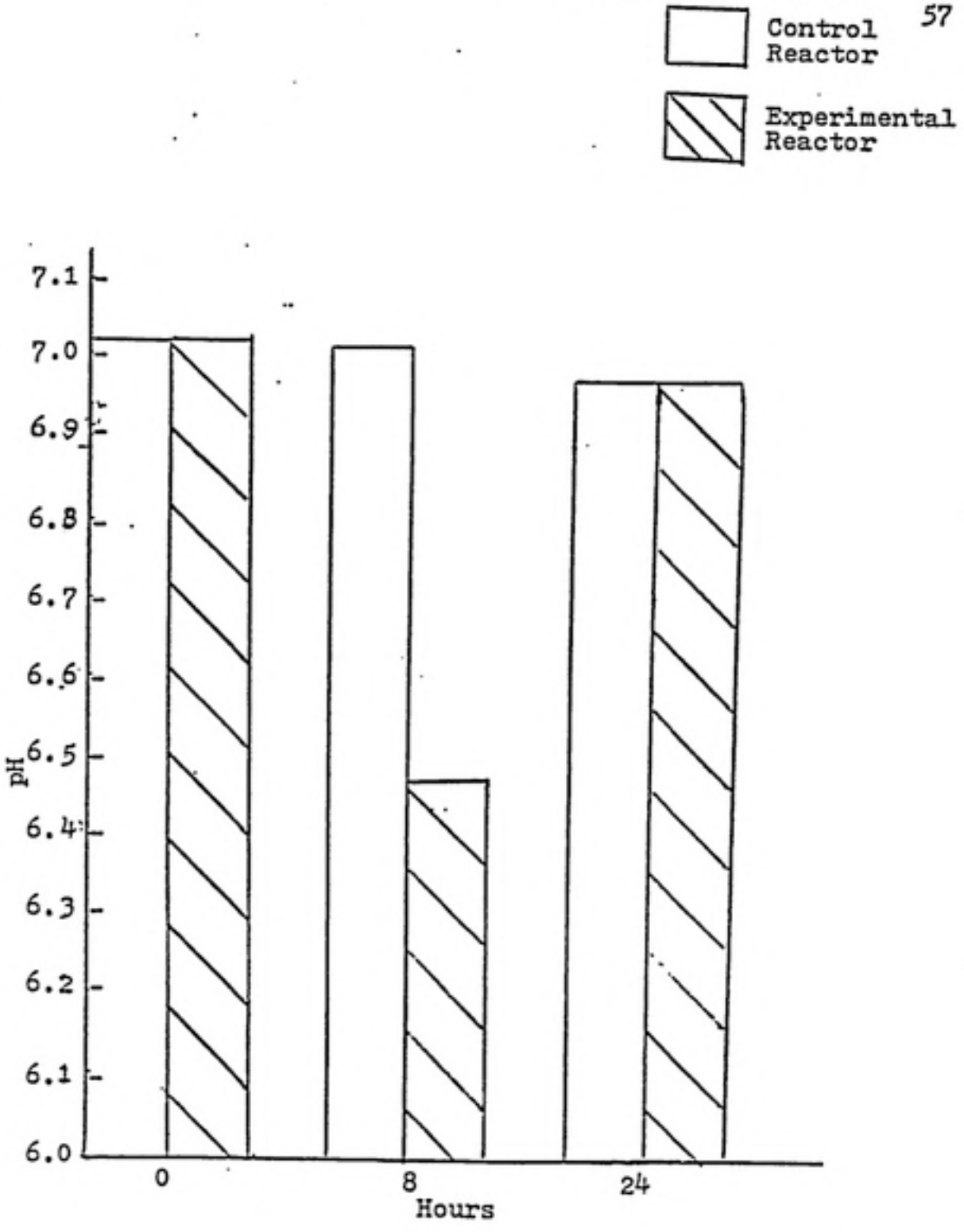


Figure 10

Mean pH Hourly Variation - Phase III

release could be attributed to the drop in pH causing calcium phosphate precipitate to become soluble.

Phosphorus

Figures 11, 12 and 13 are graphs of the phosphorus concentrations versus days in each of the three phases. The influent phosphorus concentration is shown as well as the effluent phosphorus concentration for both the control and experimental reactors. There were some days where a low influent phosphorus concentration (less than 2.0 mg/l) was measured. This low influent level of phosphorus was caused by the Water Treatment Plant's sludge, which contained alum, being present in the Mason Farm Plant's influent wastewater (Gottschalk, 1985). A substantial portion of the influent phosphorus in the wastewater was removed by chemical precipitation due to the alum.

As discussed earlier, phosphorus removal is generally preceeded by a phosphorus release. Figures 14, 15, and 16 show the mean phosphorus concentration at the three daily sampling points. As shown in these figures, only in Phase III, when additional BOD was added to the wastewater, did significant phosphorus release and removal occur (See Table 11). An acclimation period may have been necessary but the organic content of the wastewater was the obvious limiting factor. Also, the

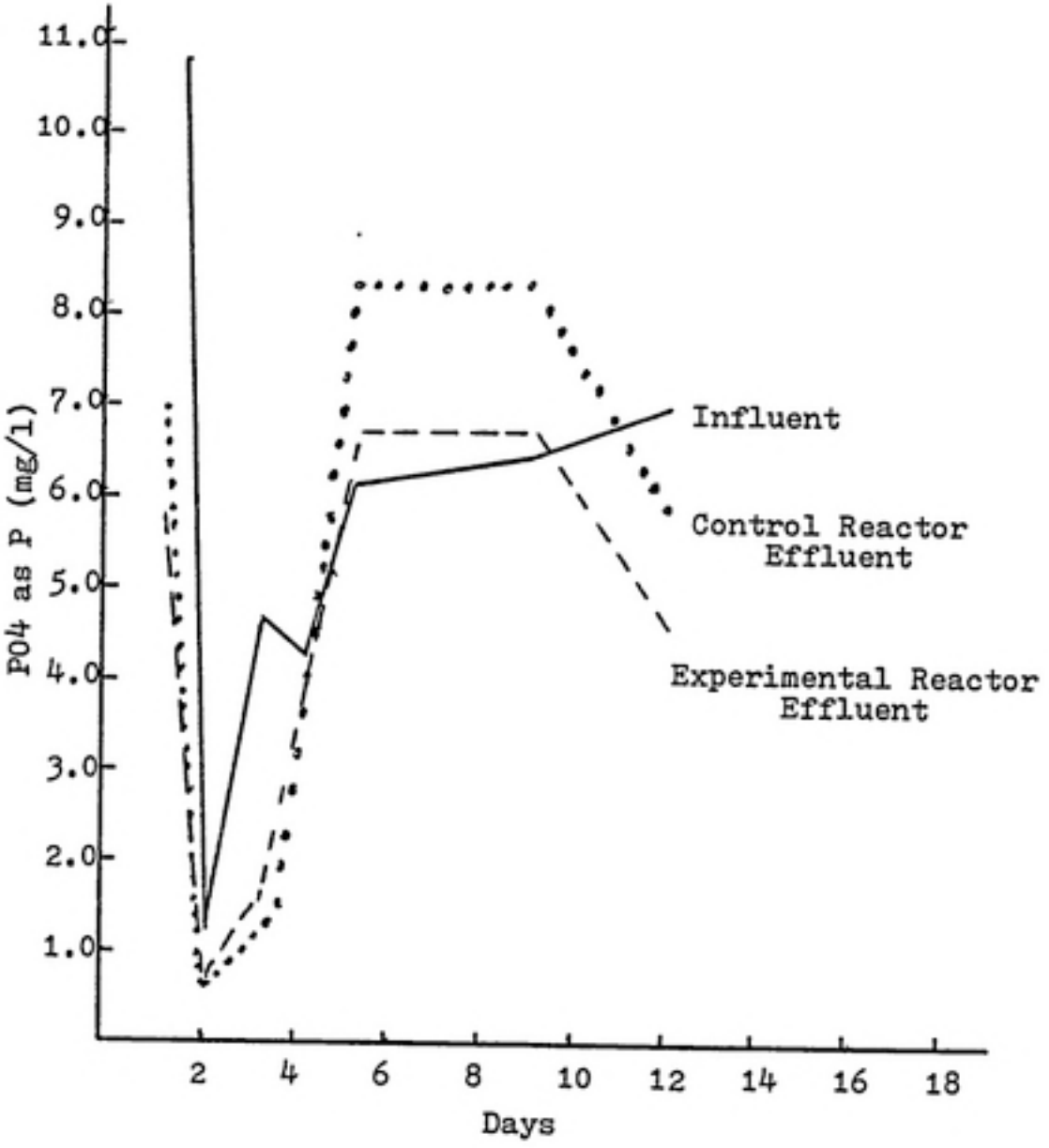


Figure 11

Phase I Results

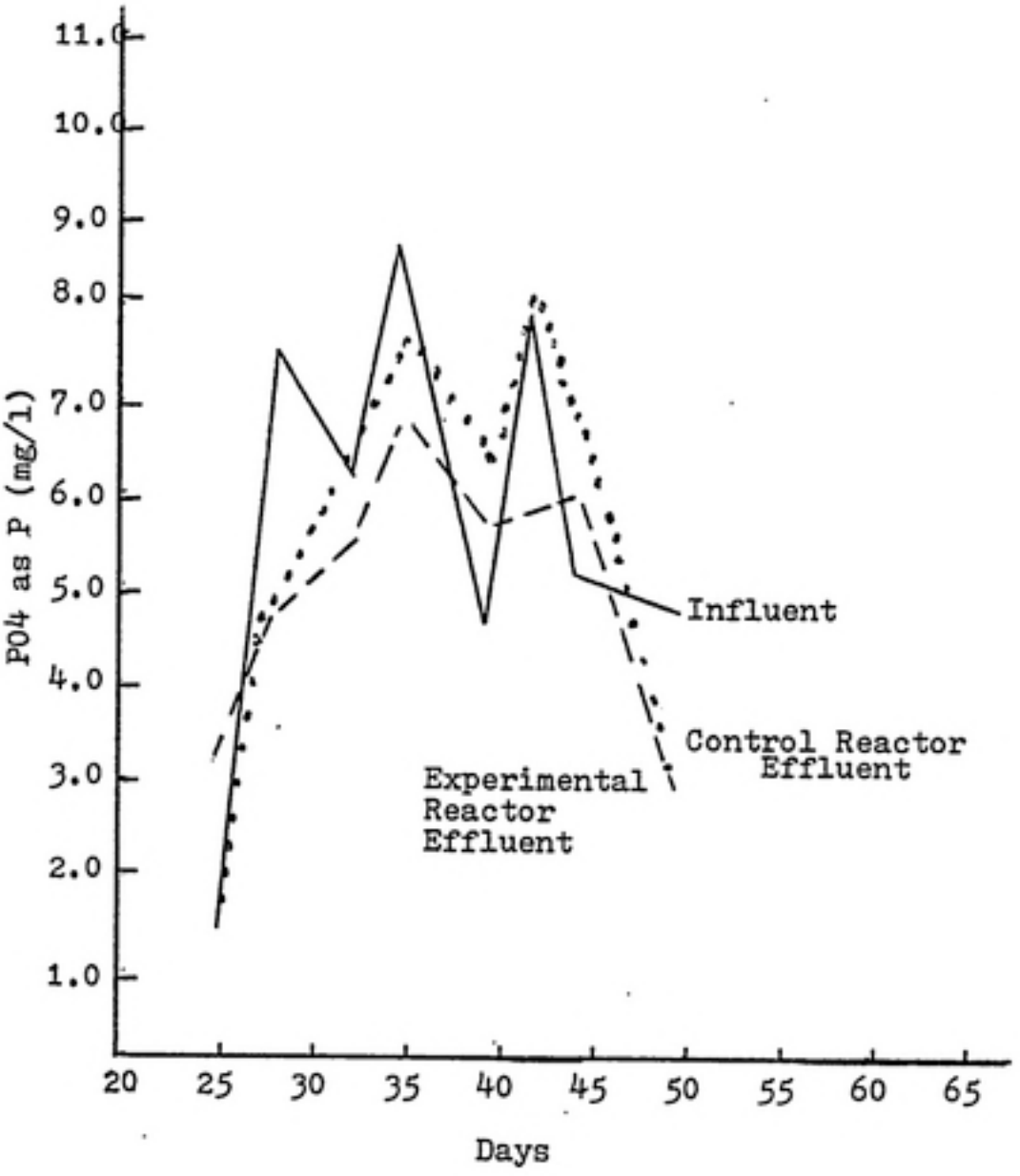


Figure 12

Phase II Results

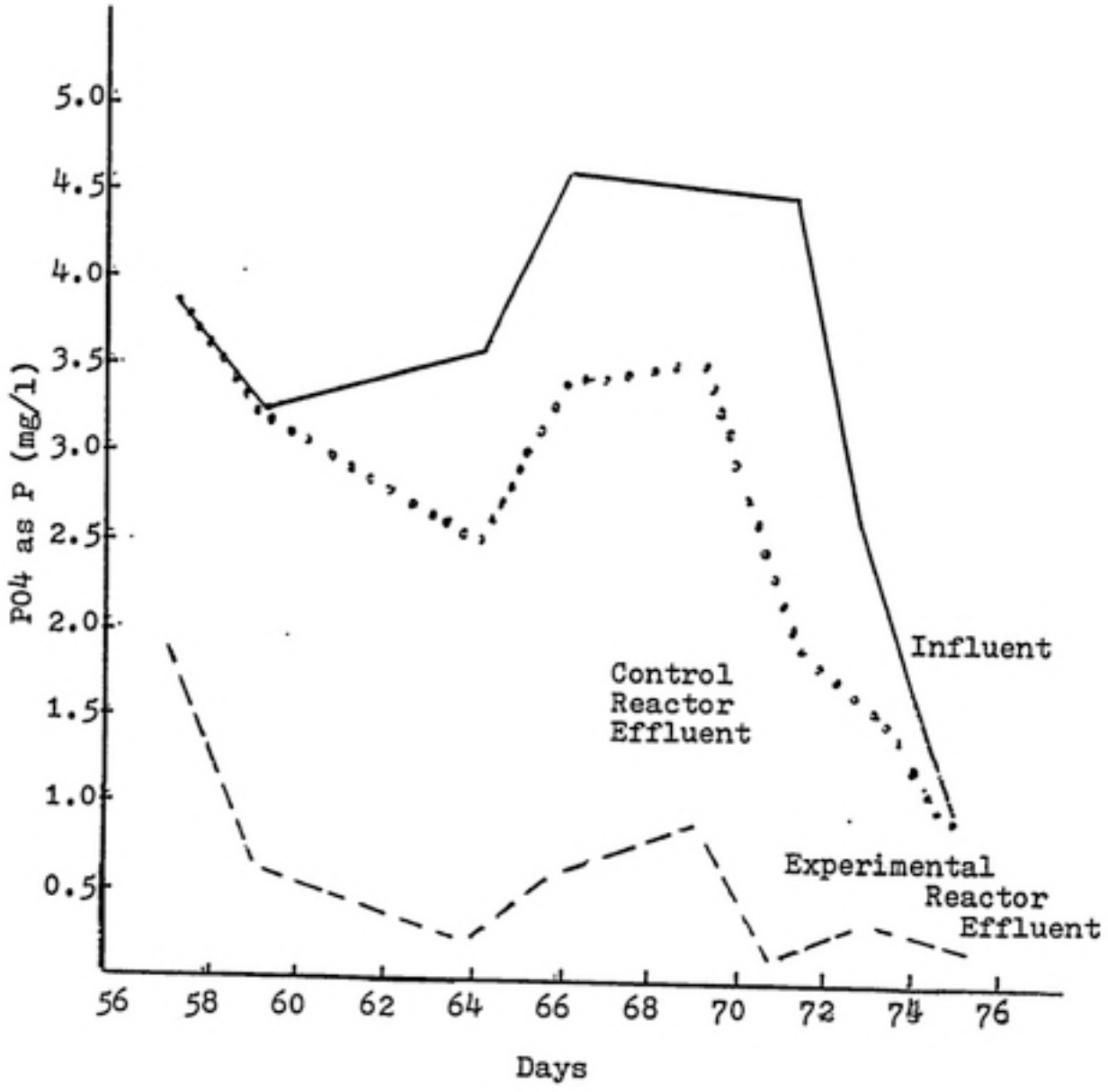


Figure 13

Phase III Results

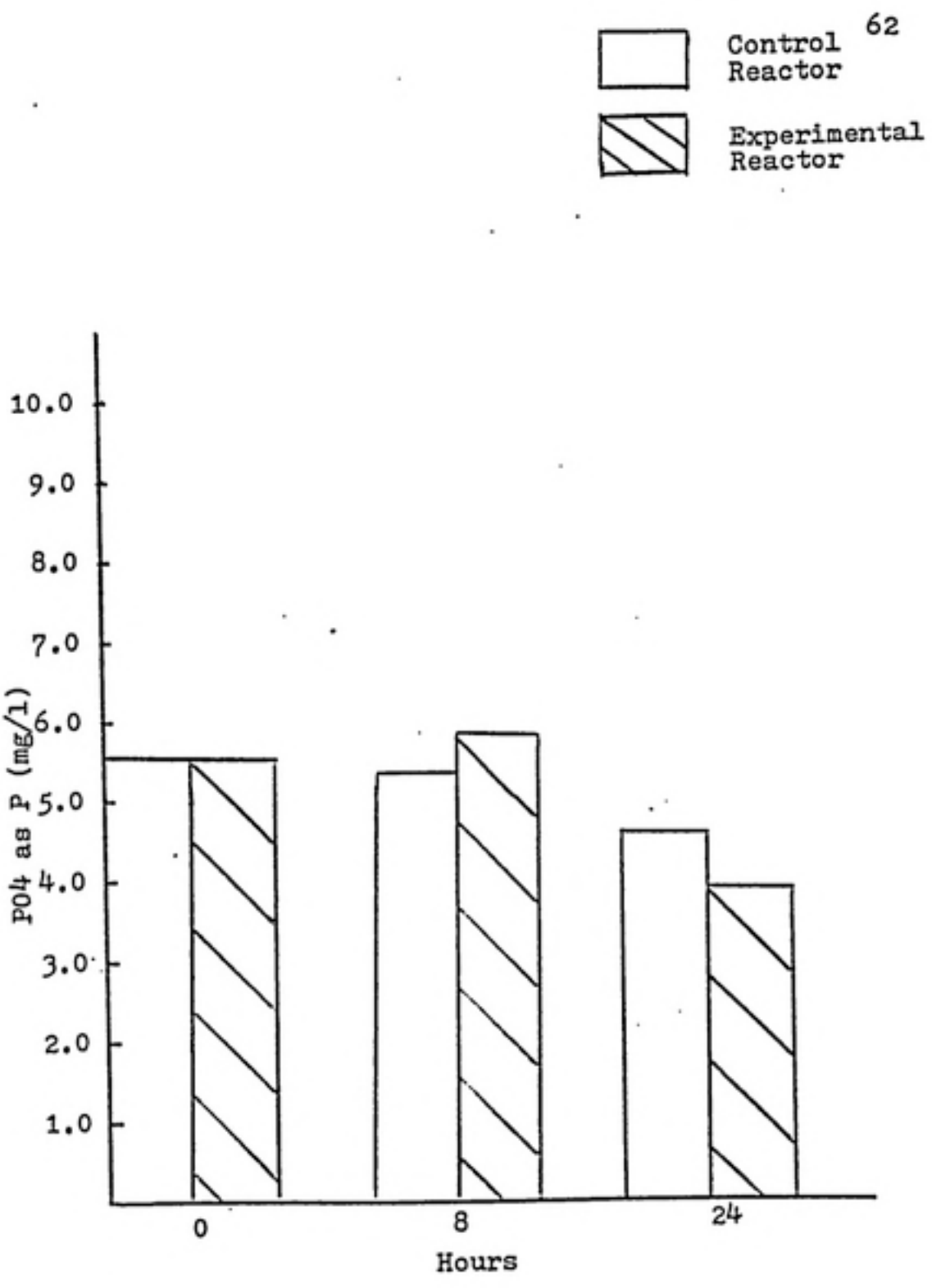


Figure 14

Mean Reactive Soluble Phosphorus Concentration
Phase I

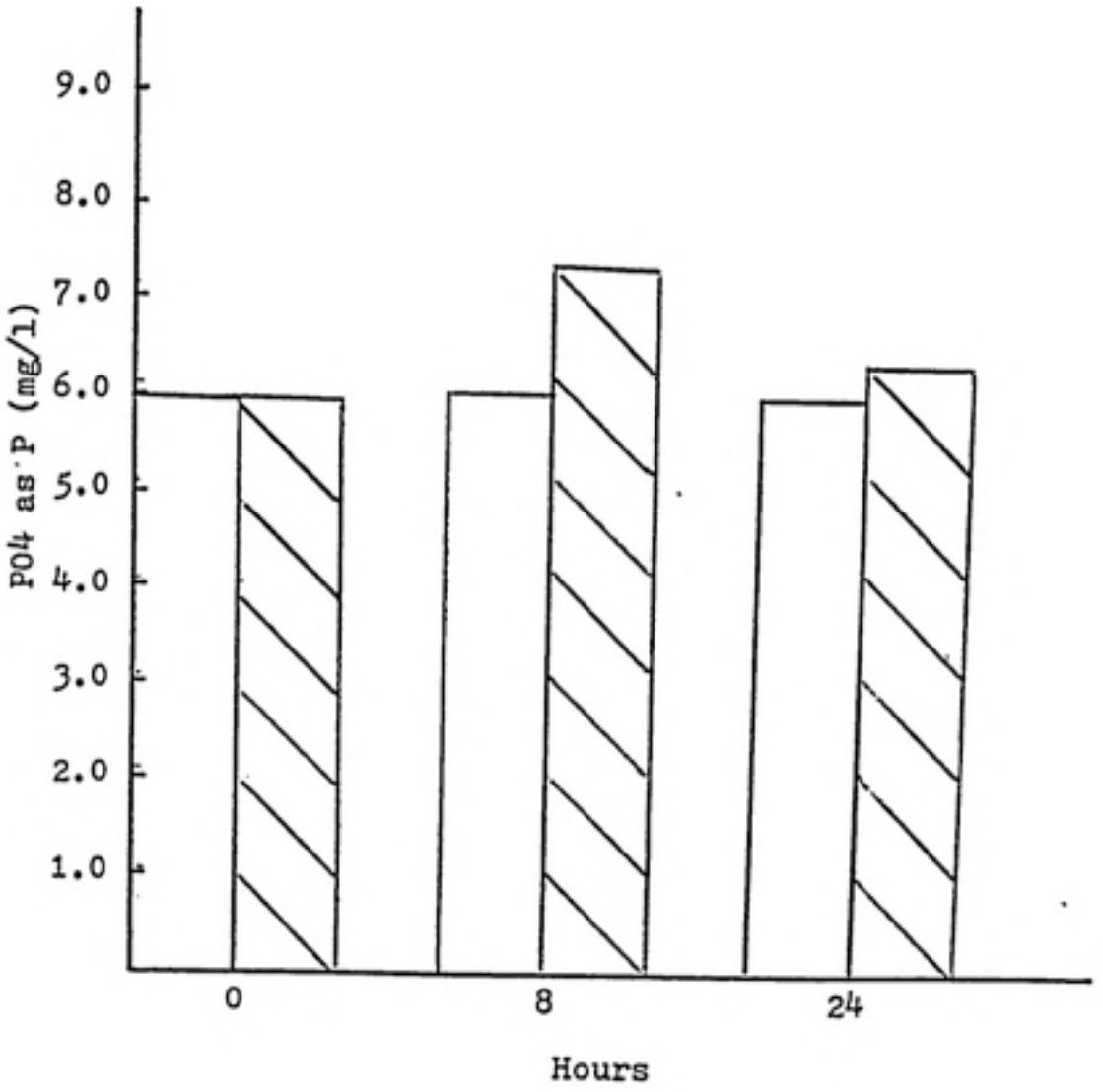


Figure 15

Mean Reactive Soluble Phosphorus Concentration
Phase II

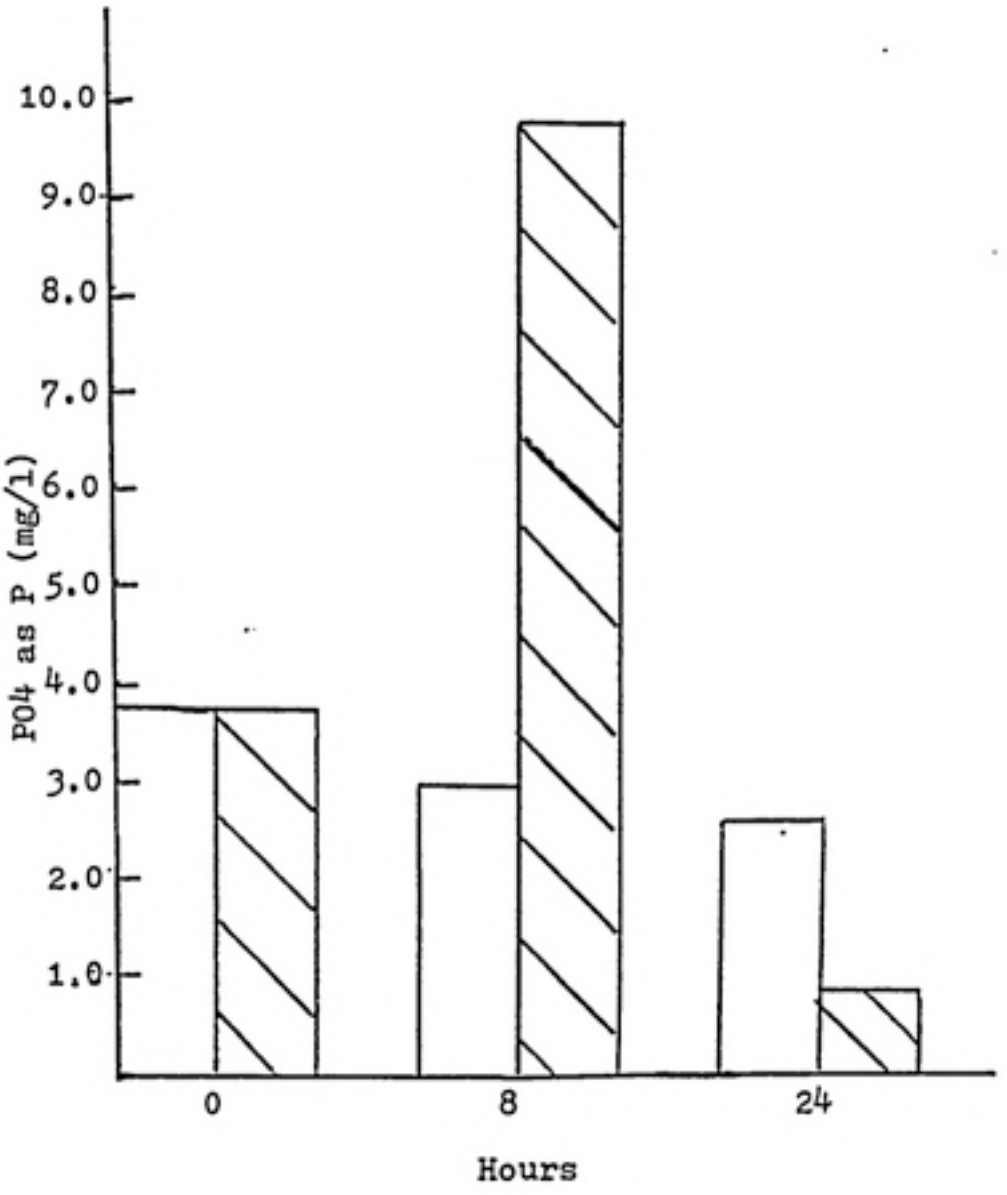


Figure 16

Mean Reactive Soluble Phosphorus Concentration
Phase III

Table 11

Final Results

	Reactors	Phosphorus Conc. (mg/l) Influent	Effluent	% Removal
Phase I	Experimental	5.29	3.87	27
	Control	5.29	4.28	19
Phase II	Experimental	5.94	5.15	13
	Control	5.94	5.69	5
Phase III	Experimental	3.43	0.63	82
	Control	3.43	2.66	23

phosphorus removing organisms appear to have a minimum level of required BOD at which BPR will occur. This was shown when the BOD added after significant phosphorus removal had begun, day 67-75, did not affect the level of release or removal of phosphorus.

Phosphorus removal did not occur until phosphorus was released in the anaerobic stage. The release of phosphorus appears to be an important step in the phosphorus removal process.

CONCLUSIONS

In conclusion, the Mason Farm Plant's trial run using BPR did not succeed because:

1) anaerobic conditions of sufficient duration were never reached
2) the BOD concentration was too low to produce good phosphorus removal
3) only a portion of the return activated sludge was treated anaerobically

In conclusion, the results of the batch-type BPR experiment suggested;

1) the phosphorus removing organisms may have a minimum requirement for organic carbon
2) the release of phosphorus is an important step in the removal mechanism
3) a BOD of greater than 200 mg/l is necessary for good phosphorus removal.

FUTURE RESEARCH

The experiment conducted was preliminary and limited basically by being a batch-type experiment. A batch reactor with grab-sampled influent wastewater is subject to shock loads of undetected chemicals in the wastewater. Conditions present in a continuous flow such as an activated sludge operation cannot be simulated exactly in a batch study. Therefore, the follow-up studies should be conducted in a continuous flow pilot reactor, preferably, of more than 10 liters capacity to prevent shock loads. A continuous flow unit with a larger capacity could handle shock loads easier than a small batch-type unit.

In this experiment, BPR occurred when BOD was added to the reactors in the form of sodium acetate and glucose. Future research should investigate if other forms of BOD would produce the same effect or if the glucose and sodium acetate are necessary for significant phosphorus removal. Also, research to determine whether any additional BOD in any form is necessary once the phosphorus removal starts is needed.

Future research should also include studies on how

BPR is affected by; 1) changes in temperature, 2) changes in pH, 3) variations in influent phosphorus levels, and 4) variations in the anaerobic and aerobic detention times.

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Appendix A

Mason Farm Plant's BPR Results

October 1983

Days	Activated Sludge Influent BOD (mg/l)	Anaerobic Zone Avg. Dissolved Oxygen (mg/l)	Avg. Nitrates (mg/l)	Phosphorus Conc. Plant Influent (mg/l)	Plant Effluent (mg/l)
1					
2	79				
3	73				
4	69				
5	69	4.6			
6	72	5.2			
7		4.4			
8		3.3			
9	38	3.5			
10	64	1.7		9.6	6.9
11	67	1.6			
12	77			7.0	4.2
13	72	0.1		7.2	5.5
14		1.7			
15		1.1			
16	51	1.3		9.2	7.5
17	72	3.9		7.4	4.2
18	77	0.9			
19	69			7.1	5.3
20	30				
21		0.0			
22					
23	46				
24		0.4			
25	73	0.0		6.3	4.5
26	74		3.2		
27	85	0.7	1.2		
28		0.3			
29		0.1			
30	79	0.1		5.5	5.1
31	158	0.0			
Avg.	71	1.7	2.2	7.4	4.8

November 1983

Days	Activated Sludge Influent BOD (mg/l)	Anaerobic Zone Avg. Dissolved Oxygen (mg/l)	Anaerobic Zone Avg. Nitrates (mg/l)	Phosphorus Conc. Plant Influent (mg/l)	Phosphorus Conc. Plant Effluent (mg/l)
1	158	0.3	1.2	6.2	3.1
2	176	0.3	0.8	7.1	5.7
3	154	0.3	1.1		
4		0.1	1.1		
5		3.1			
6	166	0.2		6.9	3.7
7	164				
8	164	0.1	1.4	8.3	7.2
9	72	0.1	0.5	7.0	4.1
10	95	0.0			
11		0.0			
12		0.1			
13	61	0.4			
14	71	0.1	1.5	8.1	5.8
15	44	0.0	0.9	7.3	5.5
16	59	0.3	0.5	7.7	4.7
17	28	0.4	0.3		
18		0.1	0.2		
19		0.1	0.7		
20	52	0.5	0.2	5.8	2.8
21	62	0.3	1.5	7.3	3.2
22	64	0.4	1.8		
23		0.4	0.1		
24		0.4	0.1		
25		0.0	3.9		
26		0.0			
27	47	0.0		3.5	1.9
28	62	0.0	4.2	6.9	2.2
29	69		3.2	6.7	4.8
30	75		1.5		
Avg.	129	0.3	1.3	6.8	4.2

December 1983

Days	Activated Sludge Influent BOD (mg/l)	Anaerobic Zone Avg. Dissolved Oxygen (mg/l)	Avg. Nitrates (mg/l)	Phosphorus Conc. Plant Influent (mg/l)	Plant Effluent (mg/l)
1	76	0.0	1.5		
2		0.0	0.9		
3		0.0	4.0		
4	79	0.0	3.9		
5	66	2.5	1.0		
6	36	0.2	0.8		
7	72	0.7	0.3		
8	69	0.4	0.3	4.8	2.5
9		0.8	1.6		
10		0.8			
11	77	0.7	0.0	10.4	3.7
12	156	0.8	0.2	7.5	4.3
13	130	1.1	0.5	5.3	3.7
14	55	1.7	0.0		
15	54	0.5	0.9		
16		0.6			
17		0.5	1.4		
18	67	0.2	1.2	8.3	2.9
19	59	0.3	1.5	8.5	4.1
20	68	0.4	0.2	9.2	4.5
21		0.0	0.5		
22		0.2	0.9		
23		0.1	0.8		
24		0.1	0.2		
25		0.7	0.3		
26	55	1.0	0.1		
27	62	1.0	0.0		
28	53	0.5	0.2	7.0	2.5
29	46	0.3	0.1		
30		0.9	0.2		
Avg.	71	0.6	0.7	7.6	3.5

January 1984

Days	Activated Sludge Influent BOD (mg/l)	Anaerobic Zone Avg. Dissolved Oxygen (mg/l)	Anaerobic Zone Avg. Nitrates (mg/l)	Phosphorus Conc. Plant Influent (mg/l)	Phosphorus Conc. Plant Effluent (mg/l)
1					
2	92	0.4		8.3	4.2
3	50	0.4	0.4	8.4	4.8
4	63	0.1	0.7	6.9	3.7
5	50	0.6	0.8		
6		0.3	1.0		
7		0.3	1.0		
8	120	0.2	0.5	7.8	5.0
9	136	0.7	0.1	9.8	5.5
10		1.0	0.0	8.8	4.3
11	44	1.2	0.1		
12		1.6	0.0		
13		1.4	0.0		
14		2.0	0.0		
15	79	0.9	0.3		
16	99	0.7	0.1	8.5	4.6
17	84	0.3	0.0	7.0	4.6
18	81	0.3	0.0	9.2	5.0
19	101		0.0		
20			0.1		
21		0.6	0.4		
22	126	0.7	0.5	7.8	4.6
23	86	0.1	0.9	7.4	4.6
24	79	0.0	0.3	6.3	2.6
25	99	0.0	0.2		
26	73	0.1	0.1		
27		0.1	0.2		
28		0.3			
29	84	0.3		6.3	2.3
30	91	0.6	0.1	6.3	1.6
31	94	0.6	0.0		
Avg.	87	0.6	0.3	7.1	3.9

Febuary 1984

Days	Activated Sludge Influent BOD (mg/l)	Anaerobic Zone Avg. Dissolved Oxygen (mg/l)	Avg. Nitrates (mg/l)	Phosphorus Conc. Plant Influent (mg/l)	Plant Effluent (mg/l)
1	81	0.2	1.1	5.3	1.6
2	130	0.4	1.8		
3		1.4	1.6		
4		1.2	1.9		
5	100	0.7	1.6	6.5	4.5
6	150	0.1		6.7	3.2
7	150	1.2		8.4	2.1
8	130	0.3	1.0		
9	93	0.0	2.0		
10		0.1	1.9		
11		0.1	1.4		
12	69	0.1	1.2		
13	235	0.3	4.0		
14	60	0.2	3.5	6.3	4.3
15	101	0.1	1.9		
16	70	0.1	0.5	6.1	3.3
17		0.3	5.5		
18		1.6			
19	73	2.9			
20		2.8			
21	60	2.5			
22	80	2.7			
23	77	3.0			
24		4.2			
25		2.1			
26	211	1.8			
27	243				
28	280	2.7			
29	139	1.8			
Avg.	127	1.3	2.1	6.5	3.1

March 1984

Days	Activated Sludge Influent BOD (mg/l)	Anaerobic Zone Avg. Dissolved Oxygen (mg/l)	Avg. Nitrates (mg/l)	Phosphorus Conc. Plant Influent (mg/l)	Plant Effluent (mg/l)
1	163	4.2			
2		2.9			
3		2.6			
4	146	2.7			
5	204	2.4			
6	95	2.4			
7	63	6.2			
8	108	3.0			
9		3.7			
10		4.1			
11	147	3.8			
12	325	2.8			
13	216	0.8			
14	207	2.4			
15	254	2.8			
16		0.9			
17		1.9			
18	207	2.6			
19	132	0.5			
20	87	1.7			
21	151	0.5			
22	85	1.4			
23		1.6			
24		1.8			
25	112	1.2			
26	63	1.5			
27	127	0.7			
28	105	0.4			
29	70	1.7			
30		1.4			
31		1.4			
Avg.	146	2.2			

April 1984

Days	Activated Sludge Influent BOD (mg/l)	Anaerobic Zone: Avg. Dissolved Oxygen (mg/l)	Avg. Nitrates (mg/l)	Phosphorus Conc.: Plant Influent (mg/l)	Plant Effluent (mg/l)
1	100	1.2			
2	150	0.3			
3	60	0.5			
4	100	0.3			
5	131	0.6			
6		0.7			
7		0.6			
8	129	0.5			
9	108	0.8			
10	190	0.1			
11	43	0.8		10.0	4.0
12	60	0.3			
13		0.2			
14		0.3			
15	63	0.3			
16	63	0.5			
17	50	0.9		7.5	5.0
18	63	0.4			
19	162	0.2			
20		0.5			
21		1.6			
22		2.3			
23	58	2.0			
24	103	2.0		9.0	3.4
25	168	1.8			
26	148	0.9			
27		0.9			
28		0.9			
29	70	1.2			
30	90				
Avg.	100	0.8		9.0	4.1

May 1984

Days	Activated Sludge Influent BOD (mg/l)	Anaerobic Zone Avg. Dissolved Oxygen (mg/l)	Avg. Nitrates (mg/l)	Phosphorus Conc. Plant Influent (mg/l)	Plant Effluent (mg/l)
1	98	1.6			
2	70	0.3		8.8	5.8
3	94	0.5			
4		0.4			
5		0.5			
6	38	0.8			
7	53	0.5			
8	124	0.4			
9	34	1.1			
10	127	1.2		10.3	4.0
11		2.5			
12		2.5			
13	38	2.3			
14	138	0.5			
15	36	3.0			
16	42	3.2		7.0	5.6
17	30	4.0			
18		3.3			
19		3.3			
20	199	1.5			
21	99	3.0		10.0	6.2
22	87	2.3			
23	92	2.4			
24	70	3.1			
25		2.9			
26		2.9			
27		2.9			
28	48	2.9			
29	64	0.4			
30	39	6.1		6.0	2.8
31	58	0.4			
Avg.	76	2.0		8.6	4.6

June 1984

Days	Activated Sludge Influent BOD (mg/l)	Anaerobic Zone Avg. Dissolved Oxygen (mg/l)	Avg. Nitrates (mg/l)	Phosphorus Conc. Plant Influent (mg/l)	Plant Effluent (mg/l)
1		4.3			
2		5.4			
3	49	4.3			
4	52	0.7		7.3	4.5
5	62	1.8			
6	82	1.5			
7	46				
8					
9		3.4			
10	56	4.2		7.5	5.2
11	43	0.9		7.5	4.5
12	34	2.7		7.6	5.2
13	43	2.3		7.9	6.5
14	69	2.4		4.4	4.7
15		2.4			
16		2.5			
17	53	3.3			
18	49	1.8		7.9	3.8
19	27	1.3			
20	79	2.0			
21	33	3.2			
22		3.2			
23					
24	48	2.9			
25	48	3.9			
26	54	4.0			
27	52	2.8			
28	25	5.0			
29		5.1			
30					
Avg.	50	2.9		7.3	4.8

July 1984

Days	Activated Sludge Influent BOD (mg/l)	Anaerobic Zone: Avg. Dissolved Oxygen (mg/l)	Anaerobic Zone: Avg. Nitrates (mg/l)	Phosphorus Conc.: Plant Influent (mg/l)	Phosphorus Conc.: Plant Effluent (mg/l)
1	76	5.5			
2	53	5.0		8.4	4.2
3					
4	26	5.7			
5	72				
6		5.2			
7		6.2			
8	61	4.3			
9	91	3.9		8.4	3.8
10	44	4.0			
11	77	2.8			
12	103	2.4			
13		2.7			
14		3.2			
15	102	1.4			
16	74	1.6		9.3	4.9
17	51	0.9			
18	39	2.8			
19	47	3.1			
20		0.4			
21		3.6			
22	91	3.0			
23	24	0.4			
24	92	3.1		7.9	6.0
25	82	2.9			
26	38	4.4			
27		4.1			
28		4.5			
29	36	5.4			
30	48	5.4		5.5	3.0
31	77	4.9			
Avg.	64	3.5		7.9	4.4

August 1984

Day	Activated Sludge Influent BOD (mg/l)	Anaerobic Zone Avg. Dissolved Oxygen (mg/l)	Avg. Nitrates (mg/l)	Phosphorus Conc. Plant Influent (mg/l)	Plant Effluent (mg/l)
1	46	4.6			
2	25	4.8			
3		3.3			
4		3.8			
5	39	3.3			
6	54	3.2			
7	46	3.2		5.1	3.0
8	36	3.8			
9	36	2.2			
10		2.2			
11		3.4			
12	81	3.3			
13	49	2.9			
14	45	2.3		7.0	6.3
15	47	3.1			
16	46	3.1			
17		3.9			
18		2.9			
19	58	3.5			
20	54	2.2		9.3	4.9
21	46	1.8			
22	79	1.9			
23	71	1.3			
24		1.3			
25		2.1			
26	55	2.1			
27	64	0.8		8.8	5.3
28	23	0.8			
29	54	0.8			
30	59	0.7			
31		0.7			
Avg.	51	2.6		7.6	4.8

Appendix B

Table B-1

Raw Data Results

Experimental Reactor

Hours	0				8					24				
	Total P (mg/l)		Reac. P (mg/l)		D. O. (mg/l)	Total P (mg/l)		Reac. P (mg/l)		D. O. (mg/l)	Total P (mg/l)		Reac. P (mg/l)	
Days	U. F.	Fil.	U. F.	Fil.		U. F.	Fil.	U. F.	Fil.		U. F.	Fil.	U. F.	Fil.
1	9.0	7.0	10.0	10.7	3.5	11.9	11.3	11.2	10.9				6.4	5.8
2			6.8	1.3	3.8			2.9	1.3				6.9	6.7
3			8.0	4.6	3.1									
4	3.1	1.7	4.8	4.3	3.8	3.7	1.8	2.5	1.8		3.4	4.6	3.3	1.3
5			7.9	5.2				3.8	5.9				5.7	5.5
9	3.9	6.9	6.2	6.6		8.2	7.3	9.6	7.9		6.7	6.1	7.2	6.7
12	10.3	7.9	7.6	7.3		6.6	5.7	5.1	5.4		5.0	5.5	5.6	6.8
24	2.4	2.1	2.1	1.4		5.2	4.2	3.9	3.9		2.5	3.5	3.4	3.5
26	6.9	7.9	8.2	7.5		8.7	6.6	9.0	6.6		5.4	5.0	6.9	6.7
31					6.1					8.4				
32					6.1					8.3				
33					6.1					7.5				
38					6.1					7.8				
40					6.9					7.0				

D. O. - Dissolved Oxygen

Total P - Total Phosphorus

Reac. P - Reactive Phosphorus

Hours

0 - Influent

8 - Anaerobic/Aerobic Mixed Liquor

24 - Effluent

Table B-1 cont.

Raw Data Results

Control Reactor

Hours	0				8					24				
	Total P (ag/l)		Reac. P (ag/l)		D. O. (ag/l)	Total P (ag/l)		Reac. P (ag/l)		D. O. (ag/l)	Total P (ag/l)		Reac. P (ag/l)	
Days	U. F.	Fil.	U. F.	Fil.		U. F.	Fil.	U. F.	Fil.		U. F.	Fil.	U. F.	Fil.
1	9.0	7.0	14.0	10.7	8.5	9.5	8.5	7.8	7.0				9.5	6.9
2			0.8	1.3	7.4			1.7	0.7				1.1	0.7
3			0.8	4.6	7.9									
4	2.1	1.7	4.8	4.3	8.2	2.6	2.1	1.9	2.1		1.8	1.7	2.3	1.1
5			7.9	2.2				6.5	6.2				3.3	2.9
9	5.9	6.9	6.2	6.6		7.9	6.7	7.9	6.7		8.7	7.7	8.9	8.2
12	10.7	7.9	7.6	7.3		6.5	7.3	6.7	6.1		7.2	6.2	6.7	5.9
24	2.4	2.1	2.1	1.4		3.2	1.8	2.0	1.2		2.4	1.3	1.9	1.6
26	6.9	7.9	9.2	7.5		5.1	4.8	5.1	4.6		5.3	4.6	5.2	4.7
31					7.8					8.0				
32					8.0					7.5				
33					6.8					8.0				
38					7.0					7.2				
40					7.9					8.1				

D. O. - Dissolved Oxygen

Total P - Total Phosphorus

Reac. P - Reactive Phosphorus

Hours

0 - Influent

8 - Anaerobic/Aerobic Mixed Liquor

24 - Effluent