CHEMICAL AND BIOLOGICAL PHOSPHORUS REMOVAL IN THE ACTIVATED SLUDGE PROCESS

by

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A thesis submitted in fulfilment of one
half the requirements for the Degree
Master of Science in Engineering

Department of Civil Engineering,
University of Cape Town.

March, 1980

DECLARATION

I, Barry Rabinowitz hereby declare that the work contained in this thesis is my own and has not been previously submitted to another university.

Signed by candidate

March, 1980.

ACKNOWLEDGEMENTS

I wish to express my sincere thanks to the following:

Professor G.v.R.Marais, Water Resources and Public Health Engineering, University of Cape Town, under whose supervision this research investigation was conducted. His enthusiasm shown and advice given throughout the investigation is much appreciated.

The Water Research Commission, whose financial assistance made this research investigation possible.

Water Research Commission Research Officers, Dr. G.A.Ekama and Mr. A.C. van Haandel for their friendly advice and assistance.

University of Cape Town Department of Civil Engineering technical staff Mr. R.F.Beverton and Mr. P. Addington for their assistance in the construction and maintenance of the laboratory and testing equipment.

Departmental assistants Mr. Taliep Lakay, Mr. James George and Ms. Nicolette Fernandez for their cheerful assistance in the laboratory and with the drawings.

Mrs. D.F.Murcott and Mrs. L. Langman for their rapid, efficient typing of the manuscript.

Mr. Harold Cable for his even more rapid printing of the manuscript.

To my true friend, Fiona Wallace for her patience and encouragement during the investigation and for proof-reading the manuscript.

SYNOPSIS

This investigation set out to establish in what degree the phosphorus removal characteristics of the Modified Activated Sludge Process could be enhanced by the in-plant addition of iron salts. The motivation for the investigation was:

1. Due to the lack of understanding of the exact pre-requisites for inducing excess biological phosphorus removal (luxury uptake), such removal could not always be guaranteed in many activated sludge plants, even in those designed in accordance with the best available knowledge for inducing this removal mechanism.

2. There was evidence to suggest that even where excess biological phosphorus removal took place, the removal was limited by the process and the sewage characteristics. As a result, in plants where the specified phosphorus removal exceeded the possible biological removal, additional or alternative methods of removal had to be sought.

In view of these factors it was concluded that only by chemical addition to the process, could a specified effluent quality be guaranteed. A laboratory scale Modified Activated Sludge (or Phoredox) Process, similar to that proposed by McLaren and Wood (1976), but without a secondary anoxic zone was set up and the process was evaluated with and without in-plant iron salt addition. Problems were encountered in predicting the biological removal as the removal tended to differ from one sewage batch to another, making it difficult to determine accurately the efficiency of the iron salt addition.

During the course of the investigation a kinetic theory of denitrification was developed by Ekama, van Haandel and Marais (1979) by means of which reliable estimates of the nitrate removal capacity of an unaerated reactor could be made. Using this theory it became possible

to hypothesize a quantitative measure of the required state of anaerobic stress that had been put forward by Barnard (1974) as a prerequisite for excess biological phosphorus removal. Ekama *et al* (1979) hypothesized that:

1. Excess biological phosphorus removal is dependent on the establishment of a certain minimum anaerobic stress or "anaerobic potential". The anaerobic potential was defined as the difference between the nitrate removal capacity of the anaerobic reactor and the nitrate input to the reactor.

2. The attainment of this anaerobic potential is very dependent on the TKN/COD ratio of the influent, an increase in the ratio results in a decrease in the anaerobic potential for a given process configuration.

The investigation verified the above hypotheses. It was found that a minimum anaerobic potential of about 9 mg/ℓ NO_3-N was required in the anaerobic reactor to trigger a nett release of phosphorus in the reactor and induce excess biological phosphorus removal in the process. The investigation also showed that a Modified Activated Sludge Process with a total unaerated volume fraction of 40 percent all in the anaerobic and primary anoxic zones (i.e. with no secondary anoxic zone) operating at 20°C and treating raw sewage with a TKN/COD ratio of 0,10, had an anaerobic potential of 9,0 mg/ℓ NO_3-N and was on the point of inducing or not inducing excess biological phosphorus removal. The anaerobic potential of the anaerobic reactor could be increased only marginally by decreasing the underflow recycle; any large adjustment in the recycle jeopardized the performance of the settling tank. From this behaviour it was concluded that the Modified Activated Sludge Process, chiefly because of its operational inflexibility, is not the optimal process configuration for inducing excess biological phosphorus removal for wastewater flows having TKN/COD ratios > 0,09.

A new process configuration called the University of Cape Town (U.C.T.) Process was proposed which allowed far greater flexibility in attaining the anaerobic potential for excess biological phosphorus removal by relatively simple adjustments of the internal recycles. Consequently the desired anaerobic potential could be provided, for flows having a wide range of TKN/COD ratios with no adjustment necessary to the underflow recycle.

The research program was then modified to include an investigation into the U.C.T. Process with and without in-plant iron salt addition. The expected behaviour of this process was verified experimentally. The process was found to induce excess biological phosphorus removal in flows with high TKN/COD ratios up to 0,11 [The kinetic model of Ekama *et al* (1979) in fact predicts that the U.C.T. Process can provide an anaerobic potential of 9 mg/ℓ NO_3-N in flows having a TKN/COD ratio of up to 0,16 at 20°C but such high ratios have as yet, not be verified experimentally].

With regard to excess biological phosphorus removal in general, where the conditions for excess biological removal are satisfied, the findings of previous research investigations (Martin and Marais (1975), and Hoffmann and Marais (1977)) were supported, i.e. that the total biological phosphorus removal is limited and is a function of the influent COD, the sewage type (raw or settled) and the sludge age as follows:

$$\Delta P(mg/\ell) = \frac{Y(S_{bi} - S)}{1 + bR_s}\left[\alpha + f_p * f * bR_s\right] + f_p * f_{up}\frac{(S_{bi} - S)}{(1 - 1{,}48\, f_{up} - f_{us})}$$

where

ΔP = phosphorus as P removed from the influent and incorporated into the sludge wasted/day i.e. $(P_{inf} - P_{eff})$ (mg/ℓ)

Y = growth yield coefficient (mg VASS/mg COD) = 0,45

S_{bi} = biodegradable influent COD (mg/ℓ)

S = unmetabolized biodegradable COD in the effluent usually assumed to be zero

b = specific endogenous respiration rate (mg VASS/mg VASS/d)

α = fraction of P in the active sludge mass 0,025 - 0,16 mg P/mg X_a

R_s = sludge age (days)

f_p = fraction of phosphorus in the endogenous and inert sludge mass mg P/mg X_e or X_i = 0,025

f = fraction remaining as endogenous residue = 0,2

f_{up} = unbiodegradable particulate sewage fraction
= 0,09 - 0,13 for raw sewage
= 0 for settled sewage

f_{us} = unbiodegradable soluble sewage fraction
= 0,05 - 0,07 for raw sewage
= 0,06 - 0,12 for settled sewage

The amount by which the value of α exceeds f_p (= 0,025) defines the degree of excess biological phosphorus removal. For the U.C.T.Process treating raw sewage this value was found to be 0,16.

Having established a reliable method for inducing excess biological phosphorus removal, it was possible to separate out the effects of in-plant iron salt addition in a process where excess biological phosphorus removal was taking place.

With regard to chemical phosphorus removal, it was found that using in-plant iron salt addition that the chemical removal is additional to excess biological removal, i.e. the two mechanisms operate independently of each other. The chemical removal was approximately stoichiometric - 1,8 mg of iron as Fe removed 1 mg P per litre of influent, provided that:

1. the pH of the process was maintained at above 7,2. At process pH values below 7,2 the chemical removal was less efficient, and the effluent was turbid and yellow-green in colour,
2. the effluent phosphorus concentration did not fall below about 1,5 mg/ℓ as P. For effluent concentrations below 1,5 mg/ℓ the removal efficiency decreased and greater than stoichiometric dosages were required.

The effect of cyclic loading on phosphorus removal was investigated as follows:

The dosing chemicals were fed directly into the process at a constant rate while the plant was operated under both steady state and cyclic loading conditions. The results showed that there was no nett difference in the mean removal efficiency. This demonstrated the persistence effect of in-plant iron salt addition, i.e. the propensity of the process to continue to remove phosphorus under shock loading or for some time after the chemical dosing has ceased. A probable explanation for this is that the chemical removal takes place by two simultaneous reactions: A rapid direct iron phosphate precipitation and a competing side reaction of phosphate and hydroxide in the accumulated ferri-hydroxide precipitate.

During the investigation the point of iron addition was varied between the different reactors of the process. This resulted in no significant change in the system of phosphorus removal. It was concluded therefore that the dosing chemicalc can be fed into the process at any point where the mixing is good.

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irrigation purposes. In 1932 its ecological state was described as oligotrophic by Hutchinson, Pickford and Schuurman. With the increase in population in the drainage area, the condition of the dam deteriorated to such an extent that by 1958 Cholnoky described the dam as an "oxidation pond". By 1970 approximately 840 000 people were living in the catchment area, and all the purified municipal and industrial effluents from this population drained into the dam. Algal growth became excessive and it was found necessary to apply special treatment procedures in order to produce potable water for the town of Brits. Subsequently, the highly eutrophic state of the dam caused an explosive growth of water hyacinth (*Eichlornia crassipes*). To rid the dam of this growth, treatment with a toxic weed-killer became necessary.

According to Steyn *et al* (1975), nitrogen is the primary growth limiting nutrient in the Hartebeespoort Dam. They recommended, however, that in order to control the eutrophic condition, the phosphorus discharge should be curtailed to make this element the limiting one. The reason for this proposal can be found in the response of some organisms to the absence of biologically assimilable nitrogen. In a particular ecosystem the mass of phosphorus available is governed solely by the mass entering the system. In contrast, nitrogen in the form of ammonia can be generated from dissolved atmospheric nitrogen, by certain micro-organisms, e.g. blue-green algae. In this way, it becomes available for metabolism to other algae and plant life. Limitation of the sources of phosphorus to a body of water, therefore takes on a greater importance than the limitation of nitrogen.

Phosphorus limitation can be achieved in an optimal manner only if the sources of supply of the nutrient can be identified and evaluated as to their importance. The sources of phosphorus are two-fold: diffused and point sources.

1. Diffused sources: These are sources of phosphorus from urban runoff and surface runoff from agricultural and natural lands entering at many points along the length of the receiving stream. Agricultural runoff can be a source of heavy pollution due to the use of fertilizers.

2. Point sources: These are sources where significant quantities of phosphorus enter at specific locations along the lengths of the rivers. Wastewater discharges from cities, feedlots and isolated factories are examples of this type of pollution.

The relative magnitude of the two sources will depend on the degree of urbanisation and the intensity and type of farming activity in the drainage basin of the stream. Every drainage basin is unique in this regard. In the highly urbanised Johannesburg complex, Bolitho (1976) estimates that wastewater accounts for 90% of the phosphorus mass in the streams draining the area; in this instance, therefore, the control of the point sources of phosphorus is the most important.

Control of phosphorus discharge to rivers from point sources is generally easier than from diffused sources as the discharges are concentrated at a limited number of locations. Generally, diffused sources are difficult to control and in South Africa there is as yet no region where diffused sources of phosphorus have been identified as being critical. Consequently, attention has been focussed almost completely on the control of phosphorus discharge from point sources.

The most convenient point for the removal of phosphorus from point sources is at the wastewater treatment works. The method of removal available, in turn, is largely dependent on the type of works. In South Africa, the two main types of works are the trickling filter and the activated sludge process; a brief review of the phosphorus removal technologies applicable to these is instructive.

Trickling Filter

In the trickling filter process, a relatively small concentration of phosphorus is removed biologically, by incorporation into the cell mass generated. If higher removals are required, precipitation of phosphorus by chemical addition is the only alternative. Usually the effluent from the process is treated, with Fe or Al salts or lime, so that the treatment is subsequent to the secondary (or biological) treatment and is called tertiary treatment.

Tertiary treatment substantially increases the capital cost of a plant. Dosing equipment, a precipitation chamber and the settler all add to the cost. Operating costs are also increased due to chemical costs, including their transportation and handling, and the higher level of supervision required.

Activated Sludge Process

In the activated sludge process, as in the trickling filter, phosphorus is removed by two mechanisms:

1. biological phosphorus removal,
2. phosphorus removal by chemical addition.

Biological Removal

Phosphorus is required by the organism mass of the activated sludge process for basic metabolism. It is removed from the wastewater and incorporated into the cell mass and removed in the wasted sludge. Under certain circumstances, activated sludge processes have been known to take up more phosphorus than that required for cell synthesis. This is known as biological excess removal or luxury uptake. Both the basic metabolic and the luxury uptake mechanisms are discussed in greater detail in the literature review in Chapter Two.

Chemical Addition

In the activated sludge process Fe and Al salts and lime are the most common chemicals used for phosphorus precipitation. Various points of addition of the dosing chemicals have been reported, either to the raw influent, prior to the primary settler (primary treatment), or to the mixed liquor (in-plant treatment), or to the effluent from the plant (tertiary treatment).

Primary treatment: The literature indicates that removals of 70 to 90% of the influent phosphorus are possible by chemical addition to the raw influent or primary settler. This can be achieved provided the settler is not hydraulically overloaded. Chemical addition to the primary treatment unit process presents a number of problems:

(i) It not only increases the volume of sludge derived from the chemical precipitation itself, but also increases the suspended organic solids removal. This significantly increases the load placed on the digesters treating the primary sludge.

(ii) For optimal utilization, the addition of Fe and Al salts to the raw sewage has to be proportional to the phosphorus loading rate, i.e. continuous monitoring of the influent phosphorus is required for efficient dosing (Culver and Chaplick, 1978).

(iii) Phosphorus removal is far less efficient than the stoichiometric ratio would predict, especially if the chemicals are added at a constant rate.

Tertiary Treatment: The problems associated with the removal of phosphorus by tertiary treatment of the effluent from the activated sludge process are similar to those encountered with the trickling filter. Addition of Fe and Al salts at the tertiary stage "produce vast amounts of sludge, which, from a point of view of chemical costs and sludge handling, is not conducive to improving the economics of the method" (I.W.P.C., Southern African Branch, Nutrient Removal Working Committee, 1977).

In-plant Treatment: The difficulties associated with phosphorus removal by chemical addition in primary and tertiary treatment units have led investigators to focus attention on in-plant chemical addition. In-plant chemical addition is inherently simple as the chemicals are fed directly into the process, usually into the aeration zone. Effluent phosphorus qualities of below 1 mg/ℓ have been obtained using a stoichiometric ratio of Fe or Al:P of 1 to 2 with respect to the influent phosphorus concentration. Various points of addition have been advocated and pH ranges suggested but there is no clarity as to optimal values for these. In general, it would appear that in-plant dosing appears to be more efficient in terms of the dosing chemicals than either primary or tertiary treatment.(I.W.P.C. Committee, 1977).

Comparing the three modes of phosphorus removal by chemical addition reviewed above, it would appear that in-plant addition has certain advantages over primary and tertiary addition. These are that near stoichiometric (phosphorus removal):(salt added) ratios are obtained. This may mean a significant reduction in the concentration of salt to be added and, reduced productions of both organic and inorganic sludge. There is, however, still a significant lack of information on the removal potential of in-plant addition.

For example, where Fe and Al salts are added to the Modified Activated Sludge Process, should sufficient salt be added to remove the balance of the phosphorus after biological and biological luxury uptake has taken place, or does the salt addition inhibit the luxury uptake phenomenon? Is it necessary to add the salts proportionately to the cyclic phosphorus loading rate, or can they be fed into the process at a continuous rate? The cost of chemical addition on the scale required by a large sewage works justifies investigation into these questions and formed the basis for research reported in this thesis.

Specifically, the objective of this research was to investigate the following:

1. the extent to which the removal characteristics of the Modified Activated Sludge Process can be augmented with in-plant Fe salt addition,
2. the dosage efficiency of in-plant chemical addition and the effect of the plant operational mode on this efficiency.

A major problem in assessing the efficiency of phosphorus removal by in-plant chemical addition in the activated sludge process is to separate out the removal due to chemical addition and luxury uptake respectively. To obtain greater clarity on this aspect, additional work was proposed on the

3. luxury uptake phenomenon with particular attention to the nature of the anaerobic stress required to reliably induce the mechanism to operate.

Chapter Two deals with a review of literature concerning biological phosphorus removal and in-plant chemical addition. A brief account of the research program development is given in Chapter Three. Chapter Four describes the laboratory procedure. In Chapter Five the experimental investigation into the activated sludge process with and without in-plant chemical addition is reported, and the discussion and conclusions are set out in Chapters Six.

CHAPTER TWO

LITERATURE REVIEW

INTRODUCTION

According to the literature, in the activated sludge process phosphorus is removed both by biological action and inorganic precipitation. More specifically these have been categorised as follows:

1. Phosphorus is removed by the organisms for basic metabolic purposes.

2. Phosphorus is removed by the organisms in excess of basic metabolic requirements, commonly termed "luxury uptake".

3. Phosphorus is removed by some form of calcium phosphate precipitation, by combining with the calcium present in the wastewater.

4. Phosphorus is removed by forms of Fe-, Al- or Ca-phosphate precipitation due to addition of Fe, Al or Ca salts to the process.

A brief review will now be given of the work done on each of the various categories.

BIOLOGICAL REMOVAL

Metabolic Requirements

Phosphorus required for basic metabolic purposes is removed from the wastewater by the organisms and incorporated into the cell mass. The percentage removal will depend on the P/COD ratio of the wastewater and can range from 10 to 50% of the influent phosphorus. The mass of phosphorus required can be expressed as a fraction of phosphorus as P with

respect to the VSS. The fraction ranges from 2 to 4%, the average being about 2,5% (Marais and Ekama, 1976). The mass removed is virtually controlled by the mass of sludge wasted per day which, in turn, is dependent on the influent COD and the sludge age. This removal can be modelled in terms of the kinetic theory as presented by Marais and Ekama, as follows:

$$\Delta P = f_p \frac{Y(S_{bi} - S)}{1 + bR_s}(1 + 0,2\ bR_s) + f_p X_{ii} \qquad (2.1)$$

where

ΔP = phosphorus as P removed from the influent and incorporated into the sludge wasted/day i.e. $(P_{inf} - P_{eff})$ (mg/ℓ)

f_p = fraction of phosphorus as P in the sludge = 0,025

Y = growth yield coefficient (mg VASS/mg COD) = 0,45

S_{bi} = biodegradable influent COD (mg/ℓ)

S = unmetabolized biodegradable COD in the effluent

b = specific endogenous respiration rate (mg VASS/mg VASS/d) = 0,24

R_s = sludge age (days)

X_{ii} = unbiodegradable influent solids
$= SX_{ii}/1,48 = 0,13\ S_{ti}/1,48$

S_{ti} = total influent COD concentration (mg COD/ℓ)

e.g. for a process with a raw influent COD of 500 mg/ℓ and R_s = 20 days

$$\Delta P = 0,025 \frac{0,45(0,82 * 500 - 9,2)}{1 + 0,24*20}(1 + 0,2*0,24*20) + 0,025 \frac{0,13 * 500}{1,48}$$

$= 2,67$ mg/ℓ

i.e.

$\Delta P / S_{ti} = 2,67/500 = 0,0053$

As the influent P/S_{ti} ratio can range from 0,01 to 0,03 it is virtually impossible to reduce the influent phosphorus to low values by the biological reaction only.

Excess Biological Phosphorus Removal (Luxury Uptake)

Biological luxury uptake is a mechanism whereby phosphorus is taken up by the organisms in excess of that required for basic metabolic purposes. The literature concerning the mechanism has been extensively reviewed by Martin and Marais (1975), Osborn and Nicholls (1977), Hoffmann and Marais (1977) and others. Only a summary of the various findings will be presented.

In South Africa, excess biological phosphorus removal in the activated sludge process arose from an endeavour to develop a nitrification-denitrification single sludge system. Barnard (1973) proposed the system shown in Fig. 2.1 for the removal of nitrogen. In 1974 Barnard reported that under certain conditions, his system removed phosphorus in excess of basic metabolic requirements. He proposed that the excess biological removal is a consequence of stressing the organisms in an anaerobic* environment. More specifically, he suggests that the organisms must be subjected to an anaerobic condition sufficient to cause a release of phosphorus in the anaerobic zone and subsequently placed in an aerobic environment when the organisms will take up the released as well as additional phosphorus.

Following on Barnard's hypothesis, McLaren and Wood (1976) proposed to induce the anaerobic condition by dividing the anoxic reactor into two (see Fig. 2.2). The first reactor receives the influent and the underflow recycle from the settling tank and the second, the mixed liquor recycle from the aerobic zone. By subdividing the primary anoxic zone and splitting the recycles in this fashion, the nitrate load on the first anoxic reactor is reduced; thereby making it more likely to induce the anaerobic state hypothesized as a prerequisite for luxury uptake. They conducted experiments at both laboratory (Fig. 2.3) and pilot (Fig.2.4)

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* For the present purposes the term anaerobic will denote an environment that is free of both dissolved oxygen and nitrate.

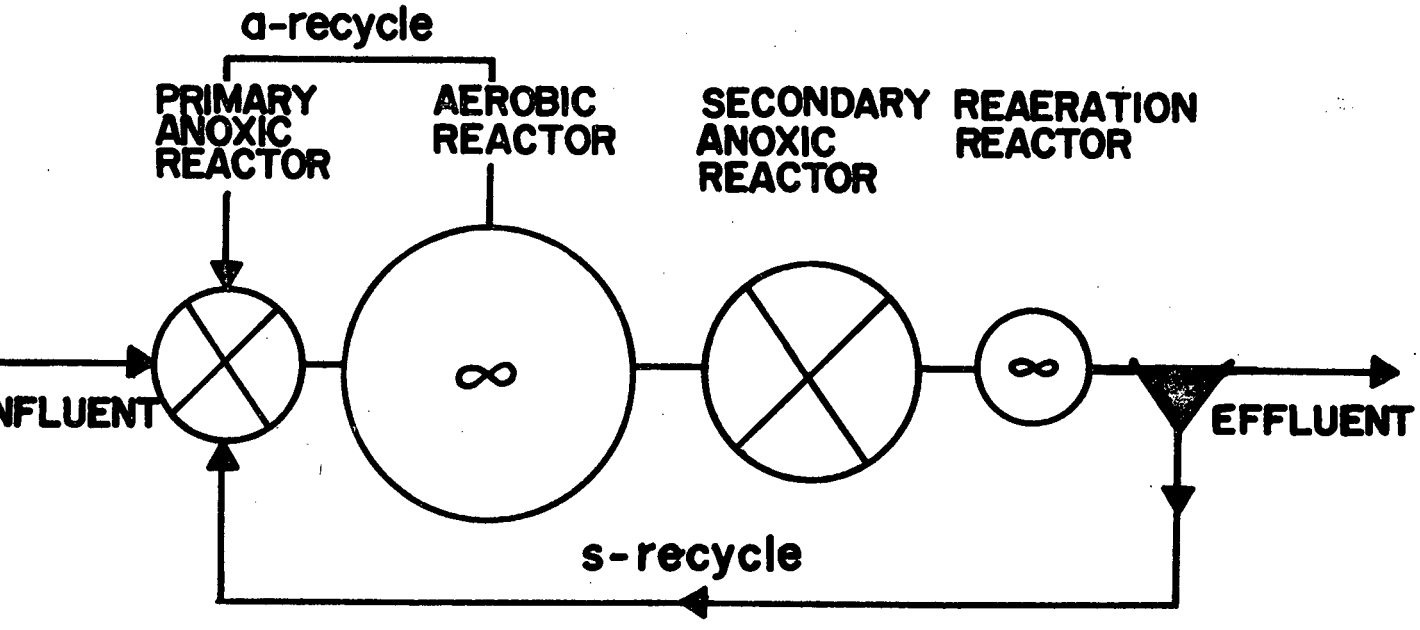

Fig. 2.1 The Barnard system for nitrification and denitrification.

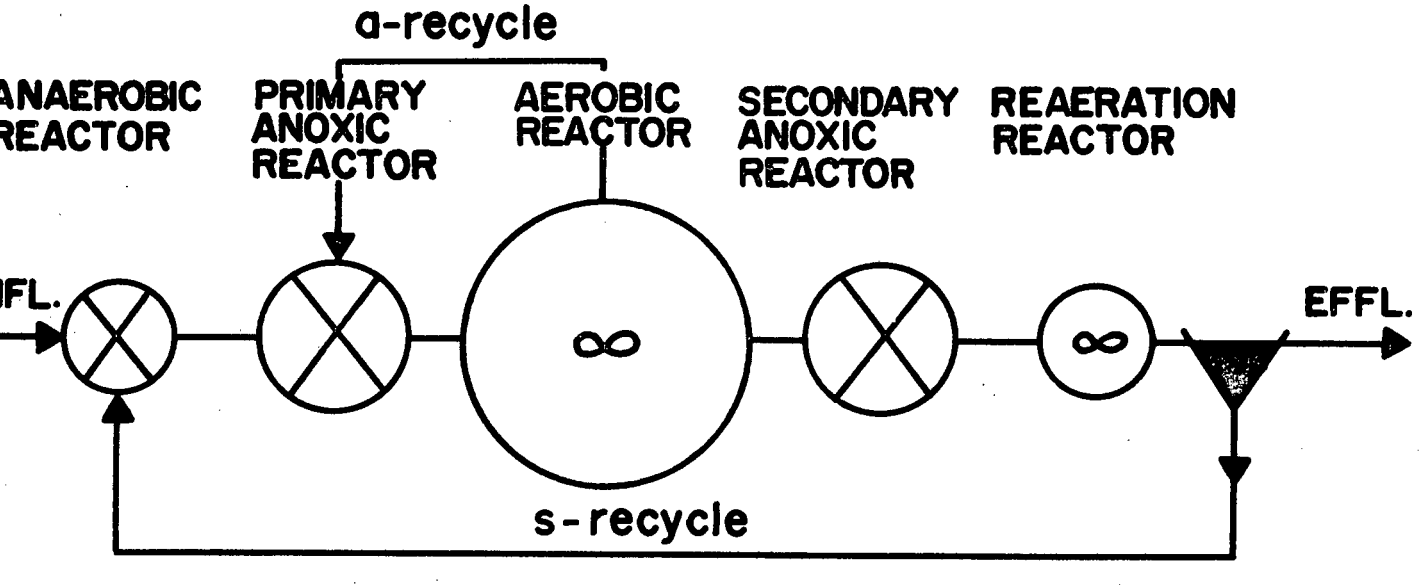

Fig. 2.2 The Modified Activated Sludge Process or "Phoredox" System.

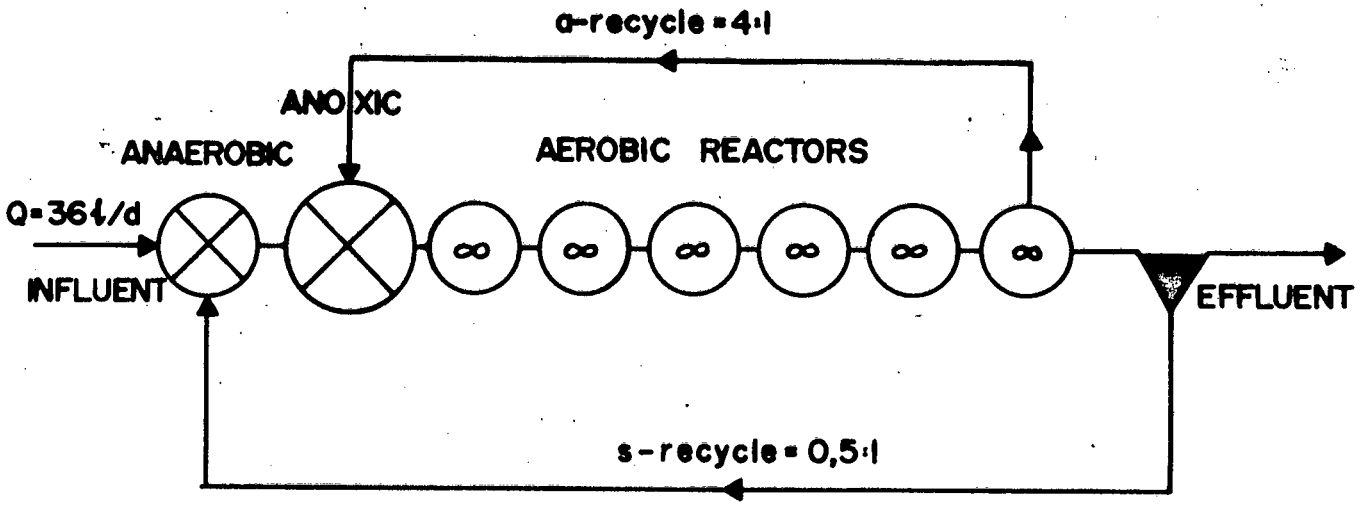

Fig. 2.3 Laboratory scale plant used by McLaren and Wood to study the effect of the primary anoxic zone of phosphorus removal.

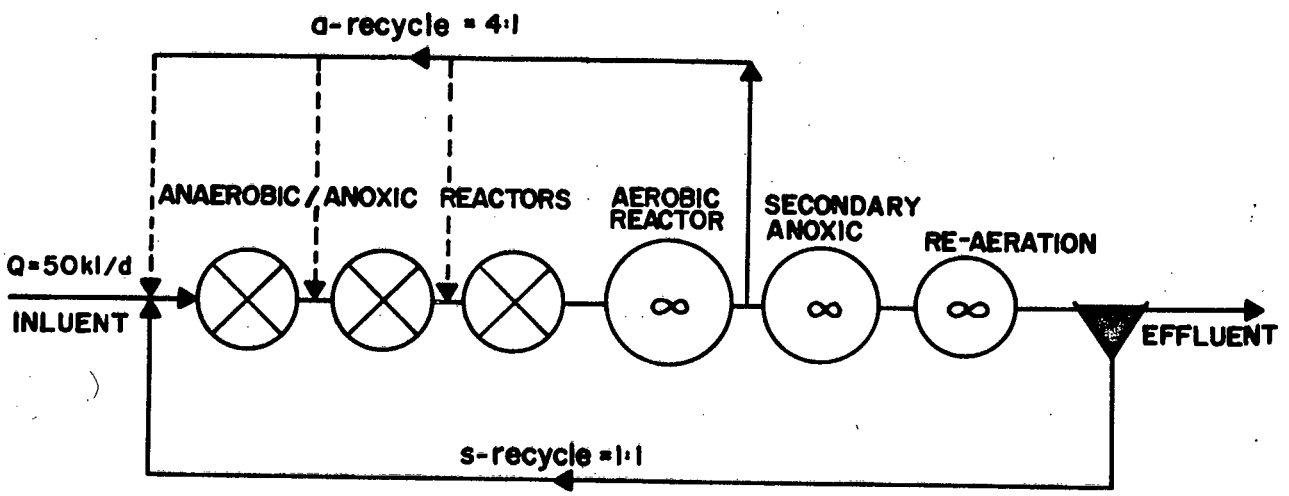

Fig. 2.4 Pilot scale plant used by McLaren and Wood.

scale level. Experimental results from these investigations indicated that "a minimum retention time in the anaerobic stage is necessary for phosphorus removal." Furthermore ..... "a strong association was shown between the system phosphorus removal and the phosphorus release in the anaerobic zone." Their process configuration has become known as the Modified Activated Sludge Process or "Phoredox" system (Fig. 2.2).

Although the Modified Activated Sludge Process has shown increased phosphorus removal, removal performance has often been erratic, probably because the exact prerequisite conditions for removal have not been quantitatively established. It would appear, however, that when excess biological uptake occurs (even though the conditions for removal are not known explicitly) the phosphorus removal can be quantified. Research at the University of Cape Town (Martin and Marais (1975), Marsden and Marais (1977) and Hoffmann and Marais (1977)) has indicated that the combined effect of basic metabolic uptake and luxury uptake is limited and is related to the influent COD and the sludge age. They suggested the following formulation derived from the general activated sludge theory of Marais and Ekama (1976):

$$\Delta P = \frac{Y(S_{bi} - S)}{1 + bR_s}(\alpha + 0{,}025*0{,}2\ bR_s) + 0{,}00225\ \frac{(S_{bi} - S)}{0{,}82} \qquad (2.2)^*$$

where

α = fraction of phosphorus present in the active sludge mass (mg/mg)

The value of α has been found to be highly variable ranging from 0,025 to 0,15. Although high values are achieved on occasions, lower values are more usual. Research work on laboratory scale units has shown α = 0,08 to be a reasonable value if the plant should exhibit excess biological phosphorus removal.

In nitrification-denitrification plants, because of the hypothesized prerequisite anaerobic condition, phosphorus removal is intimately associated with the nitrification-denitrification effects. In order to get denitrification, nitrification is required and therefore process

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* For the derivation of Eq. (2.2), see Appendix A1.

parameters must be chosen in order to ensure maximum nitrification at all times. An important aspect influencing nitrification is the combined effect of temperature and inhibitory factors in the influent.

Temperature

Downing, Painter and Knowles (1964) proposed that for purely aerobic systems, the minimum sludge age of nitrification is given approximately by:

$$R_{s\ min} = \frac{1}{\mu_{nmT}} \qquad (2.3)$$

where

μ_{nmT} = maximum specific growth rate of the nitrifying organisms

$$= \mu_{nm20}\ \theta^{(T-20)} \qquad (2.4)$$

and

$\mu_{nm20} = 0,33 - 0,65/d$

$\theta = (1,123)$

T = Temperature in °C.

The nitrification-denitrification theory of Ekama and Marais (1978) includes b_{nT}, the endogenous respiration rate of nitrifying organisms into the formulation for the minimum sludge for nitrification as follows:

$$R_{s\ min} = \frac{1}{\mu_{nmT} - b_{nT}} \qquad (2.5)$$

where

$$b_{nT} = b_{n20}\ \theta^{(T-20)} \qquad (2.6)$$

and

$b_{n20} = 0,04/d$

$\theta = 1,029$

T = Temperature in °C.

In anoxic-aerobic systems, Stern and Marais (1974) suggested that Eq. (2.3) could also be used to determine the aerobic sludge age of a process, defined as follows:

$$\frac{\text{aerobic volume}}{\text{total volume}} = \frac{R_{s\ min}(\text{aerobic})}{R_s\ (\text{total})} \qquad (2.7)$$

This allowed the maximum anoxic volume fraction, f_{xm}, which still allows nitrification to proceed in the process to be calculated as follows:

$$f_{xm} = \frac{R_s(\text{total}) - R_{s\ min}(\text{aerobic})}{R_s\ (\text{total})} \qquad (2.8)$$

Here the minimum aerobic volume fraction = $(1 - f_{xm})$.

The above method for determining the minimum aerobic volume fraction (or maximum anoxic volume fraction) presupposes that the nitrifying organisms grow and die in the aerobic zone only. However, because the nitrifying organisms are obligate aerobes, death occurs in the entire process, but growth occurs only in the aerobic zone. This causes that the method over-predicts the maximum permissible anoxic volume fraction. Ekama, van Haandel and Marais (1979) have shown that incorporating the death of the nitrifying organisms in the anoxic zone is equivalent to reducing μ_{nmT}, their maximum specific growth rate, as follows:

$$\mu'_{nmT} = \mu_{nmT}(1 - f_x) \qquad (2.9)$$

where

f_x = anoxic volume fraction of the process.

Using the value of μ'_{nmT}, Ekama *et al.* (1979) found that the effluent ammonia concentration, Na, in a process having an anoxic zone is approximately:

$$N_a = \frac{K_{nT}(b_{nT} + 1/R_s)}{\mu'_{nmT} - (b_{nT} + 1/R_s)} \qquad (2.10)$$

where

K_{nT} = half saturation coefficient (mg N/ℓ)

and

$$K_{nT} = K_{n20}\theta^{(T-20)} \qquad (2.11)$$

where

$K_{n20} = 1{,}0$

$\theta = 1{,}123$

T = Temperature in °C.

For a specified sludge age, if the anoxic volume fraction, f_x, is increased to a certain value, f_{xm}, nitrification ceases and the effluent ammonia concentration, N_a, equals net available ammonia in the influent (after synthesis has taken place), N_{ai}. Substituting N_{ai} for N_a and $\mu_{nmT}(1 - f_x)$ for μ'_{nmT} in Eq. (2.10) and solving for f_{xm}:

$$f_{xm} \simeq 1 - (K_{nT}/N_{ai} + 1)(b_{nT} + 1/R_s)/\mu_{nmT}$$

but as

$$N_{ai} >> K_{nT}, \quad K_{nT}/N_{ai} \simeq 0$$

hence

$$f_{xm} \simeq 1 - (b_{nT} + 1/R_s)/\mu_{nmT} \qquad (2.12)$$

Using Eq. (2.12), a graph giving the maximum anoxic volume fraction for various sludge ages at temperatures of 14°C and 20°C and μ_{nm20} values of 0,33/d and 0,65/d is shown in Fig. 2.5.

Inhibitory factors in the influent

In addition to temperature sensitivity, μ_{nm20} is also very sensitive to inhibitory factors in the influent. The value of μ_{nm20} ranges

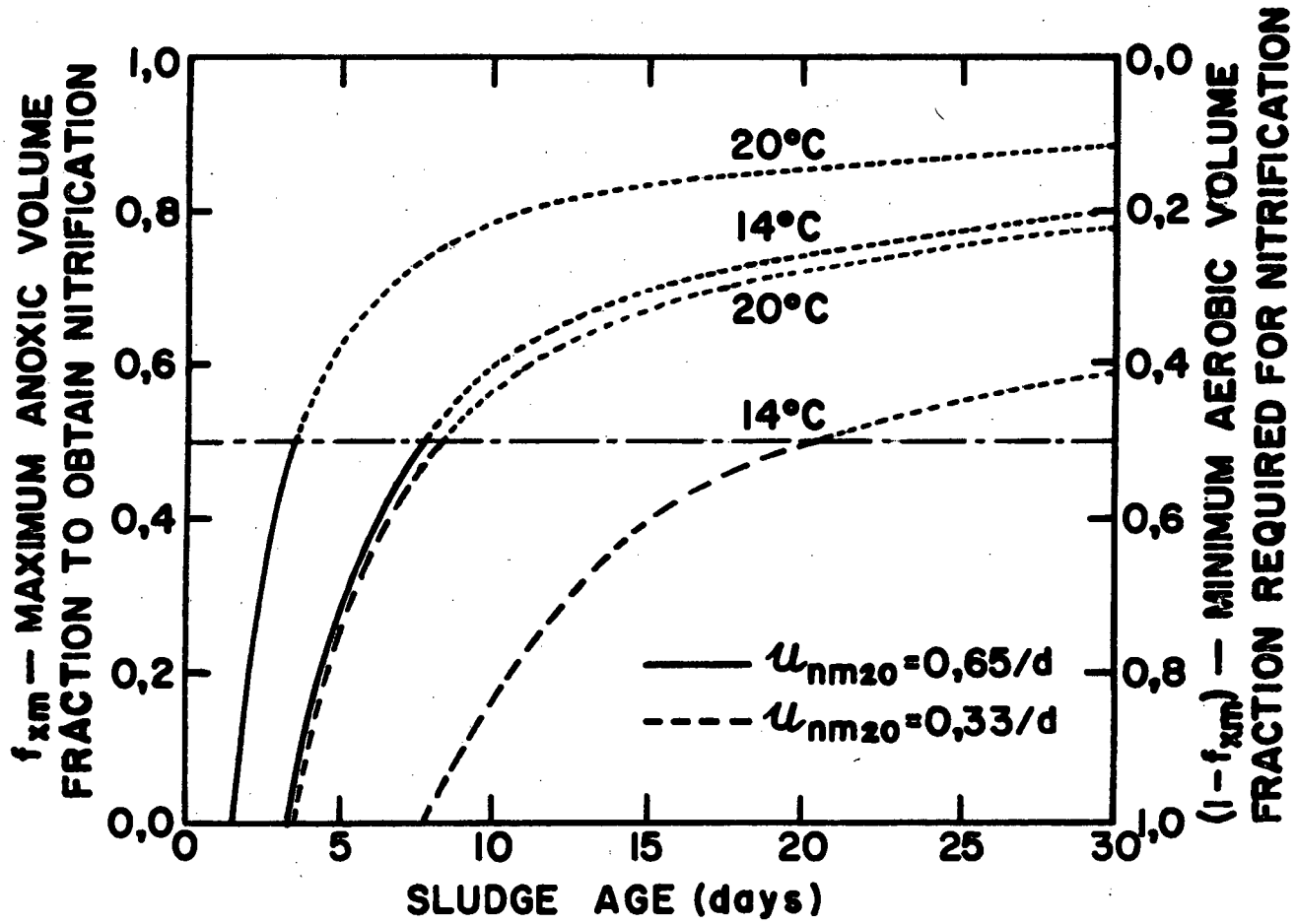

Fig. 2.5 Maximum permissible anoxic volume fraction or minimum aerobic volume fraction required to sustain nitrification versus sludge ages for different maximum specific growth rate constants of the nitrifiers at 20°C and 14°C.

Note: The above graph shows the theoretical interrelationship between the anoxic volume fraction and the various design parameters and is not suggested for use in design; because of the effect of anoxic volume fraction on the maximum specific growth rate of the nitrifiers, anoxic volume fractions greater than 50 percent are not recommended.

from 0,33/d (for sewage with an appreciable industrial component) to 0,65/d (for sewage of principally domestic origin).

The limitation set on the anoxic volume fraction by the need to ensure nitrification also sets a limit to the denitrification capacity. If the TKN/COD ratio of the influent is high (> 0,09) then the situation may arise that the effluent nitrate from the Modified Activated Sludge Process will be appreciable and it may not be possible to ensure zero nitrate in the anaerobic zone due to the high concentration of nitrate being recycled in the underflow. In this event, Barnard's prerequisite condition for biological excess phosphorus removal cannot be satisfied.

The problem stems in part from the inflexibility of the Modified Activated Sludge Process: The recycle from the settling tank is constant and for any particular configuration and influent COD, the denitrification capacity is fixed. Consequently, at high influent TKN/COD ratios, the nitrate in the effluent will be higher and a greater mass of nitrate will be recycled to the anaerobic zone. The mass of nitrate thus recycled can only be reduced by reducing the recycle ratio, but this will create the problem of sludge flotation due to denitrification of the higher sludge accumulation in the settling tank.

The lack of understanding of the exact prerequisites to induce biological excess phosphorus removal; the difficulty of even ensuring that the Barnard prerequisites can be attained in a specific configuration if the TKN/COD ratio should increase from the design value; and the limitation on the denitrification capacity imposed by the necessity to limit the anoxic volume fraction to ensure nitrification at the lower temperatures, all contribute to the uncertainty that in a particular design, excess biological phosphorus removal can be assured. We return to this aspect again in Chapter Three.

The considerations above eventually gave rise to the conclusion that from an immediate practical point of view, designs cannot be based with surety on the proposition that phosphorus removal by excess biological uptake can always be provided for. Excess biological uptake might possibly take place in a design process and if this should happen, it can be considered an advantage. For surety however, alternative phosphorus removal mechanisms should be investigated - by chemical addition.

CHEMICAL REMOVAL

Calcium Phosphate Precicpitation

Menar and Jenkins (1970) postulated that in activated sludge systems, all phosphorus removed in excess of basic metabolic requirements takes place by calcium phosphate precipitation - the organic material in the process merely creates the chemical conditions necessary for precipitation. This hypothesis is in direct opposition to the luxury uptake theory.

Hoffmann and Marais (1977) have specifically investigated the validity of the two opposing hypotheses. They concluded that at a pH range of about 7,0, a maximum phosphorus concentration of 1 to 1,5 mg/ℓ as P can be expected to be removed from the influent by calcium phosphate precipitation, provided Ca > 40 mg/ℓ Ca and P > 10 mg/ℓ P. If the pH falls below about 6,5, any precipitant formed redissolves. Consequently, where excess phosphorus removal has been observed in the activated sludge process at pH values below 7,0, the removal must be due to biological uptake only. As excess phosphorus removal has been repeatedly observed at a pH < 7,0, the work of Hoffmann and Marais supports the hypothesis that biological excess phosphorus removal does take place. They recognise, however, that phosphorus removal due to precipitation can also take place at higher pH values.

In-plant Chemical Addition

In plants where the biological phosphorus removal is inadequate, direct addition of Fe and Al salts has been advocated. Fe and Al salts are preferred as chemical additives, as the precipitates of iron and aluminium phosphate are stable and do not redissolve in the process or in the digestors treating the waste sludge. (IWPC, Southern African Branch, Nutrient Removal Working Committee, 1977).

The IWPC Committee (1977) reviewed the operations of a number of activated sludge processes in South Africa practising chemical addition. Some of the Committee's findings are reproduced below:

(i) "In the case of existing activated sludge plants, alum, ferric or ferrous salts are best applied just prior to or after the aeration stage. When dosed prior to the aeration stage, ferrous salts are oxidised to ferric which may be economically preferable."

(ii) "Chemical addition to the primary clarifier requires higher dosage rates on account of the higher prevalent alkalinity. Chemical treatment in subsequent biological stages may have distinct advantages as regards overall plant performance. The choice remains one of economics in relation to particular situations."

(iii) "The biological chemical removal of phosphate in activated sludge plants is acclaimed to be just as effective if not better than chemical dosing alone. The literature reports less flocculant will be required under these circumstances."

Specific examples of plant response discussed in the IWPC report are of interest:

(a) At Scottburgh, Natal, the addition of 150 mg/ℓ ferrous sulphate (30 mg/ℓ Fe) to a completely mixed activated sludge system resulted in a system phosphorus removal from 10 to 1,4 mg/ℓ as P (82% on average). However, no significant improvement was achieved by increasing the dosage to 200 mg/ℓ $FeSO_4$ (40 mg/ℓ as Fe). At the same plant, 150 to 200 mg/ℓ of alum (12,2 to 16,2 mg/ℓ as Al) was required to ensure a consistent effluent quality of below 1 mg/ℓ as P (80% removal on average). The influent phosphorus concentration during the alum addition period was not stated but was probably of the order of about 10 mg/ℓ as P.

(b) Ferrous sulphate addition to the Orbal pilot plant at Daspoort near Pretoria showed a constant phosphorus removal from 4,4 to 0,5 mg/ℓ as P (89% removal) even though the dosage varied between 25 and 100 mg/ℓ (5 to 20 mg/ℓ as Fe). The effluent phosphorus quality was in the range of 0,4 to 0,9 mg/ℓ as P.

There is little information available on the in-plant behaviour of processes using chemical addition. Consequently, one has to turn to batch investigations for more information on phosphorus removal chemistry. Prested, Shannon and Rush (1977) describe an extensive series of jar tests and experiments on chemical addition to the raw sewage and the mixed liquor of activated sludge processes. Their overall objective was to estimate dosages required to produce an effluent phosphorus concentration of below 1 mg/ℓ as P as stipulated in the Canada-Ontario Agreement on the Great Lakes Water Quality Control (Prince and Bruce, 1972). From the results of jar testing, an attempt was made to predict the dosage requirements of full scale works. They concluded that:

(i) more efficient phosphorus removal is achieved when chemicals are added to the mixed liquor as opposed to the raw sewage, and that

(ii) jar tests tend to overestimate the dosage requirements of full scale works. This was partly attributed to their own statistical assumptions and partly to the benefit of having a continuous recycle in a full scale works.

In a subsequent study, Prested *et al.* (1978) attempted to improve their prediction equations by developing a wastewater strength index (WSI) which classified wastewaters in terms of six common parameters (hardness, total phosphorus, suspended solids, total alkalinity, conductivity and total organic carbon). Multiple regression relationships expressing alum, iron salt and lime dosages required, as functions of raw wastewater characteristics were derived for three wastewater strength categories. The equations predicting lime dosages were found to be inconsistent. Although the equations predicting dosages for Fe and Al salts were found to be somewhat better, they concluded that these did not warrant the extra expense required for data analysis, when compared with dosages based solely on the influent total phosphorus.

The various research investigations discussed above demonstrate three important characteristics of direct salt addition to the activated sludge process:

(a) Accumulation of the metal precipitate appears to contribute to more efficient phosphorus removal.

(b) Efficiency of the dosing chemical appears to drop significantly if low effluent phosphorus concentrations are required.

(c) Jar testing cannot reproduce the conditions in a full scale works and can therefore only serve as a rough estimate of the dosage requirements of a full scale works.

As pointed out earlier by both the IWPC Committee (1977) and Prested *et al.* (1977), the presence of the accumulated precipitate appears to have a beneficial effect on phosphorus removal. This beneficial effect is possibly due to the enhanced contact opportunity provided by the

accumulated sludge in the competing reaction of Fe^{3+} with OH^- and $PO_4^{\equiv}$ or, a subsequent exchange of OH^- with the $PO_4^{\equiv}$ ion in the ferri-hydroxide precipitate, or an adsorption effect.

The research investigations reviewed above do not explicitly consider the possibilities of excess biological uptake in the process. This aspect was included in the work of Spatzierer (1978). He investigated the effect of $FeSO_4$ addition to the raw influent (just prior to combining with the return sludge) on the phosphorus removal characteristics of the Zellerbecken treatment plant. The process consisted of an aerated reactor, in which the dissolved oxygen concentration was kept at zero (in order to achieve simultaneous nitrification and denitrification) and three aerated reactors in series. For an average influent COD of 410 mg/ℓ the average biological removal of phosphorus was 5,5 mg/ℓ as P. With Fe^{3+} addition the removal increased and Spatzierer concluded from the results of various Fe dosage experiments, that in order to achieve a phosphorus concentration significantly below 1 mg/ℓ as P, the iron dosage should be 3g Fe/gP in the influent. He noted further that when the Fe salt dosage was stopped, the plant continued to remove a high phosphorus concentration for two days. The effluent P concentration gradually rose over a period of twelve days to its level prior to chemical addition.

The work of Spatzierer points to four important effects:

(i) Nitrification-denitrification features of the plant appear to enhance the phosphorus removal without the addition of chemicals in much the same fashion as achieved in the Modified Activated Sludge Process.

(ii) Iron salt dosing removed phosphorus in addition to biological removal.

(iii) Residual effect of the Fe precipitate is evident, as reported in the findings of the IWPC Committee (1977) and Prested *et al.* (1977, 1978).

(iv) High Fe dosages are required to obtain low phosphorus concentrations in the effluent.

Virtually nothing is known of the effects of metal salt addition on phosphorus removal in the nitrification-denitrification processes. However, the literature indicates that reliable phosphorus removal should be obtained by in-plant chemical addition, but there is little information available on the stoichiometric proportions of say, Fe to P to be added.

C H A P T E R T H R E E

RESEARCH PROGRAM DEVELOPMENT

The program initially proposed had the objective of investigating optimal dosages of Fe salt to the Modified Activated Sludge Process to ensure low effluent phosphorus concentrations.

The unreliability of the excess biological phosphorus removal mechanism as described in the literature review in Chapter Two and as experienced at the University of Cape Town, had given rise to the opinion that, from a practical point of view, it is not a mechanism that could be relied upon. Indeed, the climate of opinion moved towards abandoning further research into excess biological phosphorus removal and concentrating on phosphorus removal by metal salt addition to the nitrification-denitrification process.

The problem with this approach was that virtually no information was available as to the effect of the addition of metal salt to the nitrification-denitrification process. It was not known whether the presence of the anaerobic zone, for example, would affect removal by chemical precipitation. There was also a reluctance to abandon the modified configuration as, on the whole, it always showed some excess phosphorus removal. The idea then developed of accepting a modified configuration with the anaerobic, anoxic and aerobic reactors such that it would have the best likelihood of inducing complete nitrification, high denitrification and, possibly, good phosphorus removal. The criteria for such a design and the design itself are set out in Chapter Four.

An experimental unit conforming to the design criteria and having in-plant addition of Fe salt was set up. Approximately a year's operational data was obtained in this fashion. This would seem a very long testing period but one aspect that was contributory to the need for this long

period was that the phosphorus removal fluctuated appreciably from approximately 50 to 150% of the expected stoichiometric removal. In time it was established that the fluctuations could be attributed to two main causes:

(i) The chemical removal of phosphorus by Fe salt addition is pH dependent

(ii) Excess biological phosphorus removal took place intermittently.

With regard to (ii) above, little could be done for the reason that the cause for the erratic behaviour could not be identified. With regard to (i) above, a series of experiments was devised to isolate, insofar as it were possible, the pH effect. Obviously due to the effects of (ii) the effect of pH could not be quantitatively isolated to a high degree of accuracy. Recognising these problems, nevertheless the series of experiments was continued in order to determine the practical mean removal to be expected under steady state and cyclic loading conditions.

After a year's work had been completed, a new development took place - a quantitative model of the nitrification-denitrification behaviour of the Modified Activated Sludge Process was developed by Ekama, van Haandel and Marais (1979). This development gave a new impetus to investigation into biological excess phosphorus removal.

In the Barnard hypothesis for excess biological phosphorus removal, it is stated that an "anaerobic" condition must be present to release phosphorus in order to stimulate phosphorus uptake in the aerobic zone. The problem with this hypothesis is that it neither specifies nor provides a quantitative measure of the degree of anaerobic intensity, if any, that may be necessary - the hypothesis merely requires that no nitrate be present for anaerobiosis. Having a quantitative formulation for denitrification, Ekama *et al.* could establish a <u>denitrification capacity</u> for a reactor, i.e. the mass of nitrate that could be removed by the reactor, if sufficient nitrate was present. The denitrification capacity of a

reactor was found to depend largely on S_{bs}, the mass of easily biodegradable substrate available as the energy source, and, to a lesser extent, on X_a, the active mass concentration in the sludge.

If the mass of nitrate available was less than the denitrification capacity of the reactor, an anaerobic potential would be established, defined as follows:

Anaerobic potential = Denitrification capacity - nitrate in the influent to the reactor.

if +ve, then a true anaerobic potential existed,
if -ve, then the reactor is still anoxic and nitrate is still present in the effluent from the reactor.

Applying this concept to data that had been developed indicated that the concept had value, and that an anaerobic potential of approximately 9 mg N/ℓ of influent flow was necessary to cause a phosphorus release and induce excess biological phosphorus removal.

A further consequence of the investigation of Ekama *et al.* was that the Modified Activated Sludge Process configuration appeared to be an inflexible one, and in fact, not the optimal one for consistent phosphorus removal under flows having different sewage characteristics. The sewage characteristic which appears to have a crucial influence on the success or failure of a practical design of the Modified Activated Sludge Process with regard to phosphorus removal, is the influent TKN/COD ratio. For the same COD load, plants that remove phosphorus satisfactorily at low TKN/COD ratios can fail completely at high ratios. The reason for this is that for a fixed configuration and COD load, the denitrification capacity of the anaerobic reactor is fixed. The nitrate concentration recycled to the anaerobic reactor in the underflow recycle is equal to the nitrate concentration in the effluent; therefore an increase in the influent TKN/COD ratio will result in a corresponding increase in the nitrate concentration in the underflow recycle and a corresponding decrease in the anaerobic potential,to zero if the TKN/COD ratio is high.

In an endeavour to develop a system with a greater degree of control on the anaerobic potential, a new configuration called the U.C.T. Process was developed. See Fig. 3.1. This process is very flexible and it allows the establishment of a wide range of anaerobic potentials in the anaerobic reactor, even for TKN/COD ratios up to 0,16.

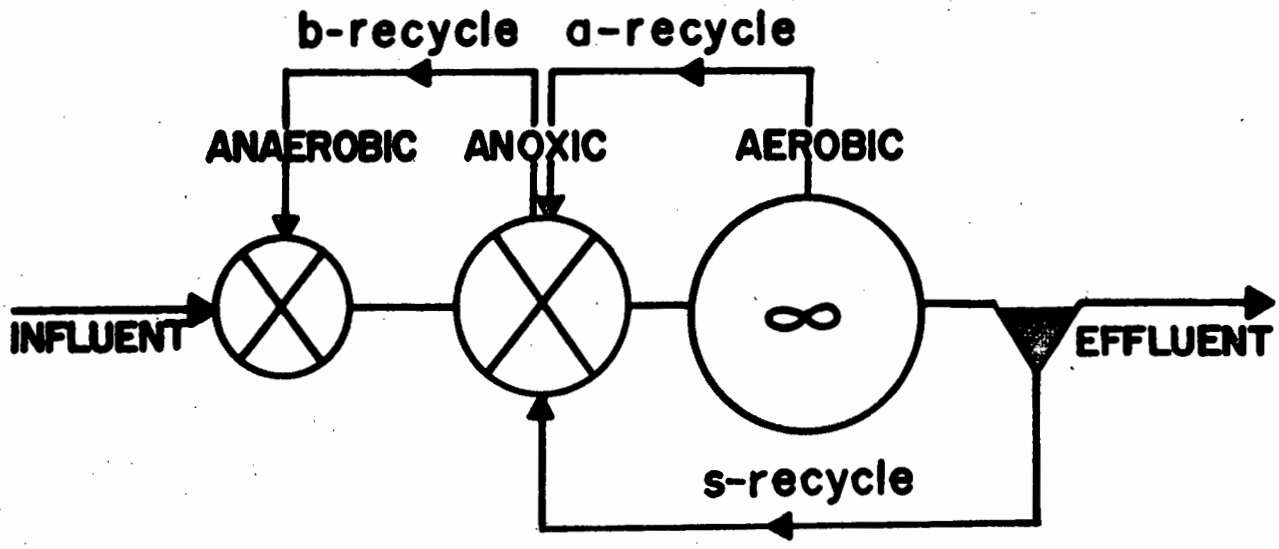

Fig. 3.1 The U.C.T. Process for nitrification, denitrification and phosphorus removal.

The U.C.T. configuration with its associated operational mode was set up experimentally and gave such a favourable response that the research program was modified to the new configuration. To test its removal potential, the process was run without the addition of chemicals over a range of TKN/COD ratios. The results of these supported the concept of anaerobic potential i.e. the modified hypothesis on the prerequisite conditions for excess biological phosphorus removal. The results showed excellent consistency and in this way formed the basis for investigation into the effects of chemical addition.

The latter part of this investigation therefore was concerned with the behaviour of the U.C.T. Process, with and without chemical addition.

CHAPTER FOUR

LABORATORY PROCEDURE

PROCESS CONFIGURATION

In order to investigate the effects of Fe salt addition on the Modified Activated Sludge Process, the configuration as shown in Fig. 4.1 was chosen.

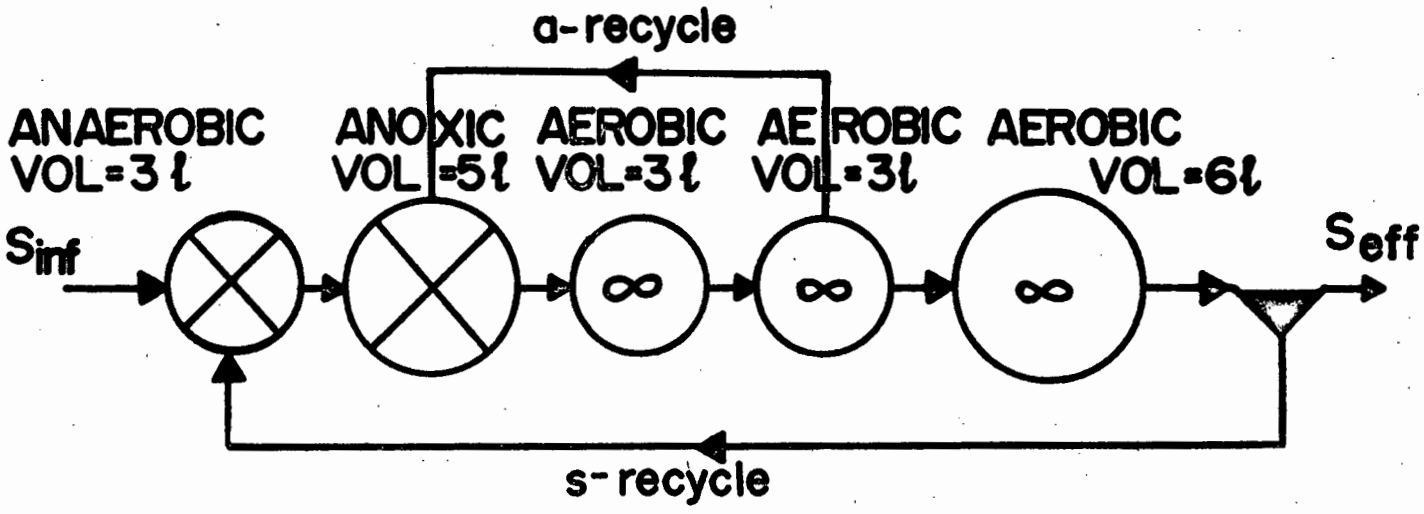

Fig. 4.1 The basic experimental unit used to test the effects of in-plant Fe salt addition.

The configuration was designed to create the necessary anaerobic conditions hypothesized as a prerequisite for biological luxury uptake according to the following criteria:

1. Anoxic Volume Fraction

Using Eq. (2.4) and a μ_{nm20} value = 0,33/d at 14°C

$$\mu_{nm20} = 0,33\ (1,123)^{14-20}$$

$$= 0,165$$

Using Eq. (2.5) and a b_{n20} value of 0,04/d at 14°C

$$b_{n12} = 0,04\ (1,029)^{14-20}$$

$$= 0,034.$$

A sludge age of 20 days was chosen as this is the sludge age now common in large scale nitrification-denitrification plants to ensure nitrification at low temperatures ($\pm$ 14°C).

Substituting these values in Eq. (2.10)

$$f_{xm} \simeq 1 - (0,034 + 1/20)/0,165$$

$$= 0,49$$

Allowing for a factor of safety of approximately 20 per cent, the anoxic volume fraction was chosen at 40 per cent.

2. Secondary Anoxic Zone

For temperatures above 17°C, the primary anoxic zone which utilizes the raw influent as an energy source for denitrification exhibits a far greater denitrification rate than the secondary anoxic zone which relies mainly on endogenous energy release as an energy course (Stern and Marais, 1974).

Once an upper limit of 0,4 is placed on the anoxic volume fraction, there is usually little advantage in including a secondary anoxic zone. If the TKN/COD is large (> 0,9) the nitrate cannot be removed totally even if the anoxic zone is located only in the primary zone; if some of the anoxic zone is transferred to create a secondary zone, the total nitrogen removal will decrease. For these reasons it was decided to omit a secondary anoxic zone in the experimental unit used in this investigation.

3. Subdivision of the Anoxic Zone

If any hopes for obtaining excess biological phosphorus removal are to be realized, the primary anoxic zone must be subdivided into anaerobic and anoxic zones as proposed by McLaren and Wood (1976). However, the decision as to the division at the time was largely empirical and at the University of Cape Town the division was simply anaerobic:anoxic 3:5.

From previous experience on laboratory scale units, the design criteria above had resulted in good reductions of nitrogen and reasonable settling sludges. It was decided therefore, to use the configuration conforming to these recommendations as the one for testing the effect of in-plant addition. (See Fig. 4.1).

The underflow or s-recycle discharged into reactor No. 1, the magnitude of the recycle being in a ratio of 1:1 with respect to the mean influent flow. This ratio is a common one in full scale works as it ensures a short retention time of the sludge in the settler thereby reducing the possibility of denitrification by the retained mass.

The a-recycle from the aerobic zone discharged into reactor No. 2. The magnitude of the a-recycle was chosen to satisfy the following requirement:

The nitrate concentration in the effluent from the anoxic zone must always be greater than 0 to ensure maximum system nitrate removal. If

the nitrate = 0 it may be due to insufficient nitrate being recycled to the anoxic reactor, in which event the mass of nitrogen that can be removed can be increased by increasing the recycle. Once the nitrate concentration is > 0 in the anoxic reactor, the removal theoretically stays constant. Higher recycles, however, may have an adverse effect by introducing more oxygen, thereby reducing the denitrification potential (Stern and Marais, 1974).

A raw influent COD of 500 mg/ℓ was chosen as this is the maximum concentration that can be guaranteed from the Strandfontein Sewage Works throughout the year. During the winter months, the sewage arrives at the works in a diluted form due to infiltration from the high water table on the Cape Flats.

When metal salt addition was being investigated, the salt solution was fed directly into the reactors. The addition of the metal salt solution has an alkalinity depleting effect, lowering the pH of the process. When the effect of reactor pH was investigated, an alkalinity source was added to raise the pH. Addition of the source was either by prior mixing into the feed batch or feeding into the influent flow just prior to the point of discharge to the unit, or feeding directly into the reactors. By choosing the alkalinity source from $HCO_3^=$, $CO_3^=$ or OH^- salts, it was possible to regulate the pH in the influent and reactors to any required value greater than the naturally occurring one.

The unit was operated in a temperature controlled laboratory at 20°C. Appendix A2 contains a detailed description of the apparatus.

EXPERIMENTAL PROCEDURE

The following routine of plant operation and testing was adhered to.

Every 10 to 14 days raw sewage was collected from the Strandfontein Sewage Works outfall in a 1200ℓ tank. The collection time was found to be critical as it affected the sewage characteristics. Due to the

long sewer length, the morning peak only arrives at the works at about midday. This peak exhibited extreme TKN/COD ratios of 0,12 - 0,15 but lasted only for about an hour. During the late afternoons, low COD values (< 500 mg/ℓ) were encountered, particularly during the winter months. For these reasons the best time to collect the sewage was between 1430 and 1600 hours daily. Sewage collected during this period generally had a COD value in the range 500 - 1000 mg/ℓ and a TKN/COD ratio of approximately 0,07. This TKN/COD ratio corresponded approximately with the mean ratio for the flow. After collection, the sewage was passed through a macerator and stored in 400ℓ stainless steel tanks at 4°C with a minimum of delay. Three tanks were filled simultaneously to ensure a uniform sewage composition in all three. To determine the strength of the raw sewage, COD tests were done on four samples from the same tank.

An important operational aspect regarding sewage collection is the necessity to clean the tanker transporting the sewage and the tanks in the cold storage room thoroughly at each batch collection. This prevents the development of anaerobic conditions with associated H_2S production in the storage batch.

The experimental unit was fed at about noon daily. The contents of the storage tank were mixed thoroughly and the required volume of sewage removed. The daily required volume (30ℓ) was prepared by diluting the sewage of known COD with tap water to a COD of 500 mg/ℓ. Prior to feeding, the sewage was aerated vigorously for about 5 minutes in order to blow off dissolved H_2S that might be present. This aeration did not appear to have any noticeable effect on the COD concentration.

A 200 mℓ sample was drawn off and stored at 4°C if necessary. The influent batch was placed in the feed container which was continuously stirred by means of a slowly revolving paddle to keep the batch well mixed. To prevent further aeration over the 24 hours, a styrene cover floated over the surface.

When it was necessary to control the influent phosphorus and TKN to specific concentrations, the phosphorus level was increased by the addition of a popular brand of washing powder and the TKN level by the addition of ammonium sulphate.

Sampling of the process itself was done at about 0830 hours, i.e. approximately 3 hours before the next feed cycle began. This was done in order to minimize the disruption of the continuity of the process which is always introduced to some degree when starting a new daily feed cycle. From each of the reactors, 100 mℓ samples were drawn, centrifuged and filtered. A 500 mℓ sample was taken from the effluent container, of which 250 mℓ was filtered. The following tests were carried out daily:

	Reactors								
	Inf.	Filt.inf.	1	2	3	4	5	Eff.	Filt.eff.
pH	√*	-	√*	√*	√*	√*	√*	√*	-
COD	√	-	-	-	-	-	-	√	-
TKN	√	-	-	-	-	-	√	√	-
P	√	√	√	√	√	√	√	√	√
O_2 demand	-	-	-	-	√*	√*	√*	-	-
VSS	-	-	-	-	-	-	√**	-	-
NO_3	-	-	√	√	√	√	√	-	√
Fe	-	-	√	√	√	√	√	√	√
Settling rate	-	-	-	-	-	-	√***	-	-

* Test done in reactor
** Test done on solids
*** Test done on mixed liquor

The tests for the COD and TKN were in accordance with "Standard Methods for the Examination of Water and Wastewater" (1971 Ed.). The nitrate (NO_3-N) and nitrite (NO_2-N) concentrations were measured by the auto-analyser automated method in accordance with the procedures described in "Technicon Auto Analyser Methodology". The pH was measured by means of a Radiometer Type 29 pH Meter, to an accuracy of 0,05 pH units. The MLVSS test was done in accordance with the method described in Appendix A3.

Only total phosphorus measurements were made. Orthophosphate measurement is not possible on effluent from the Western Cape as the natural colour in the water leads to gross inaccuracy when using colorimetric methods. The total phosphorus measurement requires the conversion of all the phosphorus to the orthophosphate form, which is then measured by the molybdate vanadate technique. The conversion to the orthophosphate form and the natural colour removal were done using a technique developed by Greenblau (1974) and is described in detail in Appendix A4.

When iron salts were added to the process, "iron leakage" was tested for. Iron concentrations in the samples and effluent were measured with an Automatic Adsorption Spectrophotometer manufactured by Varian Tectron (Model 1200) using the procedure outlined in the manufacturer's manual.

The oxygen demand rate of the aerated reactors was determined using a Model 54 Oxygen Meter manufactured by the Yellow Springs Instrument Co. connected to a Hewlett Packard Chart Recorder (Model 17500A). The dissolved oxygen concentration in the aerobic reactors was raised from the normal operating level (1 - 2 mg/ℓ O) to about 6 mg/ℓ O by sparging. Aeration was then stopped but stirring and through-flow allowed to continue. The change in dissolved ozygen concentration versus time curve was plotted on the recorder. The slope of the line (usually linear) gave the oxygen uptake rate/ℓ of mixed liquor.

Sludge settleability tests were done on the mixed liquor drawn off from the aeration zone using the settling rate test developed by White (1975). A description of the method and apparatus used appears in Appendix A5.

The sludge age was maintained by hydraulic control. The total volume to be wasted daily minus the total volume drawn off as samples was wasted soon after feeding the unit. The volume of any mixed liquor drawn off from a reactor was immediately replaced by an equivalent volume of effluent from the effluent container in order to minimise the continuity of flow and recycle.

EXPERIMENTAL INVESTIGATIONS

The following experimental tasks were carried out and are reported in Chapter 5:

1. Phosphorus removal without the addition of chemicals.

2. Phosphorus removal with the addition of $FeSO_4$ without pH adjustment.

3. Phosphorus removal with the addition of $FeSO_4$ and pH adjustment.

4. Phosphorus removal under influent cyclic loading conditions.

5. Phosphorus removal with the addition of $FeCL_3$ under low and high influent TKN/COD ratios.

6. Phosphorus removal in the U.C.T.Process using $FeCL_3$ in-plant addition.

CHAPTER FIVE

EXPERIMENTAL INVESTIGATIONS

The various experimental investigations in this chapter are reported in their logical sequence and not necessarily in the order in which they were carried out. In many cases the need for a particular experiment became evident from the results of a previous one. Whenever changes were made to the experimental mode, the unit was allowed to regain a steady state condition before the data was accepted for analysis.

1. PHOSPHORUS REMOVAL WITHOUT THE ADDITION OF CHEMICALS

In order to determine the removal of phosphorus by biological means only, the basic configuration (Fig. 5.0) was run without the addition of chemicals. The α value, i.e. the fraction of phosphorus removed as luxury uptake relative to the MLVSS was determined using Eq. (2.2). Although the conditions of the experiment remained constant, the results indicated two significantly different phosphorus removal patterns and consequently are reported as Experiments 1.1 and 1.2 respectively.

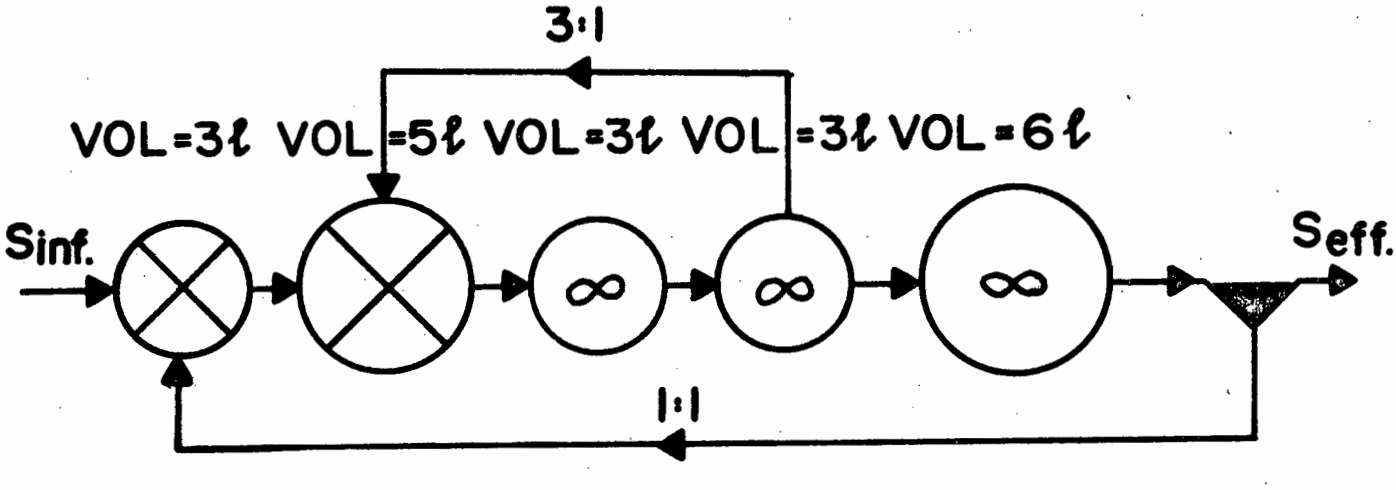

Fig. 5.0 The basic experimental configuration.

Experiment 1.1 The raw data are listed in Appendix A6. The data were analysed statistically† and tested for outliers (where such out-lying values were apparent in the statistical analysis) using the method of Laubscher (date unknown)* at 10% level of significance. The mean values listed in Table 5.1 are those from the statistics where all outliers have been eliminated.

Table 5.1 Mean Values for Experiment 1.1 (Refer to Fig. 5.0)

		Reactor No.						
	Inf.	1	2	3	4	5	Eff.	Filt.eff.
COD mg/ℓ	510	-	-	-	-	-	38	--
TKN mg/ℓ	50,0	-	-	-	-	-	1,00	-
P mg/ℓ	11,42	14,36	8,43	7,14	7,04	6,08	6,37	5,33
pH	7,15	7,15	7,10	7,05	7,00	7,10	7,20	-
NO_3 mg/ℓ	<0,20	<0,20	1,80	6,60	9,20	11,90	-	12,10
VSS	-	-	-	-	-	3433	-	-
O_2 demand mg/ℓ/h	-	-	-	63,00	42,00	18,00	-	-

From the mean phosphorus concentration in each reactor, mass balances were calculated considering the flows and phosphorus concentrations to and from each reactor as shown in Table 5.2.

The overall system phosphorus removal was 6,09 mg/ℓ. Using this value in Eq. (2.2), the α value was = 0,133 which is close to the value of 0,15 obtained by Martin and Marais (1975).

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† Using a graphical statistical technique

* N.I.W.R. Publication.

Table 5.2 Phosphorus Release and Uptake Relative to the Influent Concentration

Reactor 1:	11,42 * 1	+	5,33 * 1	-	14,36 * 2	=	-	11,97 mg/ℓ
Reactor 2:	14,36 * 2	+	7,04 * 4	-	8,43 * 6	=	+	6,30 mg/ℓ
Reactor 3:	8,43 * 6	-	7,14 * 6			=	+	7,74 mg/ℓ
Reactor 4:	7,14 * 6	-	7,04 * 6			=	+	0,60 mg/ℓ
Reactor 5:	7,04 * 2	-	6,08 * 2			=	+	1,92 mg/ℓ
Settler :	6,08 * 2	-	5,33 * 2			=	+	1,50 mg/ℓ
						Σ	+	6,09 mg/ℓ

+ve Phosphorus taken up by the sludge/ℓ of influent flow

-ve Phosphorus released by the sludge/ℓ of influent flow

In Fig. 5.1(a) a graphical plot is shown of the phosphorus and nitrate concentrations in each of the reactors in the series.

The phosphorus release and uptake relative to the influent concentration are shown in Fig. 5.1(b).

Experiment 1.2 The experimental conditions were exactly the same as in Experiment 1.1 except that a new batch of sewage was fed. The COD and TKN values were 470 and 47,4 mg/ℓ respectively, giving a TKN/COD ratio of 0,10. This value is virtually identical to the TKN/COD ratio of the influent in Experiment 1.1 (TKN/COD = 0,10). The raw data over the test period are listed in Appendix A7 and the mean values over this period are presented in Table 5.3.

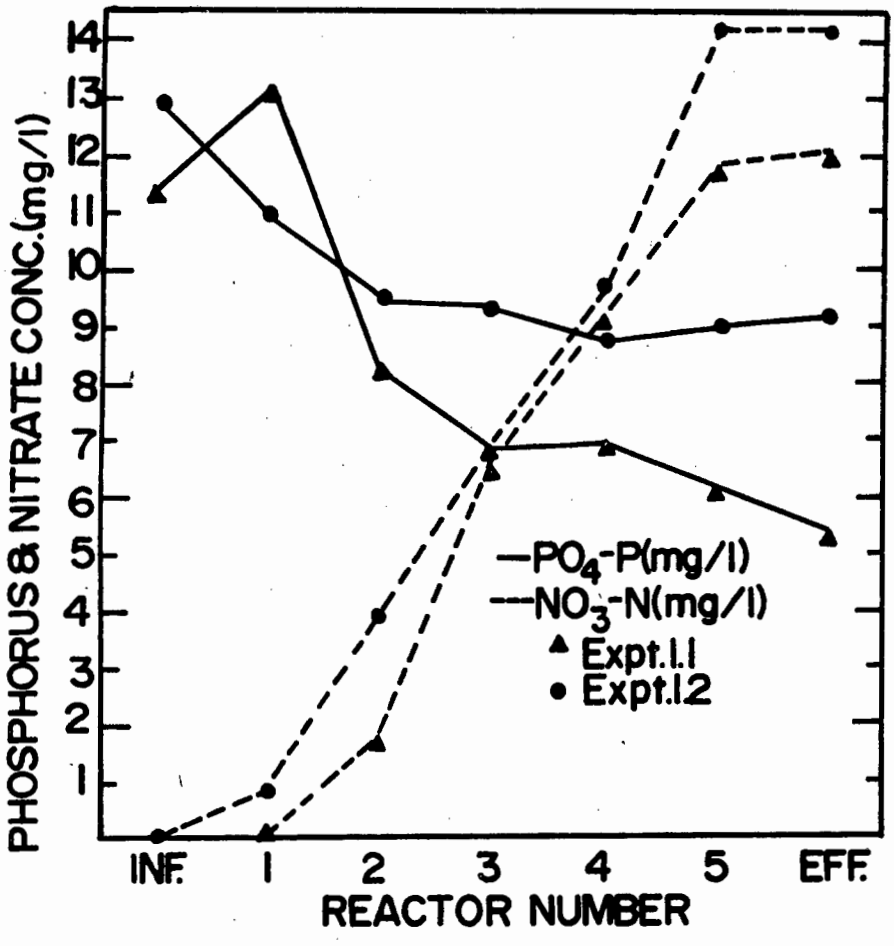

Fig. 5.1(a) Phosphorus and nitrate concentrations in each reactor.

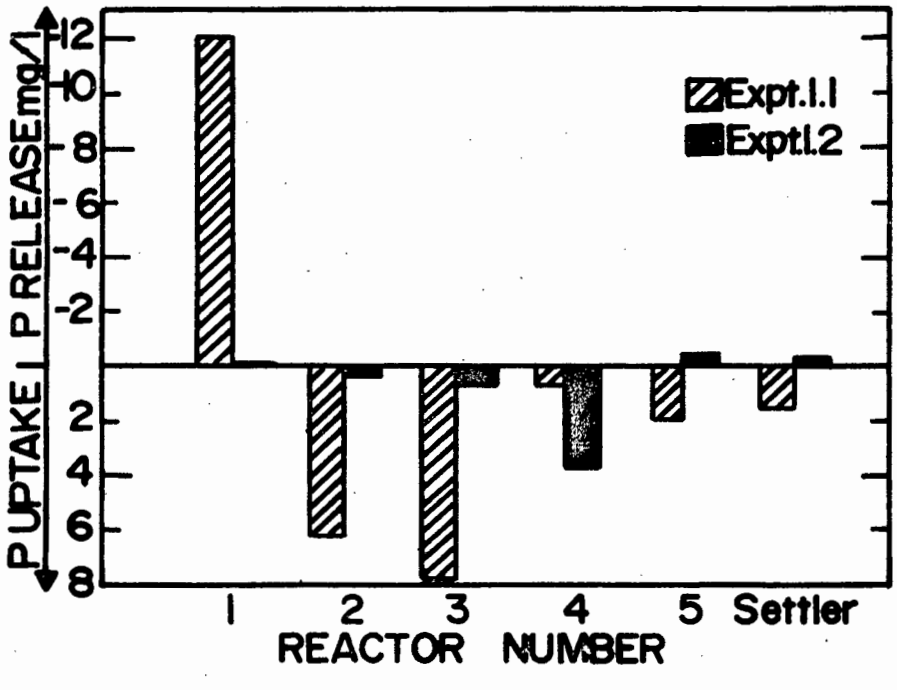

Fig. 5.1(b) Phosphorus release and uptake relative to the influent concentration.

Table 5.3 Mean Values for Experiment 1.2

		Reactor No.						
	Inf.	1	2	3	4	5	Eff.	Filt.eff.
COD mg/ℓ	470	-	-	-	-	-	35	-
TKN mg/ℓ	47,40	-	-	-	-	-	2,00	-
P mg/ℓ	12,88	11,00	9,45	9,35	8,75	9,00	9,80	9,10
pH	7,20	7,15	7,00	7,00	6,95	6,90	7,10	-
NO_3 mg/ℓ	<0,20	0,80	3,90	6,90	9,60	14,20	-	14,20
VSS	-	-	-	-	-	2982	-	-
O_2 demand mg/ℓ/h	-	-	-	68,00	48,10	19,90	-	-

Using Eq. (2.2) and a system phosphorus removal of 3,78, α = 0,060.

Phosphorus mass balances on each reactor were calculated as in Experiment 1.1 and are presented in Table 5.4.

Table 5.4 Phosphorus Release and Uptake Relative to the Influent Concentration.

Reactor	1	2	3	4	5	Settler
ΔP mg/ℓ	-0,02	+0,30	+0,60	+3,60	-0,50	-0,20

+ve Uptake of P by the sludge/ℓ of influent flow
-ve Release of P by the sludge/ℓ of influent flow

Phosphorus and nitrate concentrations in each reactor and the corresponding phosphorus mass balances on each reactor are graphically plotted in Figs. 5.1(a) and 5.1(b). Comparing the data in the above plots over the two test periods, the process responded in a significantly different

manner insofar as phosphorus removal behaviour was concerned. The system phosphorus removal declined from 6,09 to 3,78 mg/ℓ and the value of α from 0,133 to 0,060. In enquiring as to the cause for this change in behaviour, the most apparent difference in response between the two experiments is that in Experiment 1.1 a large concentration of phosphorus was released in reactor No. 1 (see Table 5.2), whereas in Experiment 1.2 there was no nett release of phosphorus in the reactor (see Table 5.4).

According to Barnard's hypothesis, the presence of an anaerobic stress to the degree that the organisms release phosphorus, is required for the luxury uptake mechanism to operate. In Experiment 1.1, where phosphorus was released in reactor No. 1, there was no nitrate present in the reactor and the system phosphorus removal was high. In Experiment 1.2 a small concentration of nitrate (0,8 mg/ℓ) was present in the reactor, and there was no nett release of phosphorus (see Figs. 5.1(a) and (b)). Barnard's hypothesized prerequisite for luxury uptake appears to be supported by these two experiments. It would also appear that in Experiment 1.2 the higher concentration of nitrate (14,20 mg/ℓ NO_3-N)in the sludge recycle exceeded the denitrification capacity of the "anaerobic" reactor. In Experiment 1.1 the nitrate concentration was slightly lower (12,10 mg/ℓ NO_3-N) in the sludge recycle. The difference in the nitrate concentration in the recycles could have arisen from the slight differences in denitrification response due to the two sewage batches.

Barnard stated that in order to induce excess biological phosphorus removal, the organisms must be stressed in an environment that has no dissolved oxygen or nitrate present. However, in his definition of the term "anaerobic" no differentiation is made between a reactor which has just removed all incoming nitrate, i.e. denitrification capacity = incoming nitrate; and a reactor whose denitrification capacity exceeds the mass of incoming nitrate by some degree. It appears more likely that in addition to the "zero nitrate" requirement, a further requirement should be added i.e. a minimum anaerobic potential to reliably trigger off the phosphorus release mechanism.

Using the denitrification theory of Ekama, van Haandel and Marais (1979), the denitrification capacity of the anaerobic reactor D_{cl} can be calculated as follows:

$$D_{cl} = (S_{bi} - S_b)\{\frac{f_{bs}(1-PY)}{2,86} + \frac{YR_s}{1 + bR_s} K_2 f_{xa}\} \qquad (5.1)$$

where

D_{cl} = denitrification capacity of the anaerobic reactor (mg N/ℓ influent)

S_{bi}, S_b = biodegradable COD in the influent and effluent respectively (mg COD/ℓ)
For raw sewage with total influent COD, S_{ti} = 500 mg/ℓ, $S_{bi} = 0,82\ S_{ti} = 410$ mg/ℓ, $S_b \simeq 10$ mg/ℓ.

f_{bs} = rapidly biodegradable fraction of the influent biodegradable COD = 0,24

P = COD:VSS ratio = 1,48

K_2 = denitrification constant associated with the second denitrification phase in predenitrification reactor = 0,0042 at 20°C (mg N/mg X_a/hr)

f_{xa} = volume fraction of the anaerobic reactor relative to the total process volume.

In Experiment 1.1, S_{ti} = 510 mg/ℓ

$$f_{xa} = \frac{3}{20} = 0,15$$

$$D_{cl} = (0,82*510-10)\{\frac{0,24(1-1,48*0,45)}{2,86} + \frac{0,45*20}{1+0,24*20} * 0,0042*0,15*24\}$$

= 21,01 mg N/ℓ influent (system removal)

System incoming nitrate (from underflow recycle)

= 12,10*1 = 12,10 mg N/ℓ

i.e . Anaerobic potential

= 21,01 - 12,10 = 8,91 mg/ℓ

= <u>8,91 mg N/ℓ</u>

i.e. the reactor had the potential to remove a further 8,91 mg N/ℓ if more nitrate had been available.

Similarly for Experiment 1.2: S_{ti} = 470 mg/ℓ

D_{cl} = (0,82*470-10) 0,0280 + 0,0235

= 19,32 mg N/ℓ

System incoming nitrate

= 14,20*1 = 14,20 mg N/ℓ

i.e. Anaerobic potential

= 19,32 - 14,20

= <u>5,12 mg N/ℓ</u>

The above results indicate that with an anaerobic potential of approximately 9 mg N/ℓ in the anaerobic reactor, phosphorus release occurred in the reactor and excess biological phosphorus removal was induced (α = 0,133).

In Experiment 1.2 an anaerobic potential of 5,12 mg N/ℓ was calculated and negligible excess removal took place (α = 0,060). Comparing the calculated nitrate removed in Experiment 1.2 with that observed, there appears to be a discrepancy. In Experiment 1.2 a small concentration of nitrate (0,8 mg NO_3-N) was measured in the effluent from the anaerobic reactor. This would indicate that the reactor was operating at its full denitrification capacity, i.e.

Denitrification capacity

$$= 14{,}20 - 0{,}80 = 13{,}60 \text{ mg N/}\ell,$$

which is less than the theoretical denitrification capacity calculated using Eq. 5.1 (19,32 mg N/ℓ). This apparent contradiction may have arisen due to difficulties experienced in the measurement of nitrate. Nitrate measurement was done using a colorimetric method which appears to produce doubtful results for nitrate concentrations < 1,0 mg/ℓ as N, apparently due to interference in the colour development in samples drawn from anaerobic reactors (Stern and Marais, 1974).

If the prerequisite for luxury uptake is in fact the presence of an anaerobic condition with a minimum anaerobic potential, the Modified Activated Sludge Process has an inherent weakness.

In a Modified Activated Sludge Process, operating at a fixed sludge age, if the influent TKN/COD ratio is low (< 0,8), virtual complete denitrification and consequently low effluent nitrate concentrations are possible. Consequently the nitrate concentration in the underflow recycle is low and an appropriate anaerobic potential can be provided for in the anaerobic reactor. If however, the influent TKN/COD ratio is high (> 0,1) there is likely to be a high nitrate concentration in the effluent and hence in the underflow recycle. This increase in nitrate concentration entering the anaerobic reactor reduces its anaerobic potential, and reduces the likelihood of establishing the hypothesized prerequities of excess biological phosphorus removal. In this situation, the only flexibility in controlling the mass of nitrate recycled to the anaerobic zone would be to reduce the underflow recycle. This, however, may not be feasible as a reduced recycle may overload the settling tank and cause a sludge build-up,leading to problems with rising sludge due to denitrification in the settler.

In order to produce a configuration with a greater flexibility than the Modified Activated Sludge Process, the following modified configuration has been proposed and is called the University of Cape Town

(U.C.T.) Process. see Fig. 5.2.

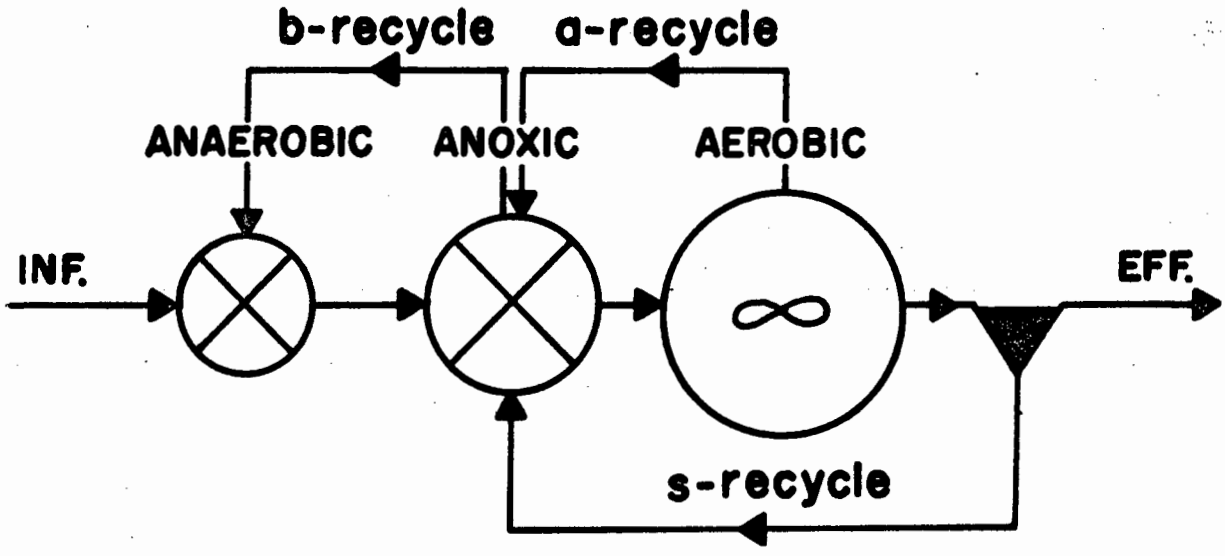

Fig. 5.2 The U.C.T. modification for nitrification, denitrification and phosphorus removal.

Referring to Fig. 5.2, the primary anoxic zone is divided into two as for the Modified Activated Sludge Process.

However, the underflow sludge recycle and the recycle from the aerobic zone both discharge to the anoxic reactor. A third recycle from the anoxic reactor to the anaerobic reactor is incorporated.

In this process the underflow or s-recycle is maintained at the usual ratio of 1:1 with respect to the influent flow. The recycle from the aerobic to the anoxic reactor (a-recycle) has a magnitude such that the nitrate in the effluent from the anoxic zone is maintained at a small positive value of 1 - 3 mg/ℓ. This magnitude is influenced principally by the TKN/COD ratio: the higher the ratio, the lower the recycle. The reason for this is that the denitrification capacity of the anoxic reactor is fixed by the size of the reactor. In contrast,

the nitrate generated in the aerobic reactor will increase as the TKN/COD ratio increases. Consequently, at higher TKN/COD ratios a lower recycle is required to supply the same mass of nitrate to the anoxic reactor. If the nitrate in the anoxic reactor is maintained at a low value, the recycle from the anoxic reactor will be supplying a small mass of nitrate to the anaerobic reactor, which has a high denitrification capacity. As a result, an anaerobic potential with a consequential phosphorus release is readily established. The anaerobic potential can be maintained by adjusting the a-recycle for influent TKN/COD ratios up to about 0,16.

By recycling from the anoxic to the anaerobic reactor the sludge concentration in the anaerobic reactor will be a function of the relative magnitude of the b-recycle with respect to the influent flow, i.e.

$$X_{v\ Anaerobic} = X_{v\ Anoxic} * \frac{1}{b+1} \qquad (5.2)$$

The reduction in sludge concentration has a relatively minor effect on the denitrification capacity of the anaerobic reactor as it is induced principally by the easily biodegradable fraction of the influent COD and takes place at a very high rate. The magnitude of the denitrification capacity of the anaerobic and anoxic reactors of the system can be readily calculated from the theory developed by Ekama, Van Haandel and Marais (1979) for steady state conditions, by making the necessary adjustments to the sludge concentrations in these reactors.

It should be noted in Fig. 5.2 that the secondary anoxic zone and the reaeration zone have been omitted. The reason for this is that for the same total anoxic volume fraction, the denitrification capacity of a system including a secondary anoxic zone, is lower than for one having

only a primary anoxic zone. If the influent TKN/COD ratio is low, there is some merit in including a secondary anoxic zone, but if the ratio > 0,09 it is not possible to have the secondary anoxic zone sufficiently large to accomplish total nitrate removal without endangering the nitrification capacity as it is necessary to limit the anoxic volume fraction to a level ensuring good nitrification. If the TKN/COD ratio is large, then even the maximum anoxic volume fraction cannot remove all the nitrate. It is therefore necessary to place the anoxic zones where they will be of maximum benefit i.e. in the primary anoxic zone.

With these remarks it will be evident that the potential of the U.C.T. Modification was sufficiently clear to demand an investigation into its behaviour. The research program was correspondingly changed and all the subsequent experiments were done on the configuration. Experiment 1.3 deals with a preliminary investigation into the process.

Experiment 1.3 The U.C.T. System (Fig. 5.3) was run using sewage with very similar characteristics to that used in Experiments 1.1 and 1.2, i.e. TKN/COD = 0,11. The raw data are listed in Appendix A8 and the mean values calculated over this period are presented in Table 5.5.

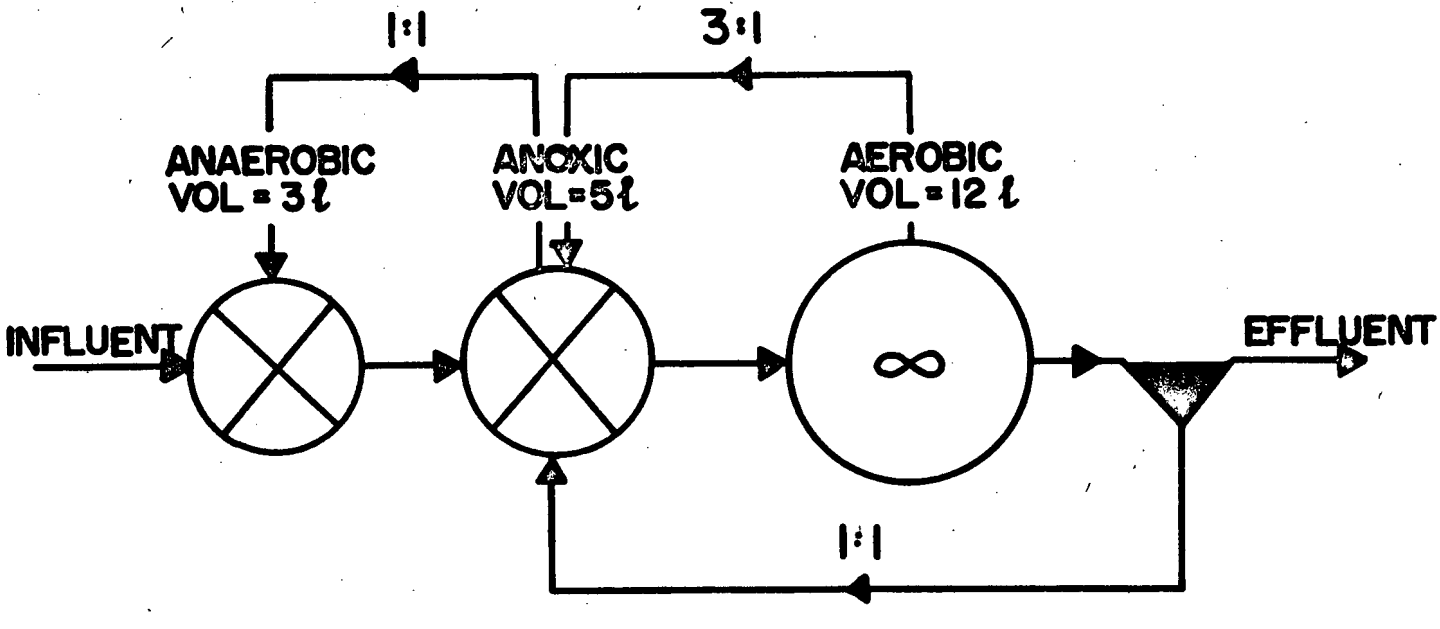

Fig. 5.3 The University of Cape Town (U.C.T.) experimental unit showing the inclusion of the b-recycle.

Table 5.5 Mean Values for Experiment 1.3

		Reactor No.				
	Inf.	1	2	3	Eff.	Filt.eff.
COD mg/ℓ	499	-	-	-	35	-
TKN mg/ℓ	53,00	24,80	7,80	2,00	1,30	-
P mg/ℓ	14,64	15,20	9,00	7,95	7,95	7,70
pH	7,30	7,35	7,20	7,10	7,35	-
NO_3 mg/ℓ	<0,20	<0,20	7,63	16,02	-	15,86
VSS mg/ℓ	-	1852	-	3430	-	-
O_2 demand mg/ℓ/h	-	-	-	38,60	-	-

Phosphorus mass balances were calculated considering the flows and phosphorus concentrations to and from each reactor as follows:

Table 5.6 Phosphorus Release and Uptake Relative to the Influent Concentration

Reactor 1	14,64*1	+	9,00*1	-	15,20*2			=	-6,76
Reactor 2	15,20*2	+	7,70*1	+	7,95*3	-	9,00*6	=	+7,95
Reactor 3	9,00*5	-	7,95*5					=	+5,25
Settler	7,95*2	-	7,70*2					=	+0,50
								Σ	+6,94

+ve Uptake of P by the sludge/ℓ of influent flow
-ve Release of P by the sludge/ℓ of influent flow

The system phosphorus removal was 6,94 mg/ℓ. Using Eq. (2.2) $\alpha = 0,159$.

The fraction of phosphorus removed as luxury uptake is in excess of the high fraction obtained by Martin and Marais (1975). When compared with Experiment 1.1, the system phosphorus removal and α value are slightly higher even though the TKN/COD ratio was the same. The advantage of the system can clearly be seen by the fact that in Experiment 1.1 and 1.2, 11,9 and 14,30 mg/ℓ of NO_3-N was discharged into the anaerobic reactor. In this system even though there were 15,86 mg/ℓ NO_3-N in the effluent, only 7,63 mg/ℓ NO_3-N were discharged into the reactor.

In order to calculate the anaerobic potential of the anaerobic reactor, an adjustment must be made to allow for the reduced sludge concentration in the reactor. Eq. 5.1 is based on the mean sludge concentration $\bar{X}_v$ in the process, assuming a uniform sludge concentration of sludge throughout the system. It is convenient to retain the concept of $\bar{X}_v$ and adjust the denitrification constant, K_2 in order to allow for the reduced sludge concentration due to the b-recycle as in Eq. 5.2 and the subsequent slight increase in sludge concentration in the remainder of the process due to the displacement of sludge from the anaerobic reactor to the remaining reactors, i.e. K_2 must be reduced by a factor

$$\frac{X_{va}}{\bar{X}_v} = \frac{1}{[f_{xa} + \frac{(b+1)(1-f_{xa})}{b}]} \qquad (5.3)$$

where

X_{va} = sludge concentration in the anaerobic reactor

f_{xa} = volume fraction in the anaerobic reactor

b = recycle ratio of the anaerobic reactor relative to the mean influent flow rate

In Experiment 1.3 $f_{xa} = 0,15$

$b = 1,0$

$$K_2' = \frac{1}{(0,15 + \frac{(1+1)(1-0,15)}{1}} * 0,0042$$

$= 0,541*0,0042$

$= 0,00227$

Using the value in Eq. 5.1 and S_{ti} = 499 mg COD/ℓ

$$D_{c1} = (0,82*499 - 10)(0,028 + \frac{0,45*20}{1+0,20*20}\ 0,00227*24*0,15)$$

$$= 16,24 \text{ mg N/ℓ}$$

System recovering nitrate to anaerobic reactor from anoxic reactor

$$= 7,63*1 = 7,63 \text{ mg N/ℓ}$$

i.e. Anaerobic potential of the anaerobic reactor

$$= 16,24 - 7,63$$

$$= 8,61 \text{ mg N/ℓ}$$

It should be noted that even though the phosphorus release in the first reactor was less in the U.C.T. System (6,76 versus 11,97 mg/ℓ P) than in Experiment 1.1, this mass of phosphorus was released by half the sludge concentration.

2. PHOSPHORUS REMOVAL BY DOSING WITH $FeSO_4$ AND NO pH ADJUSTMENT

The basic unit (not the U.C.T. Process) was run as before except that a $FeSO_4$ solution was fed into reactor No. 1. This solution was equivalent to 10,8 mg Fe/ℓ of influent (see Fig. 5.4).

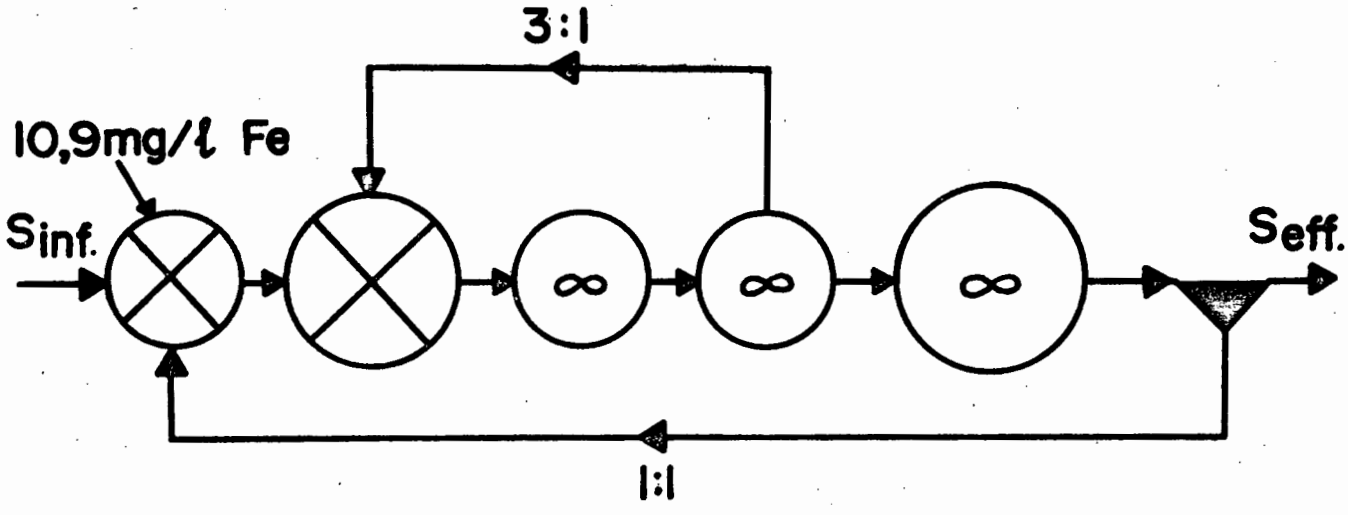

Fig. 5.4 Basic experimental unit showing addition of Fe salt solution

From the raw data listed in Appendix A9, the mean values for the investigation period were calculated and are listed in Table 5.7.

Table 5.7 Mean Values for Experiment 2.

		Reactor No.						
	Inf.	1	2	3	4	5	Eff.	Filt.eff.
COD mg/ℓ	474	-	-	-	-	-	41	-
TKN mg/ℓ	53,40	-	-	-	-	-	4,10	-
P mg/ℓ	10,78	4,17	3,78	3,70	3,59	3,38	4,08	3,36
pH	7,40	7,05	6,90	6,75	6,65	6,70	6,90	-
NO_3 mg/ℓ	<0,20	3,80	7,50	11,70	13,60	14,10	-	14,80
VSS mg/ℓ	-	-	-	-	-	2307	-	-
O_2 demand mg/ℓ/h				63,60	41,40	15,60		

Phosphorus mass balances on each reactor are presented in Table 5.8.

Table 5.8 Phosphorus Release and Uptake Relative to the Influent Concentration.

Reactor	1	2	3	4	5	Settler
ΔP mg/ℓ	+5,80	+0,21	+0,40	+0,55	+0,42	+0,04
+ve Uptake of P by the sludge/ℓ influent flow -ve Release of P by the sludge/ℓ influent flow						

The above data showed that the addition of 10,9 mg/ℓ Fe increased the system removal from 3,78 mg/ℓ in Experiment 1.2 to 6,70 mg/ℓ.

From the fact that nitrate was present in reactor No. 1 no release could be expected in the reactor. An α value of 0,06 was used to calculate the phosphorus removal due to biological processes only, in this experiment.

ΔP (assuming no chemical addition) = 3,67 mg/ℓ

i.e. Extra P removed = 6,70 - 3,67 = 3,03

i.e. $\Delta P/Fe$ = 3,03/10,9 = 0,279

or 3,59 mg Fe^{++} removed 1 mg of P.

Stoichiometrically, the mass ratio for Fe^{++} and P is 1,8:1. This means that the removal of phosphorus by iron salt addition was approximately only 50% efficient. The effluent was light yellow green in colour and turbid. The turbidity contained approximately 0,7 mg/ℓ of phosphorus and was therefore a source of phosphorus in the effluent. It was concluded that this adverse response was due to the low pH, i.e. 6,75 - 6,85 in the aerobic zone. It was decided therefore, to raise the pH so that it would not fall below 7,0 at any stage in the process.

3. PHOSPHORUS REMOVAL BY DOSING WITH $FeSO_4$ WITH pH ADJUSTMENT

The investigation was done in two stages: Experiments 3.1 and 3.2 using $FeSO_4$ and $Ca(OH)_2$ addition; Experiments 3.3 and 3.4 using $FeSO_4$ and $NaHCO_3$ addition.

Experiment 3.1 The experimental conditions were kept the same as in Experiment 2, except that 66,7 mg/ℓ $Ca(OH)_2$ (i.e. 2 g/30ℓ) was mixed into the influent to raise the pH of the process (see Fig. 5.5). This addition raised the influent pH from 7,45 to 8,65 and the pH range in the process from 6,75 - 7,05 to 7,35 - 7,90. The iron feed was fed into reactor No. 5.

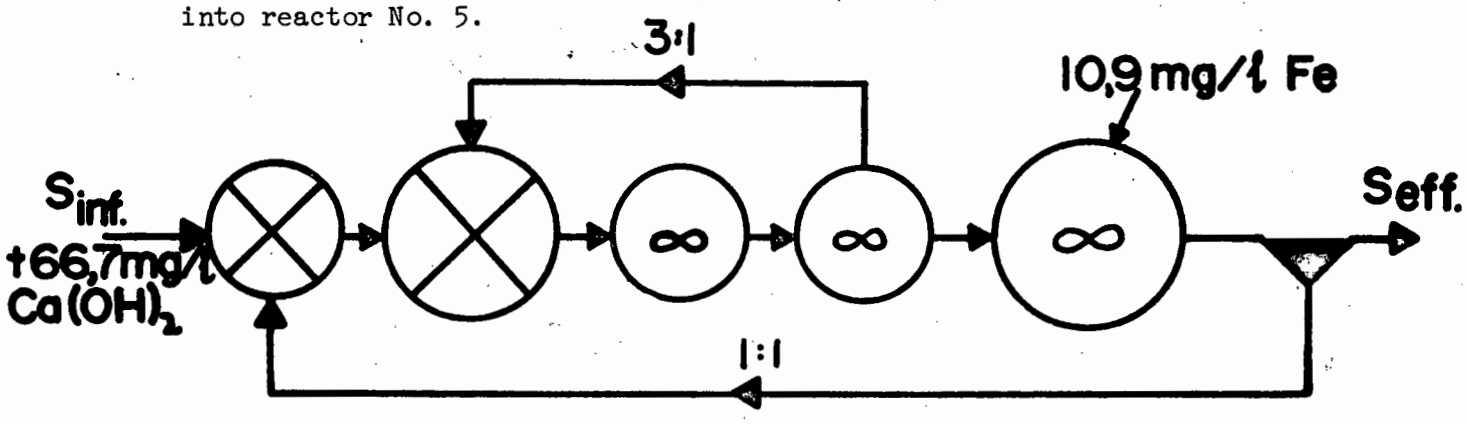

Fig. 5.5 Basic experimental unit showing addition of Fe salt and $Ca(OH)_2$

The raw data are presented in Appendix A10 and the mean values for the investigation period in Table 5.9.

Table 5.9 Mean Values for Experiment 3.1

		Reactor No.						
	Inf.	1	2	3	4	5	Eff.	Filt.eff.
COD mg/ℓ	462	-	-	-	-	-	25	-
TKN mg/ℓ	38,50	-	-	-	-	-	3,60	-
P mg/ℓ	10,55	3,60	2,85	2,20	2,42	1,63	2,20	2,10
pH	8,65	7,90	7,60	7,35	7,45	7,40	7,50	-
NO_3 mg/ℓ	< 0,20	1,00	3,00	6,90	7,60	7,90	-	6,70
VSS mg/ℓ	-	-	-	-	-	2210	-	-
O_2 demand mg/ℓ/h	-	-	-	51,90	19,80	11,10	-	-

Phosphorus mass balances on each reactor are presented in Table 5.10.

Table 5.10 Phosphorus Release and Uptake Relative to the Influent Concentration

Reactor	1	2	3	4	5	Settler
ΔP mg/ℓ	+5,45	+0,21	+3,25	-1,10	+1,58	-0,94
+ve Uptake of P by the sludge/ℓ of influent flow -ve Release of P by the sludge/ℓ of influent flow						

The effluent quality improved immediately with the raising of the reactor pH. The turbidity and colour disappeared, the effluent being clear and colourless. The system phosphorus removal improved considerably to 8,35 mg/ℓ.

From Table 5.9 it is evident that there was a small concentration of nitrate present in reactor No. 1. Again, no nett release of phosphorus can be

expected, and an α value of 0,06 was used to calculate the biological removal.

ΔP (assuming no chemical addition) = 3,81 mg/ℓ, i.e.

Extra P removed = 8,35 - 3,81 = 4,54 mg/ℓ, i.e.

$\Delta P/Fe$ = 4,56/10,9 = 0,417, or

2,40 mg Fe^{++} removed 1 mg P.

It was concluded that raising the pH of the process improved both the phosphorus removal and the effluent quality.

In both Experiment 2 and Experiment 3.1, the assumption that α = 0,06 is made. Whether this is correct or not cannot be determined. However, this does not adversely affect the conclusions from these two experiments, i.e. that the pH affects the phosphorus removal due to iron salt addition. All the parameters with the exception of the system phosphorus removal and the pH remained approximately the same.

Experiment 3.2 In order to achieve a lower phosphorus concentration in the effluent the iron dosage was increased from 10,9 to 13,4 mg/ℓ and fed into reactor No.3. The $Ca(OH)_2$ dosage was increased from 66,7 to 100 mg/ℓ (i.e. 3g/30ℓ) and fed directly into the influent flow just prior to the point of discharge to the unit (see Fig. 5.6). The extra alkalinity raised the process pH to between 7,45 and 8,10.

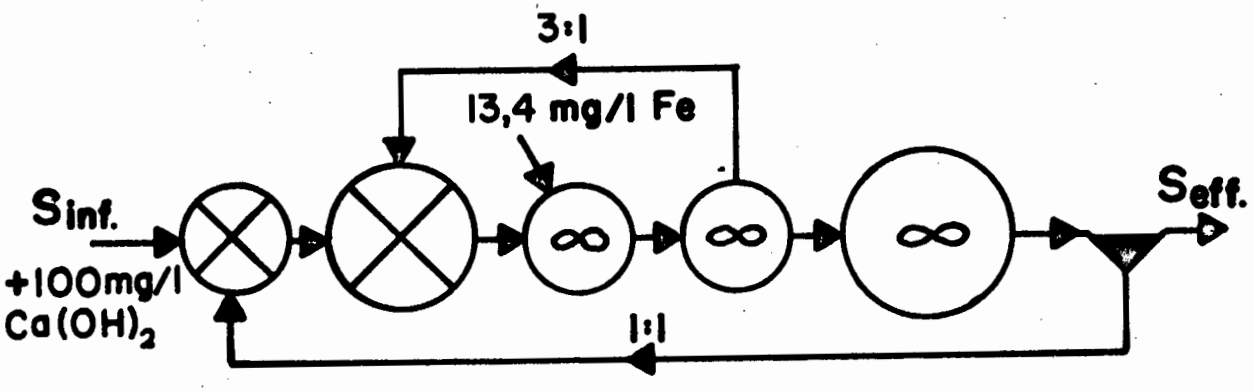

Fig. 5.6 Basic experimental unit showing addition of Fe salt and $Ca(OH)_2$ solution.

The raw data are presented in Appendix 11 and the mean values for the investigation period in Table 5.11.

Table 5.11 Mean Values for Experiment 3.2

		Reactor No.						
	Inf.	1	2	3	4	5	Eff.	Filt.eff.
COD mg/ℓ	503	-	-	-	-	-	28	-
TKN mg/ℓ	35,20	-	-	-	-	-	1,30	-
.P mg/ℓ	11,00	3,55	2,95	2,43	2,32	1,42	1,50	1,48
pH	7,00	8,10	7,65	7,50	7,40	7,50	7,50	-
NO_3 mg/ℓ	-	< 0,20	<0,20	2,30	4,00	5,00	-	4,80
VSS mg/ℓ	-	-	-	-	-	3367	-	-
O_2 demand mg/ℓ/h	-	-	-	55,40	35,90	20,70	-	-

Phosphorus mass balances on each reactor are presented in Table 5.12.

Table 5.12 Phosphorus Release and Uptake Relative to the Influent Concentration

Reactor	1	2	3	4	5	Settler
ΔP mg/ℓ	+5,38	-0,69	+2,60	+0,55	+1,80	-0,12
+ve Uptake of P by the sludge/ℓ of influent flow -ve Release of P by the sludge/ℓ of influent flow						

With the increase in chemical dosage the phosphorus removal increased from 8,35 to 9,50 mg/ℓ. However, from Table 5.11, there were no nitrates present in reactor No. 1 and consequently the same α value used in the previous experiment could not be assumed. In fact, it was not possible to obtain a reliable value for α.

From the above data it is evident that, although there was no nitrate present in reactor No. 1. there was a considerable nett uptake of phosphorus in the reactor. This would appear to be contrary to the theory concerning luxury uptake. It is possible that the apparent uptake of P could be due to calcium phosphate precipitation. To test this hypothesis, it was decided to change the alkalinity source from $Ca(OH)_2$ to $NaHCO_3$, as the latter does not raise the pH of the calcium content of the influent, but provides a buffer capacity against pH change in the process.

Experiment 3.3 In order to test to what degree the use of $Ca(OH)_2$ in the influent contributed to system phosphorus removal an equivalent amount of alkalinity (as $CaCO_3$) of $NaHCO_3$ was used as the alkalinity source. The experimental conditions of Experiment 3.1 were kept constant except that 150 mg/ℓ $NaHCO_3$ (i.e. 4,54 g/30 ℓ) were mixed into the influent instead of the lime. 10,9 mg/ℓ Fe were fed directly into reactor No. 3 (see Fig. 5.7).

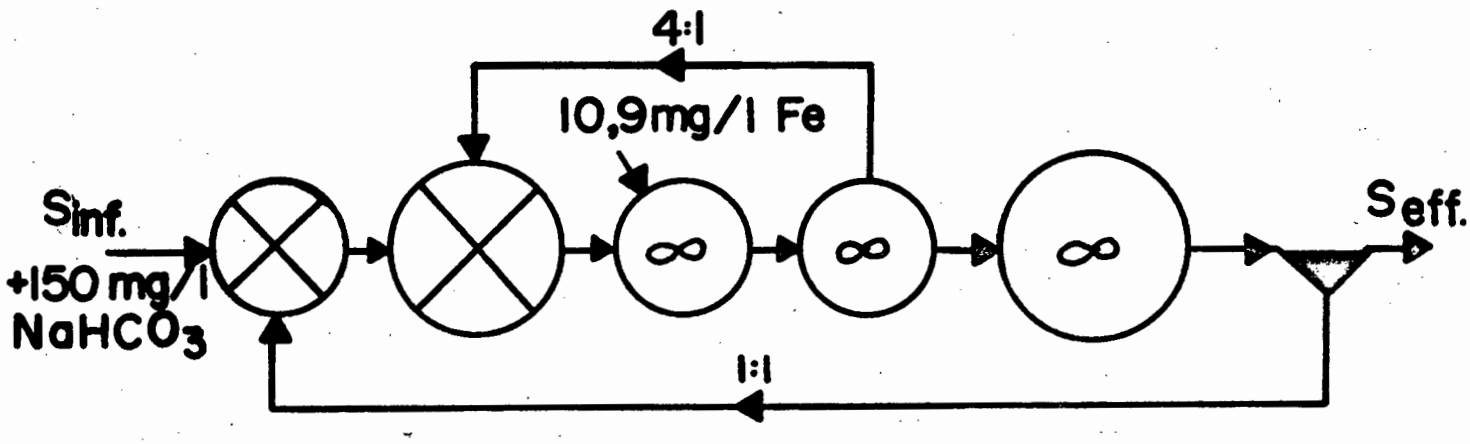

Fig. 5.7 Basic experimental unit showing addition of Fe salt and $NaHCO_3$

The raw data are listed in Appendix 12 and the mean values for the investigation period in Table 3.13.

Table 5.13 Mean values for Experiment 3.3

		Reactor No.						
	Inf.	1	2	3	4	5	Eff.	Filt.eff.
COD mg/ℓ	537	-	-	-	-	-	37	-
TKN mg/ℓ	46,30	-	-	-	-		2,40	-
P mg/ℓ	11,74	11,90	5,50	5,20	4,24	2,77	3,19	2,97
pH	7,40	7,45	7,45	7,35	7,45	7,55	7,65	-
NO_3 mg/ℓ	<0,20	<0,20	<0,20	5,60	7,00	7,20	-	7,10
VSS mg/ℓ	-	-	-	-	-	3191	-	-
O_2 demand mg/ℓ/h	-	-	-	83,80	30,90	23,30	-	-

Phosphorus mass balances on each reactor are presented in Table 5.14.

Table 5.14 Phosphorus Release and Uptake Relative to the Influent Concentration

Reactor	1	2	3	4	5	Settler
ΔP mg/ℓ	-9,09	+7,76	+1,80	+5,76	+2,94	-0,40

+ve Uptake of P by the sludge/ℓ of influent flow
-ve Release of P by the sludge/ℓ of influent flow

The system phosphorus removal was 8,55 mg/ℓ which is not significantly different from the removal achieved in Experiment 3.1 using $Ca(OH)_2$ as the source of alkalinity. However, the phosphorus removal pattern was completely different . In reactor No 1 there was a large nett release of phosphorus (9,09 mg/ℓ) in accordance with Barnard's hypothesis.

The experimental results are discussed more fully at the end of Experiment 3.4.

Experiment 3.4 The experimental conditions were kept the same as in Experiment 3.2, except that $NaHCO_3$ provided the source of alkalinity instead of $Ca(OH)_2$: 224 mg $NaHCO_3/\ell$ of influent (equivalent alkalinity to 100 mg $Ca(OH)_2/\ell$ as $CaCO_3$) was mixed into the influent. The iron salt dosage was kept the same at 13,4 mg Fe/ℓ of influent and fed into reactor No. 3. (See Fig. 5.8). The pH in the process was 7,30 - 7,50.

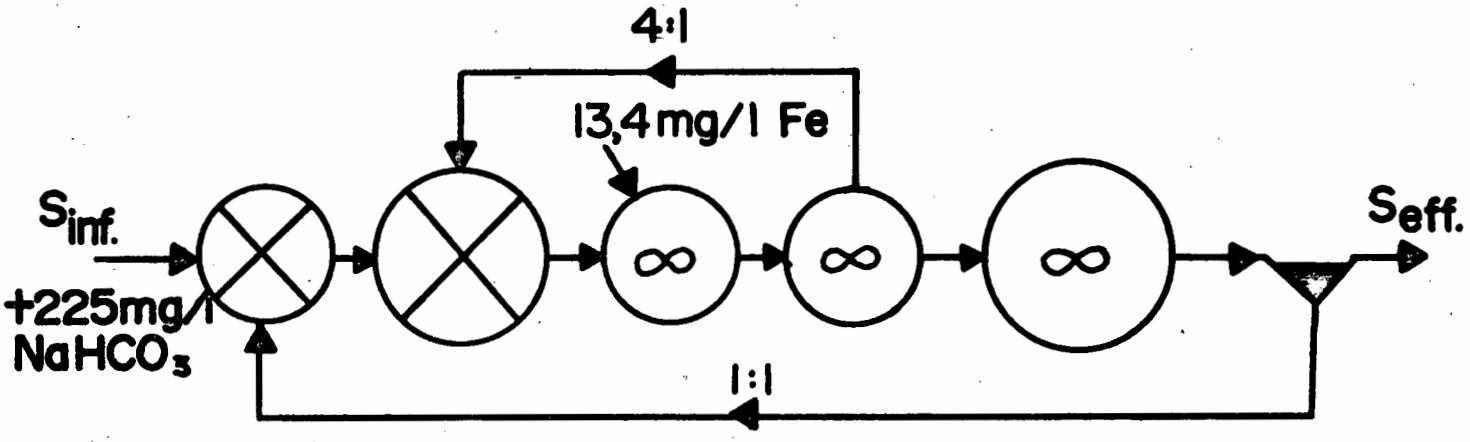

Fig. 5.8 Basic experimental unit showing addition of Fe salt and $NaHCO_3$.

The raw data are presented in Appendix A13 and the mean values for the investigation period in Table 5.15.

Table 5.15 Mean values for Experiment 3.4

		Reactor No.						
	Inf.	1	2	3	4	5	Eff.	Filt.eff.
COD mg/ℓ	515	-	-	-	-	-	33	-
TKN mg/ℓ	41,00	-	-	-	-	-	2,10	-
P mg/ℓ	12,02	10,20	4,48	3,13	2,18	1,95	2,50	2,12
pH	7,25	7,40	7,45	7,30	7,40	7,50	7,70	-
NO_3 mg/ℓ	<0,20	<0,20	1,20	6,50	6,70	7,60	-	7,60
VSS mg/ℓ	-	-	-	-	-	3148	-	-
O_2 demand mg/ℓ/h	-	-	-	78,80	25,60	21,40	-	-

Phosphorus mass balances on each reactor are presented in Table 5.16.

Table 5.16 Phosphorus Release and Uptake Relative to the Influent Concentration

Reactor	1	2	3	4	5	Settler
ΔP mg/ℓ	-6,26	+2,24	+8,40	+5,70	+0,46	-0,34
+ve Uptake of P by the sludge/ℓ of influent flow -ve Release of P by the sludge/ℓ of influent flow						

The system phosphorus removal was 9,52 mg/ℓ as P which is similar to the removal in Experiment 3.2 using an equivalent concentration of added iron and $NaHCO_3$ as an alkalinity source.

Comparing the phosphorus removal between the experiments the process was equally efficient if either $Ca(OH)_2$ or $NaHCO_3$ was used to raise the pH. It would appear therefore, that $Ca(OH)_2$ addition did not result in an overall removal of phosphorus by calcium phosphate precipitation.

Although the phosphorus removal was the same, the behaviour pattern of the phosphorus was distinctly different between $NaHCO_3$ and $Ca(OH)_2$ addition (compare the phosphorus profiles in Fig. 5.9). In Experiments (3.1 and 3.2) where $Ca(OH)_2$ was added to the influent, there appeared to be a nett uptake of phosphorus in reactor No. 1. In contrast, in Experiments (3.3 and 3.4) where $NaHCO_3$ was added, there appeared to be a nett release in the reactor. In both these sets of experiments no nitrate was recorded in the 1st reactor and the influent COD and TKN values were approximately the same. With $Ca(OH)_2$ addition, the fraction of the overall phosphorus removal took place in reactor No. 1, and the balance in reactor No. 3, the first aerobic reactor and point of Fe^{++} addition. With the $NaHCO_3$ addition however, most of the removal took place in reactor No. 3, the first aerobic reactor and point of Fe^{++} addition and reactor No. 4, the second aerobic reactor.

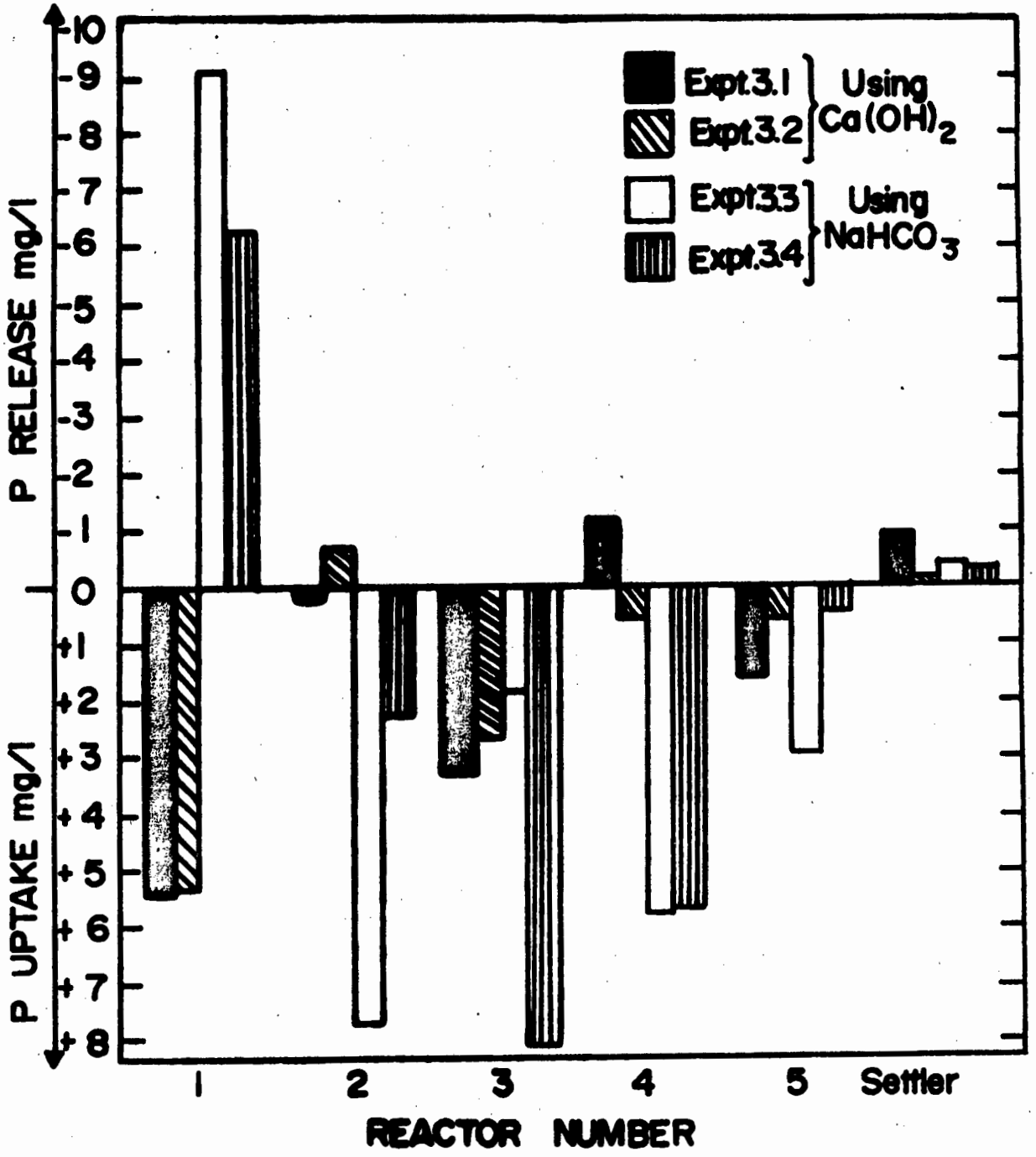

Fig. 5.9 Phosphorus release and uptake (relative to the influent concentration) profiles in Experiment 3

A possible explanation for the difference in behaviour pattern is to be found in previous research done in this laboratory, where it was repeatedly shown that, although some form of calcium phosphate is precipitated by the addition of $Ca(OH)_2$ at a pH of about 9,1, the precipitant is unstable and redissolves at lower pH encountered in the subsequent reactors. In the sets of experiments under discussion here using $Ca(OH)_2$ addition, biological release might take place in the 1st reactor, but due to calcium phosphate precipitation in the influent and 1st reactor, the combined effect is manifested as a nett uptake of phosphorus. Similarly in the subsequent reactors, the reduced phosphorus uptake apparently observed (or even released, observed in Experiment 3.1) in the aerobic reactors, may reflect a degree of calcium phosphate redissolution.

With $NaHCO_3$ addition, no $PO_4^{\equiv}$ precipitation takes place and the balances reflect normal biological and $FePO_4$ precipitation phenomena.

From the comparison of the behaviour of the process with $Ca(OH)_2$ and $NaHCO_3$ addition respectively, the $Ca(OH)_2$ addition causes temporary calcium phosphate precipitation (possibly due to the raised pH, although this is not certain) which redissolves later, resulting in no nett effect on the system removal of phosphorus.

4. CYCLIC FLOW BEHAVIOUR

Phosphorus Removal Using $FeSO_4$ Addition and pH Adjustment

In the following experiments, the efficiency of chemical addition to the activated sludge process under cyclic loading conditions was investigated. The average influent flow rate was kept at 30 ℓ/d except that this volume was fed at 15 ℓ/d for the first 12 hour period and at 45 ℓ/d for the remaining 12 hours (see Fig.5.10(a)). The a- and s-recycles were kept constant at 4:1 and 1:1 respectively, with respect to the mean daily flow. The $FeSO_4$ solution was fed at a constant rate into reactor No. 3. No phosphorus balances were calculated on each

reactor, as each reactor was not in a steady state over the 24 hour period and, as such, balances are of little informative value. A balance, using the mean phosphorus removal over each day was, however, calculated. The investigation was divided into two experiments as follows:

Experiment 4.1: System Phosphorus Removal using $FeSO_4$ under Cyclic Loading Conditions and $Ca(OH)_2$ as an Alkalinity Source.

Experiment 4.2: System Phosphorus Removal using $FeSO_4$ under Cyclic Loading Conditions and $NaHCO_3$ as an Alkalinity Source.

Experiment 4.1 The experimental conditions were kept the same as in Experiment 3.2 except that the influent was fed in a square wave loading pattern instead of a constant loading rate. The $FeSO_4$ addition was 13,4 mg Fe/ℓ with respect to the mean daily influent flow and was fed into reactor No. 3 at a constant rate. As in Experiment 3.2, in order to raise the process alkalinity, 100 mg/ℓ $Ca(OH)_2$ (i.e. 3 g/30 ℓ) was mixed into the influent. This resulted in an influent pH of 8,95 and a reactor pH range of between 7,35 and 8,15. Samples of the reactor contents were drawn off only once daily, near the end of each feed cycle, i.e. towards the end of the high feeding rate period. An effluent sample representing the mean effluent quality over the 24 hour period was also taken at this point. The raw data are listed in Appendix A14 and the mean values for the investigation period are presented in Table 5.17.

The mean system phosphorus removal over the whole investigation period was 9,75 mg/ℓ as P. This value (for the cyclic flow experiment) compares favourably with that of the steady state experiment, Experiment 3.2 (system removal = 9,50 mg/ℓ as P). It would appear that the process worked equally efficiently under cyclic as under steady state loading conditions, even though the iron salt was fed directly into the process at a continuous steady rate.

Table 5.17 Mean Values for Experiment 4.1

		Reactor No.						
	Inf.	1	2	3	4	5	Eff*	Filt.Eff.*
COD mg/ℓ	504	-	-	-	-	-	33	-
TKN mg/ℓ	43,00	-	-	-	-	-	1,10	-
P mg/ℓ	10,87	3,54	2,27	1,68	1,52	1,06	1,12	0,92
pH	8,95	8,15	7,75	7,50	7,35	7,45	7,75	-
NO_3 mg/ℓ	<0,20	<0,20	<0,20	4,20	7,40	9,30	-	8,90
VSS mg/ℓ	-	-	-	-	-	3364	-	-
O_2 demand				pm: 53,00	18,30	16,10		
mg/ℓ/h				am: 76,90	58,60	23,00		

* Sample representing mean effluent quality over 24 hour period, i.e. 24 hour composite sample.

Experiment 4.2 The experimental conditions of Experiment 4.1 were repeated except that the alkalinity of the influent was raised by the addition of 226 mg/ℓ $NaHCO_3$ (i.e. 6,81 g/30 ℓ) instead of lime. (Addition of this alkalinity source affects the influent pH only minimally). The influent was fed in the square wave loading pattern as before and 13,4 mg Fe/ℓ as $FeSO_4$ were fed into reactor No. 3 at a constant rate. Once again samples for the reactors were drawn off near the end of the high feeding rate period and a 24 hour composite sample was taken of the effluent. The raw data are listed in Appendix A15 and the mean values for the investigation period are presented in Table 5.18.

The system phosphorus removal was 9,31 mg/ℓ as P which compares well with that of Experiment 4.1 (system removal = 9,72 mg/ℓ) in which an equivalent quantity of alkalinity (as $CaCO_3$) in the form of $Ca(OH)_2$ was added to the influent. The system removal also compares well with that of Experiment 3.4 (system removal = 9,52 mg/ℓ) in which the same quantities of $NaHCO_3$ and $FeSO_4$ were used but under steady state loading conditions.

Table 5.18 Mean Values for Experiment 4.2

		Reactor No.						
	Inf.	1	2	3	4	5	Eff.*	Filt.Eff.*
COD mg/ℓ	454	-	-	-	-	-	33	-
TKN mg/ℓ	52,50	-	-	-	-	-	3,30	-
P mg/ℓ	11,75	10,90	5,78	4,50	3,86	2,50	2,44	2,14
pH	7,20	7,40	7,35	7,35	7,25	7,40	7,65	-
NO_3 mg/ℓ	<0,20	<0,20	3,10	7,10	12,20	14,30	-	13,30
VSS mg/ℓ	-	-	-	-	-	3259	-	-
O_2 demand mg/ℓ/h				am: 74,40	66,00	20,60		

*Sample representing mean effluent quality over 24 hour period

The process works equally well under influent steady state and cyclic loading conditions even though the chemicals are fed in at a constant rate. Experiments 4.1 and 4.2 support the observations of Experiments 3.1 - 3.4, i.e. that:

1. at a pH of about 7,2, calcium phosphate precipitation does not appear to take place, nor does it contribute to the system phosphorus removal, and
2. raising the pH to about 9,0 by $Ca(OH)_2$ addition causes some calcium phosphate precipitation but the precipitate is unstable and redissolves if lower pH values are present in the process.

One 24 hour test was done where effluent samples were taken every hour over a 24 hour period. The effluent quality over the period is plotted in Fig. 5.10(b). Although the effluent quality varied cyclically, the mean system removals (9,75 and 9,31 mg/ℓ as P) were not significantly

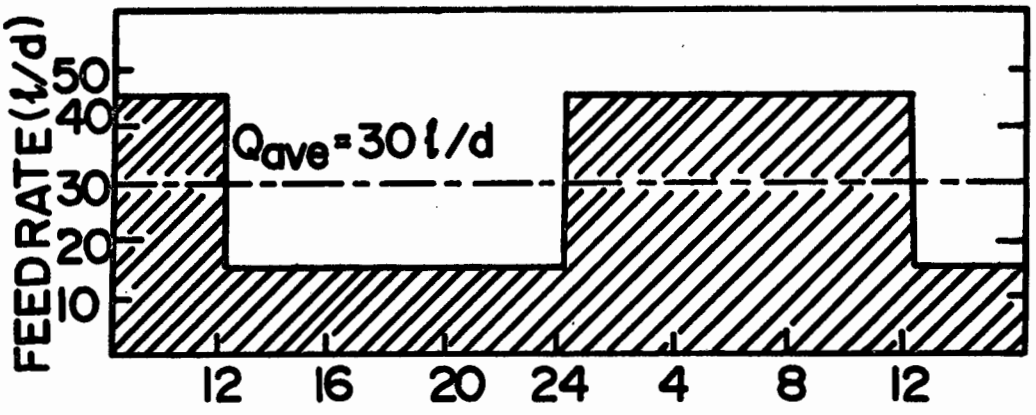

Fig. 5.10(a) The square wave influent loading rate used in Experiments (4.1 and 4.2).

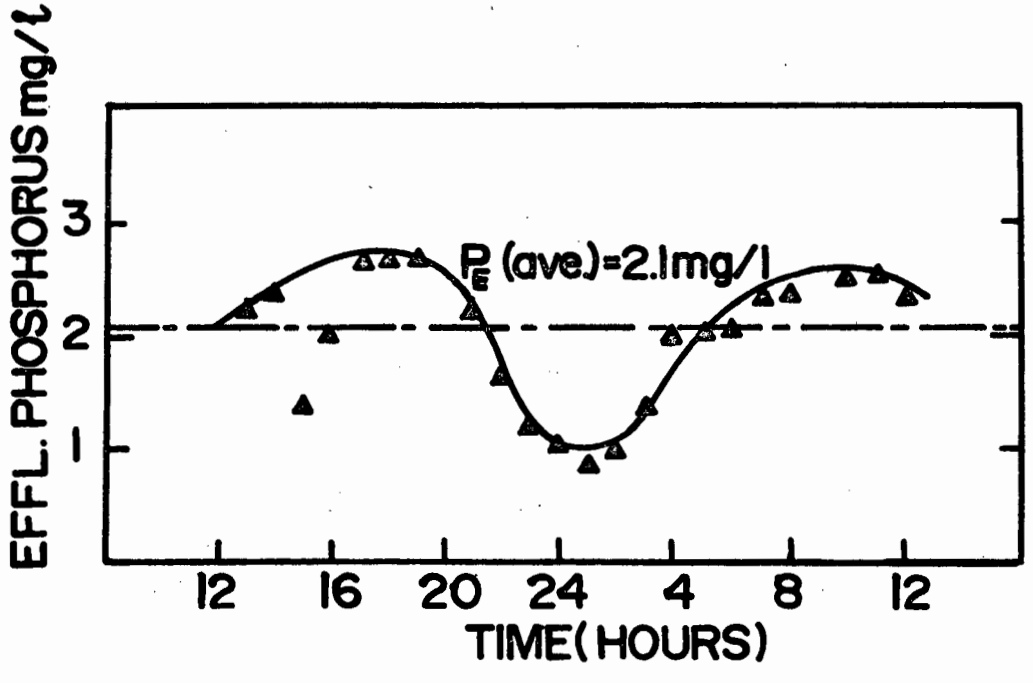

Fig. 5.10(b) The filtered effluent quality under daily cyclic loading in Experiment 4.2

different from those of the steady state experiments (9,50 and 9,72 mg/ℓ as P). The phosphorus concentration in the effluent from the settler showed a bimodal behaviour. Peaks occurred in both the low and high flow periods, with a minimum value at the end of the low flow period. The cyclicity does not appear to be consistently in or out of phase with the flow rate. The reason for this is that the effluent was sampled from the discharge point of the settler, which had a considerable volume (1,5 ℓ) relative to the low flow rate (15 ℓ/d or 0,625 ℓ/h). During the low flow period the lag in the effluent concentration was three times longer than during the high flow period. This caused a distortion of the effluent quality cyclic response compared with the cyclic flow pattern.

5. PHOSPHORUS REMOVAL BY DOSING WITH $FeCl_3$ (INSTEAD OF $FeSO_4$) WITH pH ADJUSTMENT

Steady State Investigation

Up to this stage all chemical dosing for phosphorus removal was by $FeSO_4$ addition. Ferric chloride is also widely used as a dosing chemical. The objective of this series of investigations was to gauge the effliciency of $FeCO_3$ addition for low and high dosages of the metal salt.

The series was divided into the following four experiments:

Experiments 5.1, 5.2 and 5.3 deal with the addition of 5, 10 and 15 mg Fe/ℓ of influent to the basic experimental unit.

Experiment 5.1 The basic experimental unit was run with a $FeCL_3$ solution equivalent to 5 mg Fe/ℓ of influent being fed into reactor No. 3. The pH of the process was raised by the addition of 66,7 mg/ℓ $Ca(OH)_2$ (i.e. 2 g/30 ℓ) to the influent. see Fig. 5.11.

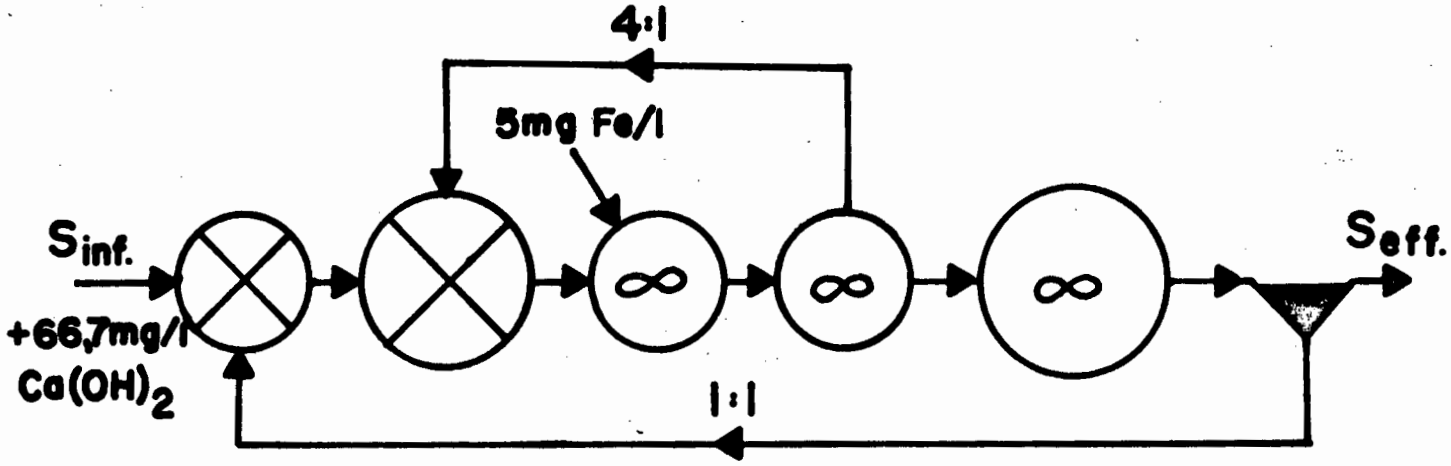

Fig. 5.11 Basic experimental unit showing $FeCL_3$ and $Ca(OH)_2$ addition

The raw data for the investigation period are listed in Appendix A16 and the mean values presented in Table 5.19.

Table 5.19 Mean Values for Experiment 5.1

		Reactor No.						
	Inf.	1	2	3	4	5	Eff.	Filt.Eff.
COD mg/ℓ	509	-	-	-	-	-	38	-
TKN mg/ℓ	40,50	-	-	-	-	-	0,80	-
P mg/ℓ	13,21	6,70	5,43	4,94	4,79	4,53	4,79	4,45
pH	8,75	7,65	7,20	7,00	7,05	7,15	7,25	-
NO_3 mg/ℓ	<0,20	<0,20	1,40	4,50	5,20	6,80	-	7,50
VSS mg/ℓ	-	-	-	-	-	3077	-	-
O_2 demand mg/ℓ/h	-	-	-	68,30	34,90	23,40	-	-

Phosphorus mass balances on each reactor are shown in Table 5.20.

Table 5.20 Phosphorus Release and Uptake Relative to the Influent Concentration

Reactor	1	2	3	4	5	Settler
ΔP mg/ℓ	+4,26	-0,02	+2,94	+0,90	+0,52	+0,16
+ve Uptake of P by the sludge/ℓ of influent flow -ve Release of P by the sludge/ℓ of influent flow						

Experiment 5.2 The experimental conditions of Experiment 5.1 were kept constant except that the $FeCl_3$ salt dosage was increased to 10 mg Fe/ℓ of influent. The $Ca(OH)_2$ dosage was increased to 100 mg/ℓ (i.e. 3 g/30 ℓ), see Fig. 5.12.

The raw data for the investigation period are listed in Appendix A17 and the mean values presented in Table 5.21.

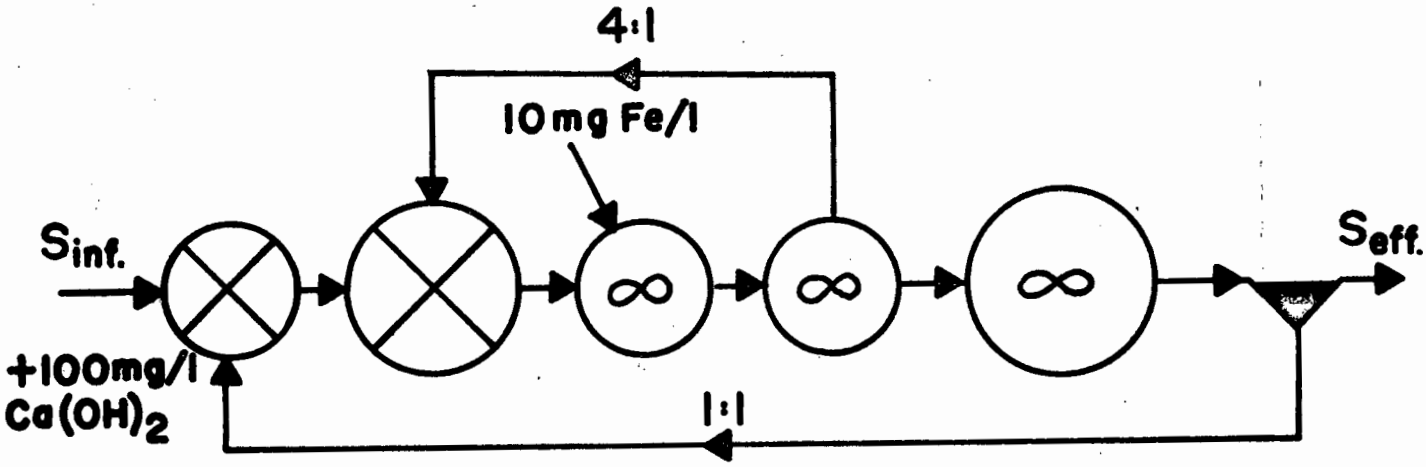

Fig. 5.12 Basic experimental unit showing $FeCl_3$ and $Ca(OH)_2$ addition.

Table 5.21 Mean Values for Experiment 5.2

		Reactor No.						
	Inf.	1	2	3	4	5	Eff.	Filt.Eff.
COD mg/ℓ	522	-	-	-	-	-	29	-
TKN mg/ℓ	44,60	-	-	-	-	-	3,00	-
P mg/ℓ	14,50	9,20	5,35	4,35	4,00	3,35	3,30	3,10
pH	9,10	7,90	7,50	7,25	7,20	7,35	7,50	-
NO_3 mg/ℓ	<0,20	<0,20	<0,20	2,40	4,00	6,40	-	6,30
VSS mg/ℓ	-	-	-	-	-	3197	-	-
O_2 demand mg/ℓ/h	-	-	-	78,60	44,50	19,50	-	-

Phosphorus mass balances on each reactor are shown in Table 5.22.

Table 5.22 Phosphorus Release and Uptake Relative to the Influent Concentration

Reactor	1	2	3	4	5	Settler
ΔP mg/ℓ	-0,80	+2,50	+6,00	+2,10	+1,35	+0,50
+ve Phosphorus taken up by sludge/ℓ of influent flow -ve Phosphorus released by sludge/ℓ of influent flow						

With the increase in Fe salt addition from 5 to 10 mg Fe/ℓ of influent the system phosphorus removal increased from 8,42 to 11,20 mg/ℓ as P.

Experiment 5.3 The experimental conditions of Experiment 5.2 were kept constant except that the $FeCl_3$ dosage was increased from 10 to 15 mg Fe/ℓ of influent. The $Ca(OH)_2$ dosage was maintained at 100 mg/ℓ and mixed into the influent, see Fig. 5.13

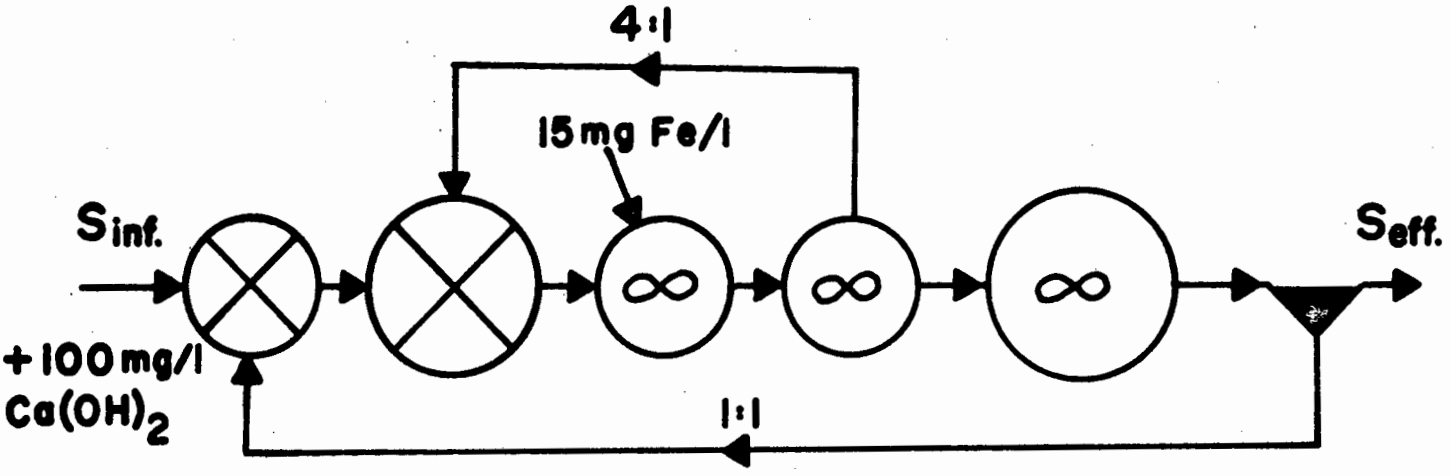

Fig. 5.13 Basic experimental unit showing the addition of $FeCl_3$ solution and $Ca(OH)_2$

The raw data are listed in Appendix A18 and the mean values for the investigation period are presented in Table 5.23.

Table 5.23 Mean Values for Experiment 5.3

		Reactor No.						
	Inf.	1	2	3	4	5	Eff.	Filt.Eff.
COD mg/ℓ	516	-	-	-	-	-	37	-
TKN mg/ℓ	38,30	-	-	-	-	-	1,70	-
P mg/ℓ	15,10	12,35	4,55	2,72	2,15	1,31	2,10	1,60
pH	9,10	7,55	7,30	7,10	7,10	7,30	7,50	-
NO_3 mg/ℓ	<0,20	<0,20	<0,20	1,80	2,50	4,30	-	3,90
VSS mg/ℓ	-	-	-	-	-	3248	-	-
O_2 demand mg/ℓ/h	-	-	-	88,69	52,50	23,40	-	-

Phosphorus mass balances on each reactor are shown in Table 5.24.

Table 5.24 Phosphorus Release and Uptake Relative to the Influent Concentration

Reactor	1	2	3	4	5	Settler
ΔP mg/ℓ	-8,00	+6,00	+10,98	-3,42	+1,68	-0,58
+ve Uptake of P by the sludge/ℓ of influent flow -ve Release of P by the sludge/ℓ of influent flow						

With the increase in Fe salt addition from 10 to 15 mg Fe/ℓ of influent, the system phosphorus removal increased from 11,20 to 13,00 mg/ℓ as P.

Comparison of Experiments 5.1, 5.2 and 5.3

Using Eq. (5.1) to calculate the denitrification capacity of the anaerobic reactor, and subtracting the concentration of system incoming nitrate as before, we find that the anaerobic potentials of Experiments 5.1, 5.2 and 5.3 respectively were as follows:

Experiment 5.1 : 13,48 mg N/ℓ influent
Experiment 5.2 : 15,23 mg N/ℓ influent
Experiment 5.3 : 17,38 mg N/ℓ influent

Comparing the above values with those in Experiments (1.1 and 1.2) we can assume that a reasonable degree of excess biological phosphorus removal took place.

The degree of phosphorus release in the anaerobic reactor of these experiments is of little quantitative value because the $Ca(OH)_2$ addition to the influent may have caused some calcium phosphate precipitation in the influent and in the anaerobic reactor (as was demonstrated in Experiments 3.1 - 3.4). However, from Tables (5.20, 5.22 and 5.24), the phosphorus balances on the anaerobic reactor in the three experiments are as follows:

Experiment 5.1 : +4,26 mg P/ℓ influent
Experiment 5.2 : -0,80 mg P/ℓ influent
Experiment 5.3 : -8,00 mg P/ℓ influent

and appear to be roughly proportional to the degree of anaerobic potential in the anaerobic reactor.

A plot of the system phosphorus removal versus Fe^{3+} addition is shown in Fig. 5.14. Also drawn in the diagram is the theoretical relationship for the removal due to biological excess phosphorus removal and chemical precipitation due to $FeCL_3$ addition, the latter case assuming stoichiometric removal. The equation for the total theoretical phosphorus removal versus Fe^{3+} addition is:

$$\Delta P = \frac{Y(S_i-S)}{1+bR_s}(\alpha + 0,025*0,2\ bR_s) + 0,00225\ \frac{(S_i-S)}{0,82} + 1,8*Fe^{3+}\text{added} \quad (5.4)$$

Assuming $\alpha = 0,10$

$\Delta P = 5,16 + 1,8*Fe^{3+}$added.

The value of α is not precisely known; however the close correspondence and in particular the concurrence of the experimental and theoretical slopes indicates that the removal due to chemical precipitation is correctly given by assuming stoichiometric removal. The results were all obtained from data in which the filtered effluent phosphorus concentration did not fall below 1,6 mg/ℓ as P. There are indications, however, that where the filtered effluent phosphorus concentration is about 2,0 mg/ℓ or less the efficiency of the chemical removal is reduced.

The observation that biological excess removal appears to have taken place (i.e. the prerequisites for biological excess removal were present) prompted the question whether or not the conditions for excess biological removal could be upset by decreasing the anaerobic potential of the first reactor.

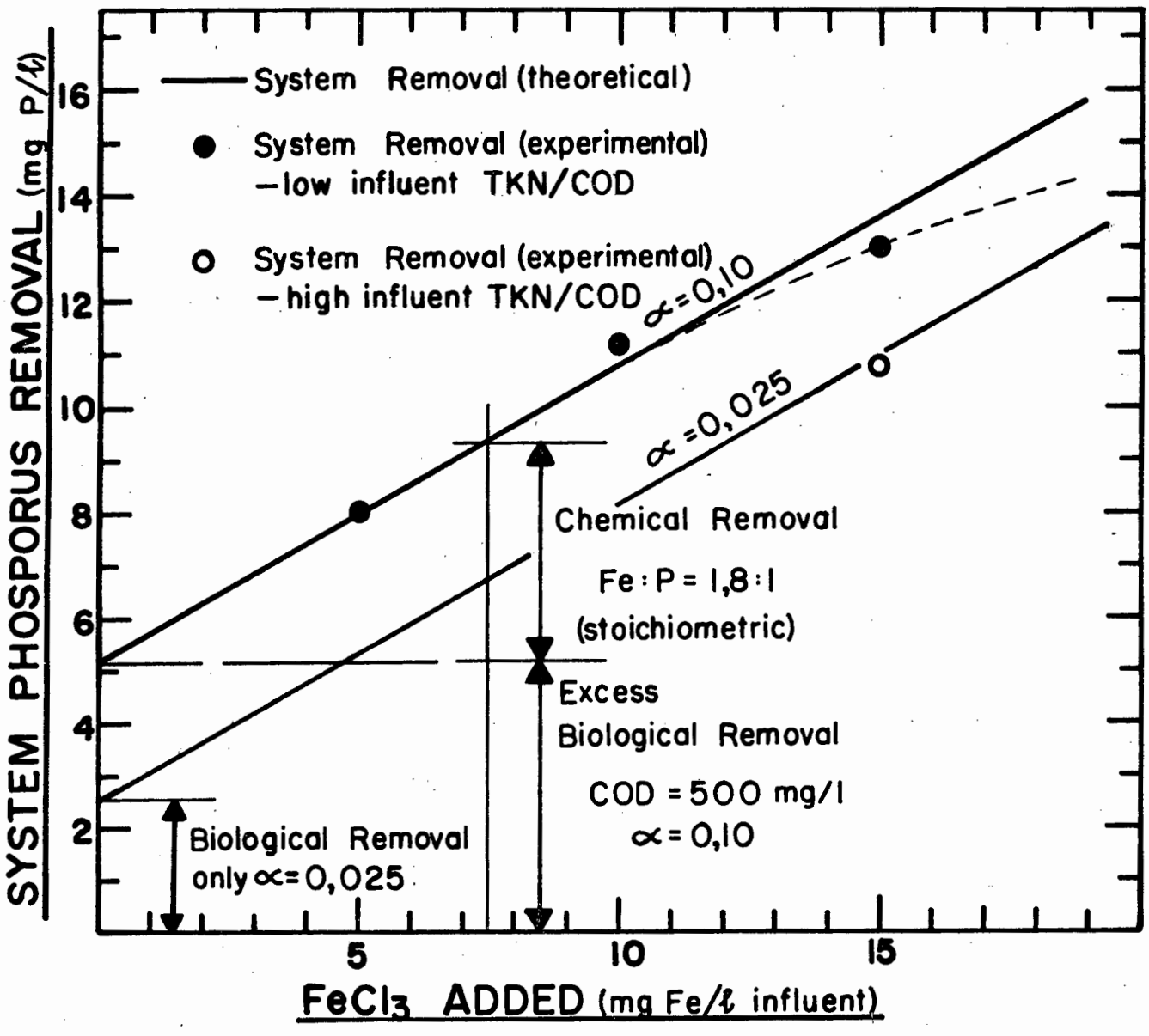

Fig. 5.14 Theoretical and experimental system phosphorus removal values for the Experiments 5.1, 5.2, 5.3 and 5.4.

An additional experiment, Experiment 5.4, was instituted in which NH_4^+ was added to the influent thereby increasing its TKN/COD ratio. In this way it was hoped to increase the effluent nitrate concentration, thereby reducing the anaerobic potential of the anaerobic reactor, with the aim of eliminating excess biological phosphorus removal.

Experiment 5.4

The experimental conditions were kept the same as in Experiment 5.3 except that ammonium sulphate was added to the influent so that its TKN/COD ratio was equal to 0,11. See Fig. 5.15.

The raw data are listed in Appendix A19 and the mean values for the investigation period are presented in Table 5.25.

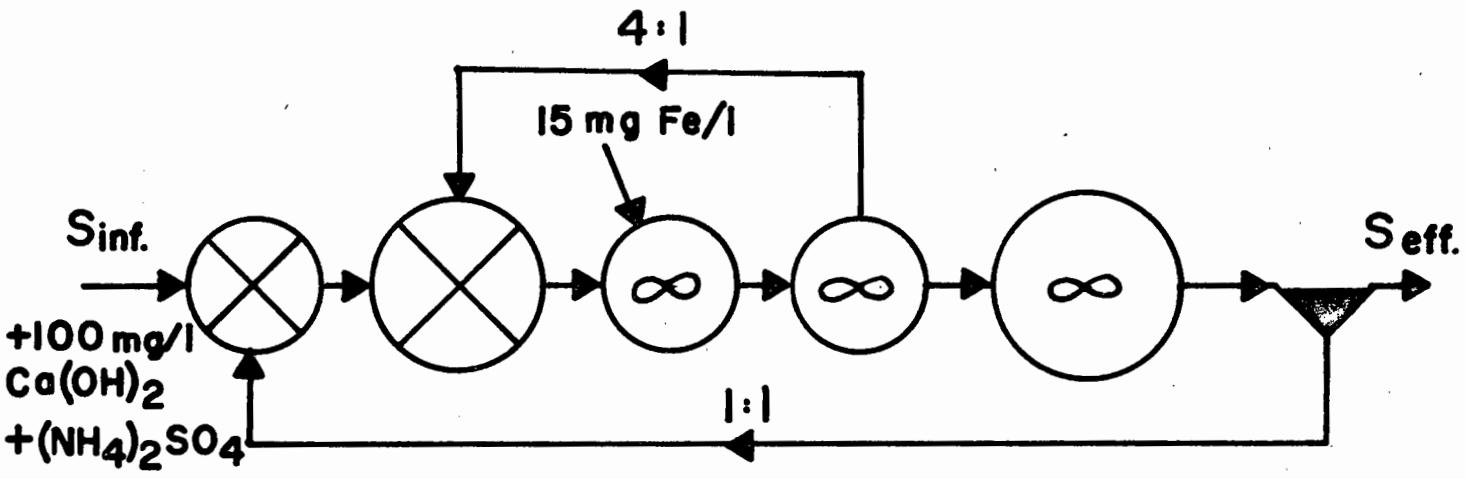

Fig. 5.15 Basic experimental unit showing the addition of $FeCL_3$ solution, $Ca(OH)_2$ and $(NH_4)_2SO_4$.

Table 5.25 Mean Values for Experiment 5.4

		Reactor No.						
	Inf.	1	2	3	4	5	Eff.	Filt.Eff.
COD mg/ℓ	515	-	-	-	-	-	37	-
TKN mg/ℓ	56,40	-	-	-	-	-	6,80	-
P mg/ℓ	14,40	5,75	4,20	3,45	3,45	3,60	4,10	3,60
pH	8,90	7,60	7,20	7,00	7,00	6,90	6,90	-
NO_3 mg/ℓ	<0,20	<0,20	4,20	6,90	8,40	14,80	-	14,90
VSS mg/ℓ	-	-	-	-	-	3329	-	-
O_2 demand mg/ℓ/h	-	-	-	80,10	58,30	44,90	-	-

Phosphorus mass balances on each reactor are shown in Table 5.26.

Table 5.26 Phosphorus Release and Uptake Relative to the Influent Concentration

Reactor	1	2	3	4	5	Settler
ΔP mg/ℓ	+7,00	+0,70	+4,50	-0,90	-0,50	+0,50

+ve Phosphorus taken up by the sludge/ℓ influent flow
-ve Phosphorus released by the sludge/ℓ influent flow

With the increase in the influent TKN/COD ratio from 0,074 in Experiment 5.3 to 0,110 in Experiment 5.4, the system phosphorus removal dropped from 13,00 to 10,80 mg/ℓ as P, i.e. by 2,20 mg/ℓ as P. See Fig. 5.14. This difference is roughly equal to the concentration removed as luxury uptake in Experiment 5.3, see Eq. (5.4) and Fig. 5.14.

Using Eq. (5.1) to calculate the denitrification capacity of the anaerobic reactor and subtracting the incoming nitrate concentration as before, the anaerobic potential of the reactor dropped from 17,38 mg N/ℓ in Experiment 5.3 to 6,38 mg N/ℓ in Experiment 5.4 with the increase in influent TKN/COD ratio. We can therefore assume that the excess biological phosphorus removal mechanism was not operating even though there was a zero nitrate condition in the anaerobic reactor. The above results lend support to the hypothesis that a minimum anaerobic potential, in addition to a zero nitrate requirement, is necessary for the biological excess removal mechanism to operate.

6. PHOSPHORUS REMOVAL IN THE U.C.T. PROCESS BY DOSING WITH $FeCl_3$ WITH pH ADJUSTMENT

Up until this stage, all experiments using Fe salt addition were carried out on the Modified Activated Sludge Process configuration (Fig. 4.1). The objective of this experiment was to compare the phosphorus removal performance of the U.C.T. Process (Fig. 5.3) and the Modified Activated Sludge Process, with both processes using in-plant $FeCL_3$ addition and pH adjustment.

Experiment 6. The U.C.T. Process was set up as in Fig. 5.17 with a $FeCl_3$ solution, equivalent to 15 mg Fe/ℓ of influent being fed into reactor No. 3. Influent with very similar sewage characteristics to those in Experiment 5.4 (i.e. TKN/COD = 0,1) was used. The pH of the process was raised by the addition of 100 mg/ℓ $Ca(OH)_2$ (i.e. 3 g/30 ℓ) to the influent.

The raw data are listed in Appendix A20 and the mean values for the investigation period are presented in Table 5.25.

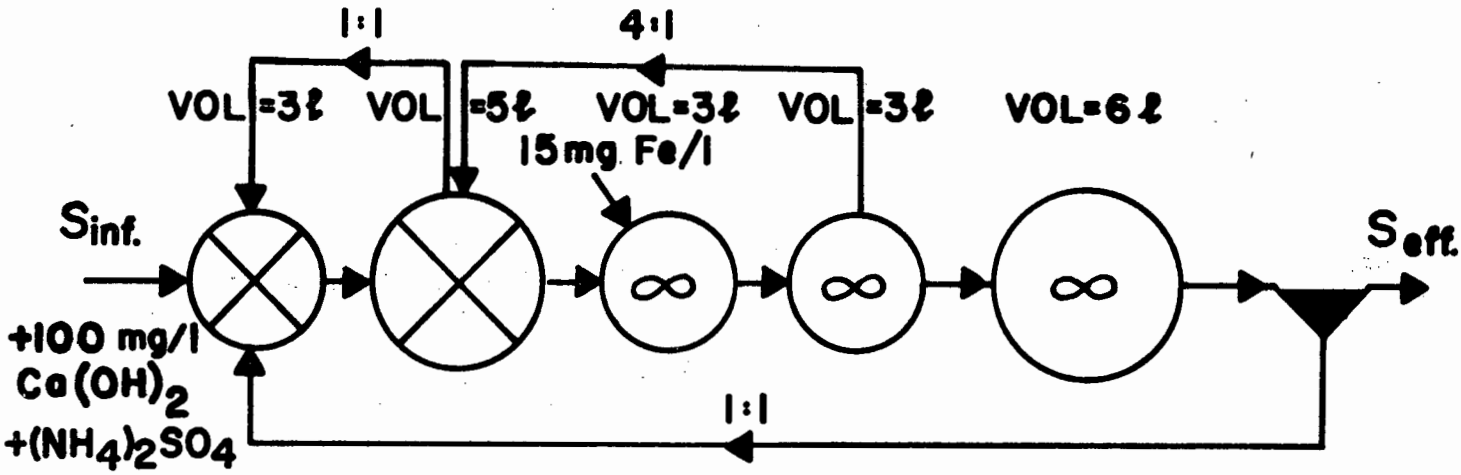

Fig. 5.17 The U.C.T.Process showing the addition of Fe salt, $Ca(OH)_2$ and $(NH_4)_2SO_4$.

Table 5.25 Mean Values for Experiment 6.

		Reactor No.						
	Inf.	1	2	3	4	5	Eff.	Filt.Eff.
COD mg/ℓ	528	-	-	-	-	-	33	-
TKN mg/ℓ	50,70	-	-	-	-	-	1,40	-
P mg/ℓ	14,85	6,80	2,92	2,44	2,24	1,98	2,26	1,90
pH	9,00	8,00	7,20	7,00	7,00	7,10	7,30	-
NO_3 mg/ℓ	<0,20	<0,20	4,70	9,00	10,40	11,30	-	11,30
VSS mg/ℓ	-	1807	-	-	-	3347	-	-
O_2 demand mg/ℓ/h	-	-	-	86,10	34,10	15,60	-	-

Phosphorus mass balances on each reactor are shown in Table 5.26.

Table 5.26 Phosphorus Release and Uptake Relative to the Influent Concentration

Reactor	1	2	3	4	5	Settler
ΔP mg/ℓ	+4,17	+4,02	+2,88	+1,20	+0,52	+0,16
+ve Phosphorus taken up by the sludge/ℓ influent flow -ve Phosphorus released by the sludge/ℓ influent flow						

The system phosphorus removal was 12,59 mg/ℓ as P. The value is significantly higher than the system removal of 10,80 achieved in Experiment 5.4 using the Modified Activated Sludge Process with identical chemical addition and similar sewage characteristics and about equal to the Modified Activated Sludge Process when the TKN/COD ratio was 0,074 (Experiment 5.3, system removal = 13,00 mg/ℓ). If we assume that in these three experiments the chemical removal was approximately the same, then a significant difference can clearly be seen between the biological phosphorus removal characteristics of the two processes operating under high influent TKN/COD ratios.

Modifying Eq. (5.1) to allow for the reduced sludge concentration in the anaerobic reactor (as in Experiment 1.3) and subtracting the concentration of incoming nitrate, the anaerobic potential in the reactor = 12,42 mg N/ℓ influent, which is considerably higher than that achieved in the Modified Activated Sludge Process with a similar influent TKN/COD ratio in Experiment 5.4 (6,38 mg N/ℓ). The experiment shows the higher likelihood of achieving the necessary anaerobic potential for excess biological phosphorus removal in the U.C.T. Process than in the Modified Activated Sludge Process provided the a-recycle is controlled in such a fashion that the nitrate load on the anoxic reactor is nearly equal to its denitrification capacity.

CHAPTER 6.

DISCUSSION

The investigation can be considered to have contributed to phosphorus removal in the activated sludge process in two main areas: that of excess biological removal and chemical precipitation removal.

EXCESS BIOLOGICAL PHOSPHORUS REMOVAL

Considering excess biological phosphorus removal, the investigation has brought greater understanding in two aspects:

1. The prerequisites for excess biological phosphorus removal, and

2. Process configuration to satisfy these prerequisites.

1. Prerequisites for Excess Biological Phosphorus Removal

When Barnard (1974) reported that under certain conditions, the sludge mass of the Bardenpho Process (Fig. 2.1) removed phosphorus in excess of the sludge's basic metabolic requirement, he attributed the excess removal as a consequence of stressing the organisms in an anaerobic environment to such a degree that phosphorus is released into the supernatant; the organisms, when stressed in such an environment, will, on entering the aerobic zone, take up the released as well as additional phosphorus.

The observation that biological phosphorus removal is enhanced when phosphorus release is achieved in the anaerobic zone appears to be supported by the results obtained in this investigation. However, it

did not appear that a condition of no nitrate/nitrite was sufficient for phosphorus release - in an anaerobic state other preconditions needed to be satisfied before release occurred. Furthermore, it did not appear that the anaerobic condition *per se* was the cause of phosphorus release. Dawson and Murphy (1972) report that between 20 and 50 percent of the organisms in the activated sludge process can utilize nitrate as an electron acceptor. The remaining organisms are therefore, for all intents and purposes in an anaerobic state from the moment the dissolved oxygen concentration is reduced to zero, i.e. from the moment anoxic conditions are established. One could reasonably ask: "Why do these organisms not exhibit at least some degree of phosphorus release under anoxic conditions?"

Now, an anaerobic state can exist in various"degrees of intensity" by noting that, in such a state, the redox potential can have different values, depending on the reduced state of the environment. It would seem,therefore, that the redox potential may be the basic parameter within which the conditions for release could be formulated.

The problem with applying the concept of redox potential, is that there is, as yet, no satisfactory measurement allowing a reliable assessment of the value of the redox potential. Consequently, its possible correlation with phosphorus release is difficult to establish experimentally. Yet the approach appears to provide a possible criterion for establishing when phosphorus release will occur or not.

It was eventually decided to look for an associated parameter which shows the same behavioural tendency as the redox potential and which is reliably quantifiable. In this way an approximate alternative to the redox potential would be available to serve as criterion. This substitute parameter was the "anaerobic potential".

The anaerobic potential was established as follows:

Using the theoretical formulation of Ekama, van Haandel and Marais (1979), it is possible to calculate the denitrification capacity of the

anaerobic reactor. By subtracting the system incoming nitrate concentration to the reactor from the denitrification capacity and, if the denitrification capacity is greater than the system incoming nitrate concentration, an anaerobic potential is established and can be quantified. The anaerobic potential is, therefore, the system concentration of nitrate that could have been removed by the reactor if more nitrate had been available. If the anaerobic potential is high, the redox potential will be low and phosphorus release could possibly take place.

In this investigation the concept of anaerobic potential was used as a criterion to quantify the prerequisite conditions for phosphorus release. The investigation has indicated that an anaerobic potential of about 9 mg N/ℓ influent or greater always resulted in phosphorus release and subsequent excess biological phosphorus removal.

Due to the lack of a functional relationship between the anaerobic potential and the basic redox potential, the minimum anaerobic potential needed will probably vary from one system to another. For this reason an allowance or factor of safety should be introduced in design. Provision of an anaerobic potential of 12 mg N/ℓ is likely to ensure that the mechanism operates.

2. Process Configuration

This investigation has shown that for flows with a high TKN/COD ratio the Modified Activated Sludge Process (Fig. 2.2), chiefly because of its operating inflexibility, is not the optimal configuration for inducing excess biological phosphorus removal. For a given configuration the denitrification capacity is fixed by the influent COD. Any increase in the influent TKN results in an increase in the effluent nitrate concentration and hence an increase in the mass of nitrate being recycled to the anaerobic reactor. This in turn causes a decrease in the anaerobic potential of the reactor, even to zero, thereby reducing the possibility of satisfying the prerequisites for excess biological phosphorus removal. In this investigation, for

example, it was shown that in a Modified Activated Sludge Process with an anoxic volume fraction equal to 40 percent, an adequate anaerobic potential cannot be provided for flows having an influent TKN/COD ratio > 0,10 at 20°C. The only way to overcome this problem was to change the interflow connections as developed in the U.C.T. Process (Fig.3.1).

In the U.C.T.Process the underflow recycle is directed to the anoxic reactor instead of the anaerobic reactor and an additional recycle from the anoxic to the anaerobic reactor is instituted. Its advantage over the Modified Activated Sludge Process lies chiefly in the fact that in the U.C.T. Process, the anaerobic potential of the anaerobic reactor is largely a function of the nitrate concentration in the anoxic reactor rather than the effluent nitrate concentration. The nitrate concentration in the anoxic reactor can be readily limited to a low value by adjusting the a-recycle from the aerobic zone, thus ensuring the desired anaerobic potential in the anaerobic reactor. Thus the U.C.T. Process with its associated operational mode provides a far greater degree of flexibility and, as such, can induce excess biological phosphorus removal for flows having TKN/COD ratios greater than 0,1.

The development of the U.C.T. Process can be considered to have brought surety into the design of activated sludge process for excess biological phosphorus removal - a surety that did not exist before. This surety arises from the fact that the design procedure incorporates the characteristics of the influent sewage in the choice of the process configuration and operational mode.

CHEMICAL PRECIPITATION PHOSPHORUS REMOVAL

Considering chemical phosphorus removal using in-plant $FeSO_4$ and $FeCl_3$ addition to the Modified Activated Sludge Process and to the U.C.T. Process, the investigation has confirmed a number of aspects:

1. Chemical addition enhanced the phosphorus removal characteristics of the activated sludge process. The iron phosphate chemical removal mechanism and the excess biological phosphorus removal mechanism appear to operate independently of each other. For this reason, chemical phosphorus removal can be considered to be additional to excess biological removal and in-plant iron salt addition can be used to supplement the phosphorus removal characteristics of a process designed for nitrification, denitrification and excess biological phosphorus removal.

2. Chemical phosphorus removal is strongly pH dependent. For both $FeSO_4$ and $FeCl_3$ addition, if the process pH < 7,0, the stoichiometric removal efficiency decreases, the effluent becomes yellow-green in colour and the turbidity increases. At a process pH ≥ 7,2 the stoichiometric removal efficiency increases to a maximum, the effluent is virtually colourless and the turbidity is low.

3. For process pH values ≥ 7,2, using in-plant $FeSO_4$ addition, an estimated stoichiometric chemical removal efficiency of approximately 80 percent was achieved. Using in-plant $FeCl_3$ addition, an estimated stoichiometric chemical removal efficiency of 100 percent was achieved. There are indications, however, that when the effluent phosphorus concentration falls to about 1,5 mg/ℓ as P and below, the removal efficiency decreases. Consequently, should an effluent quality of less than 1,5 mg P/ℓ be required, greater than stoichiometric chemical dosages are required,

4. In-plant chemical addition demonstrates a "persistence effect". When the process was operated under cyclic loading conditions, the effluent phosphorus concentration varied cyclically. However, the system phosphorus removal based on the <u>mean</u> effluent quality over the 24 hour period indicated that the process appeared to have worked equally efficiently under steady state and cyclic loading conditions even though the dosing chemical was fed in at a constant rate. This constitutes an advantage of in-plant chemical addition over primary

addition. For processes using primary addition, Culver and Chaplick (1978) found that in order to achieve a high degree of removal efficiency the dosing chemical had to be fed at a rate proportional to the influent phosphorus loading rate.

Clearly then, one major advantage of in-plant chemical addition is the accumulation of the ferri-precipitate in the sludge mass. It seems likely that the additional phosphorus removal is a result of two simultaneous reactions: A rapid direct Fe^{3+} - P precipitation and a competing side reaction of $PO_4^{\equiv}$ and OH^- in the accumulated ferri-hydroxide precipitate, i.e. an ion exchange phenomenon. This confirms the findings of Martin and Marais (1975) and Spatzierer (1978) who reported that processes using in-plant iron salt addition continued to remove additional phosphorus for a number of days after the iron salt dosing was stopped.

5. In this investigation, the point of iron salt addition was varied between the reactors. When such a change was made, it did not appear to have any significant effect on the system chemical phosphorus removal of the process.

6. During the experiments using $FeCl_3$ addition, the effluent iron concentration was measured in order to test for "iron leakage". The effluent iron concentration was consistently low (< 0,1 mg/ℓ as Fe) and it was concluded that virtually all of the added Fe salt precipitated out of solution and was adsorbed onto the sludge mass.

A general conclusion is that in an activated sludge process having excess biological phosphorus removal characteristics, chemical precipitation of phosphorus using in-plant iron salt addition to reduce the phosphorus to about 1 mg/ℓ as P will reflect stoichiometric removal for $FeCl_3$ addition and approximately 80 percent of stoichiometric removal for $FeSO_4$ addition provided the process pH is greater than about 7,2. The salt can be fed anywhere in the plant, preferably where the mixing is good. The rate of feeding can be constant even though the influent flow and load may show daily cyclic fluctuations.

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APPENDIX A1

DERIVATION OF EQUATION (2.2)

Phosphorus is removed from the wastewater, by incorporation into the cell mass and subsequent removal from the process via the daily sludge wastage, i.e.

Mass of P removed from wastewater = mass of P in wasted sludge

$$P * Q = f_P \frac{MX_v}{R_s}$$

where

f_P = fraction of phosphorus as P in X_v = 0,025 mg P/mg VSS.

Excess biological phosphorus removal is probably only possible by the active sludge fraction X_a. In this event, f_p only applies to X_e and X_i Assume α = fraction of P in X_a, where $\alpha > 0{,}025$ if excess biological phosphorus removal occurs.

i.e.

$$\Delta P * Q = [\alpha MX_a + f_p(MX_e + MX_i)]/R_s$$

where

$$MX_a = \frac{Y(S_{bi} - S)QR_s}{1 + bR_s}$$

$$MX_e = f * b * R_s * MX_a$$

$$= f * b * R_s \left[\frac{Y(S_{bi} - S)QR_s}{1 + bR_s}\right]$$

and

f = fraction remaining as endogenous residue = 0,2.

For raw municipal sewage, assume

$$X_{ii} \approx f_{up} * S_{ti} \quad \text{where } f_{up} = 0,09 - 0,13$$

$$MX_{ii} \approx f_{up} * S_{ti} * Q$$

Substituting:

$$\Delta P * Q = \frac{Y(S_{bi} - S)Q * R_s}{1 + bR_s} [\alpha + f_p * f * bR_s]/R_s$$

$$+ f_p * f_{up} * S_{ti} * Q * R_s/R_s$$

$$\Delta P(mg/\ell) = \frac{Y(S_{bi} - S)}{1 + bR_s} [\alpha + f_p * f * bR_s] + f_p * f_{up} * S_{ti}$$

Now $S_{bi} = S_{ti} - S_{xii} - S_u$

$$(S_{bi} - S) = S_{ti} - S_{xii} - S_u - S$$

where

$$S_{xii} = 1,48\ X_{ii}$$

and

$$S_u = f_{us} * S_{ti} \quad \text{where } f_{us} = 0,05 - 0,07$$

Assuming S to be negligible

$$\frac{(S_{bi} - S)}{S_{ti}} = (1 - 1,48\ f_{up} - f_{us})$$

Hence:

$$\Delta P(mg/\ell) = \frac{Y(S_{bi})}{1+bR_s} [\alpha + f_p * f * bR_s]$$

$$+ f_p * f_{up} \frac{(S_{bi})}{(1 - 1,48\ f_{up} - f_{us})}$$

For raw sewage:

Assuming $f_p = 0,025$ mg P/mg VSS

$f_{up} = 0,09$ mg VSS/mg COD

$f_{us} = 0,05$ mg COD/mg COD

i.e.

$$\Delta P = \frac{Y(S_{bi})}{1+bR_s} [\alpha + 0,025 * 0,2\ bR_s] + 0,00225\ S_{bi}/0,82.$$

APPENDIX A2

APPARATUS

The general layout of the basic experimental unit is shown in Fig. A2.1.

ANOXIC AND ANAEROBIC REACTORS

The anoxic and anaerobic reactors were constructed from perspex in accordance with the design in Fig. A2.2. Air infiltration was minimised by a sealed bearing on the stirrer shaft and a rubber O-ring between the cover and the reactor. The stirrer was driven by a small 115 v. D.C. brush motor at approximately 100 r.p.m. The paddle consisted of two flat blades glued diagonally onto a 25 mm length of 60 mm diameter perspex tubing and screwed onto the stainless steel shaft. The paddle size was determined empirically so as to provide good mixing without too intense turbulence. A 13 mm baffle plate was glued vertically along the inside of the reactor to prevent vortex formation and improve vertical mixing. The reactor volume could be adjusted by passing the effluent from the reactor through an inverted U-tube which could be set at any level. A 38 mm diameter access port was provided in the cover for taking samples and pH measurements. The port was sealed by means of a rubber stopper.

AEROBIC REACTOR

The aerobic reactors similar to the anoxic reactors except that the access port was kept open and was large enough to allow the oxygen meter probe to be dipped into the mixed liquor (see Fig. A2.3). Aeration was provided by means of a porous air stone attached to a perspex tube which passed through a hole in the cover. A Lopis fish tank air pump provided a constant source of air. The oxygen level in the reactor was kept at 1 - 2 mg/ℓ and was maintained in this range by adjusting the height of the air stone.

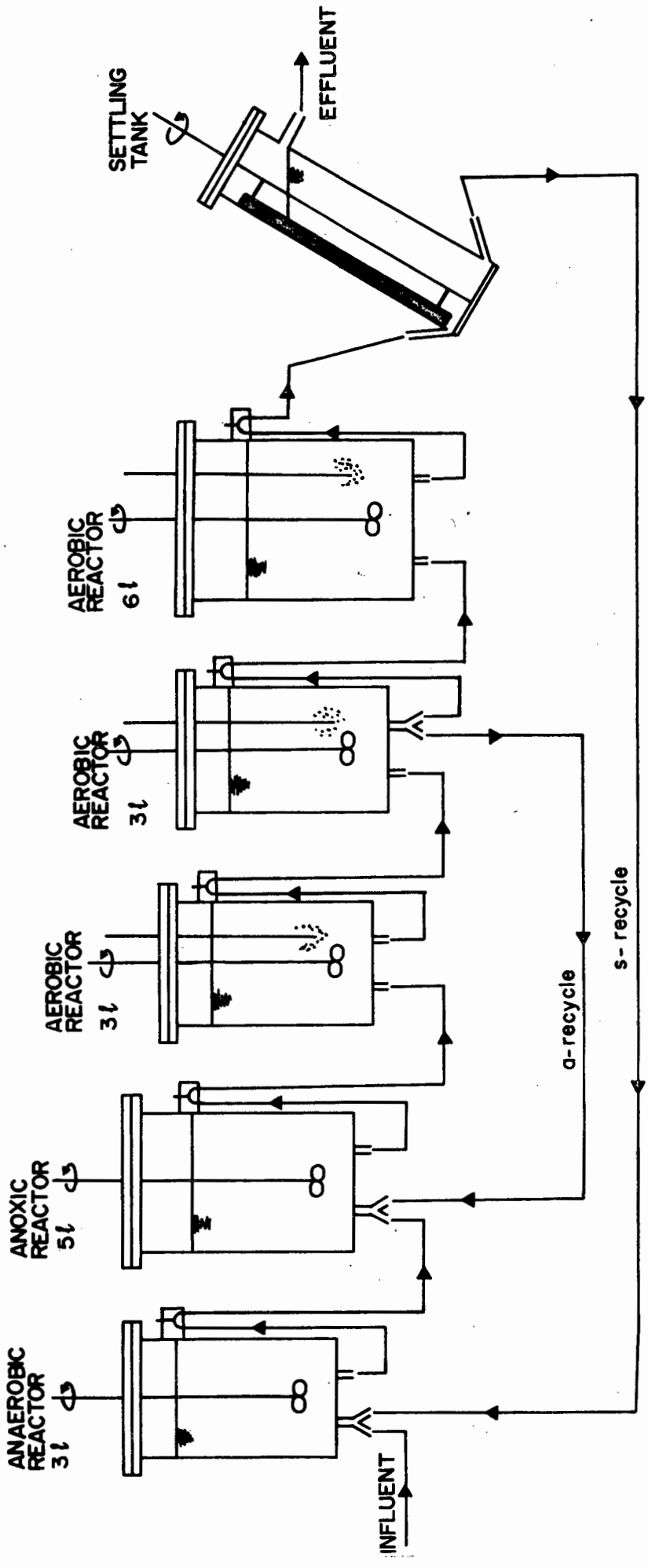


Fig. 2.1 General layout of the basic experimental unit

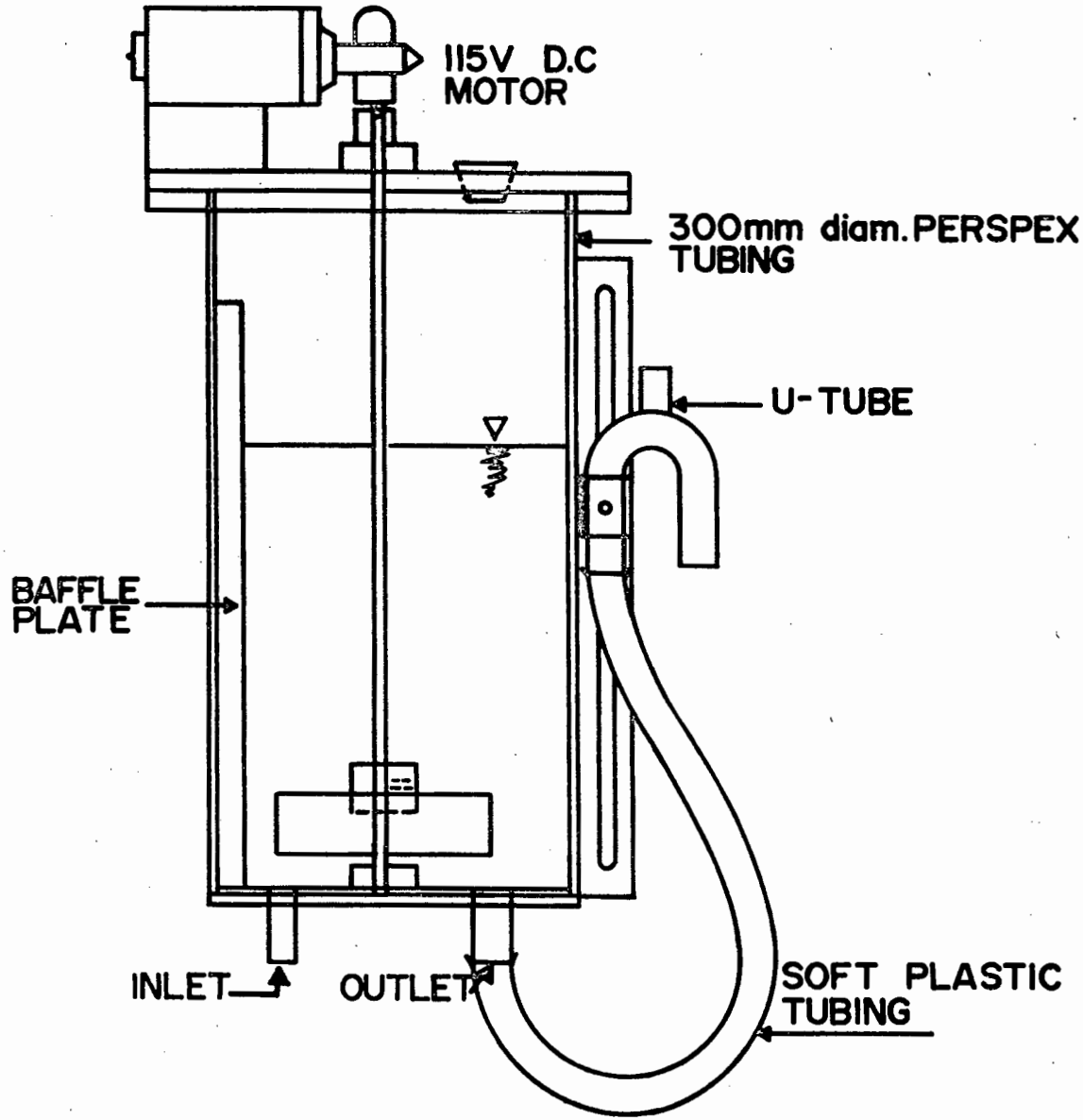


Fig. A.2.2 Anoxic reactor

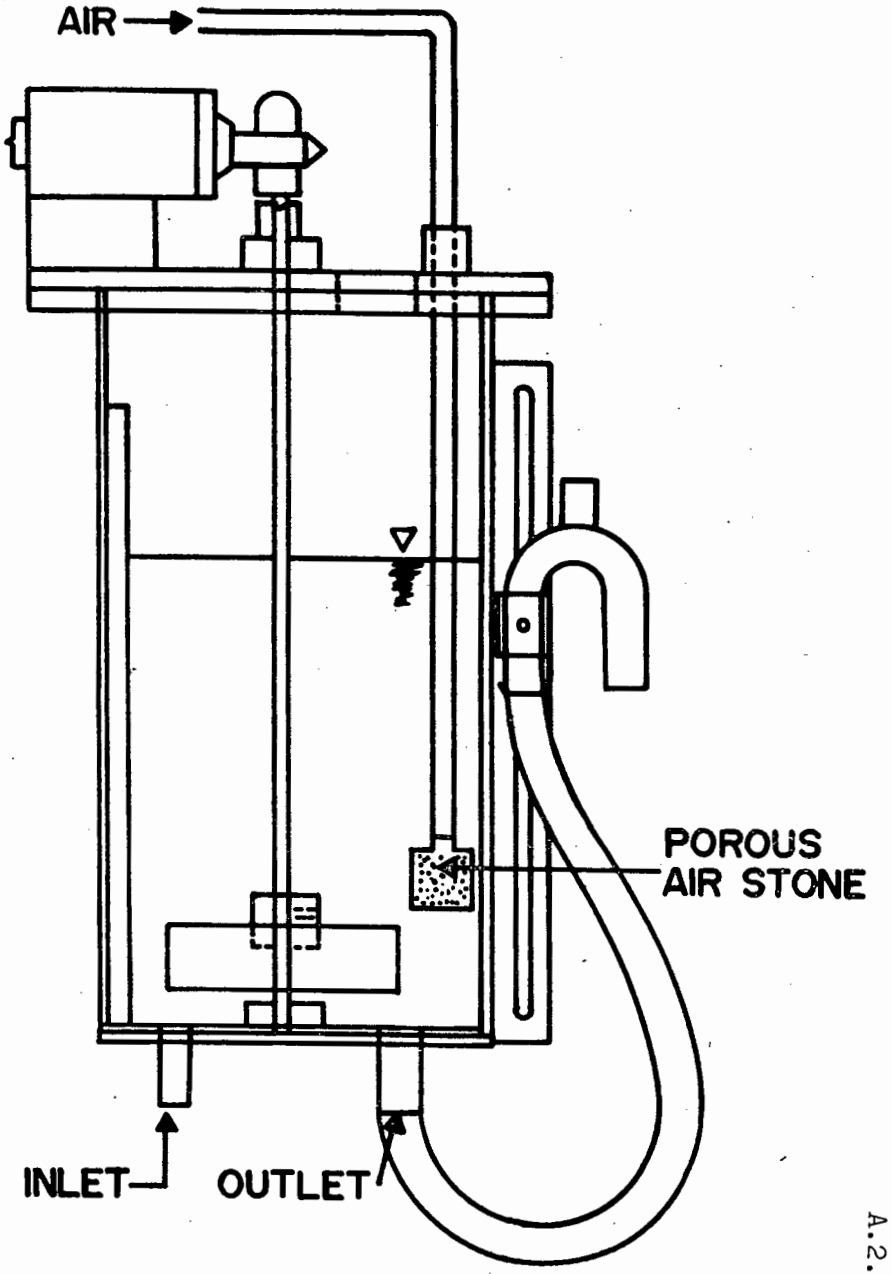


Fig. A.2.3 Aerobic reactor

SETTLING TANK

The settling tank was constructed from perspex as shown in the design in Fig. A2.4. It's chief function was to provide efficient solid-liquid separation and it was inclined at 60° to the horizontal. Both the mixed liquor was introduced to and the settled sludge was withdrawn from the bottom of the tank. A rubber wiper blade attached to the central shaft prevented sludge from adhering to the sides of the tank. The shaft was driven by a slowly revolving motor connected to a timer to rotate for 15 seconds every 3 minutes.

TUBING AND PUMPS

All connecting pipelines consisted of soft transparent plastic tubing. Tube lengths were kept to a minimum to reduce residence time. Tube sizes were chosen such that they had the minimum diameter that could ensure continuous free flowing without blocking up.

Peristaltic pumps, developed at the University of Cape Town Civil Engineering workshops, were used to regulate the influent and recycle flow rates. These pumps drove up to eight pumping tubes and proved to be both consistent and reliable. The magnitude of the flow rate was adjustable by a widely variable pumping cycle range using on-off timers.

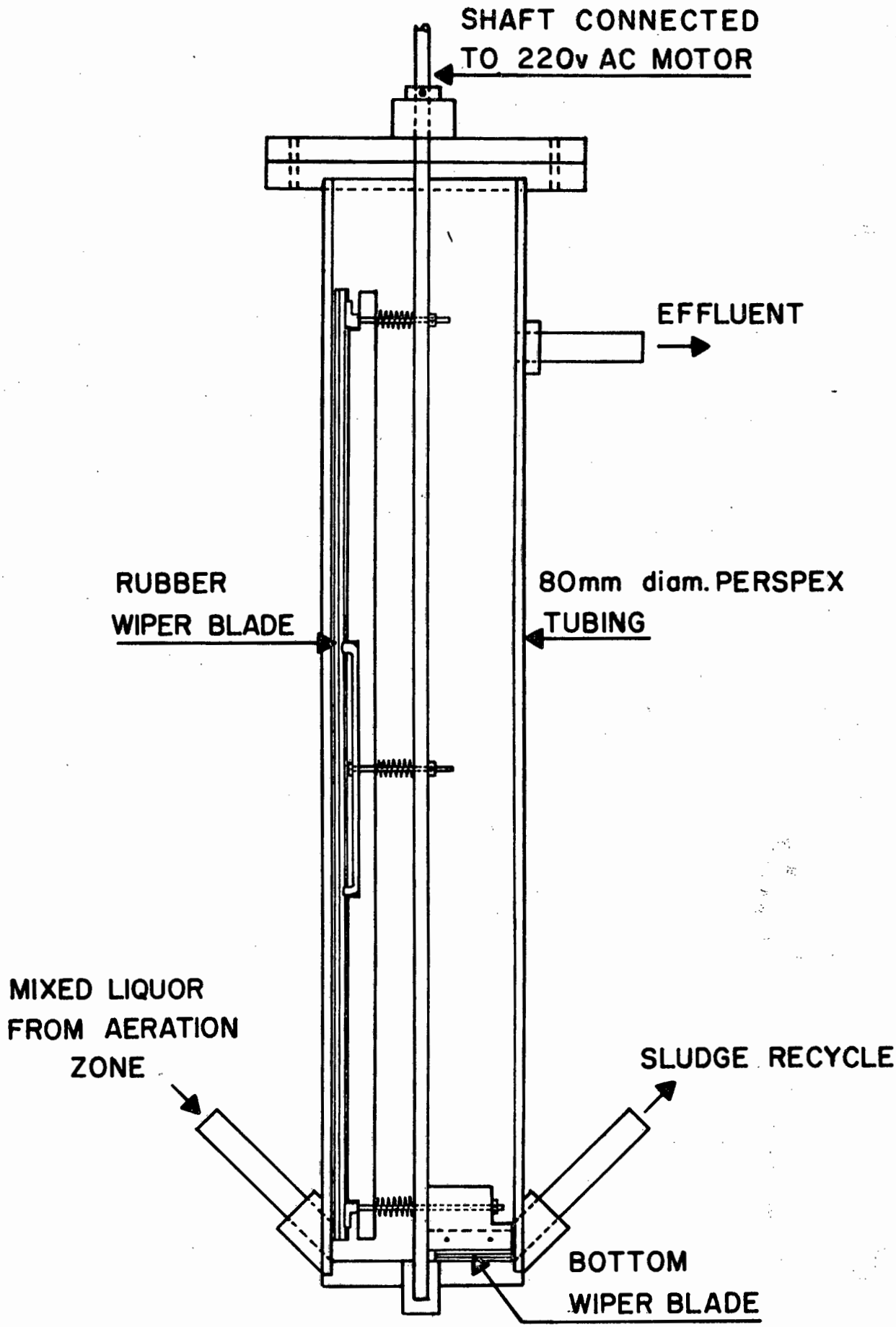


Fig. A2.4 Settling tank

APPENDIX A3

MEASUREMENT OF THE MIXED LIQUOR VOLATILE SETTLEABLE SOLIDS (MLVSS)

1. Centrifuge a 100 mℓ mixed liquor sample at r.p.m. for ten minutes. Pour off the supernatant.

2. Using distilled water wash all the remaining sludge into a porcelain crucible.

3. Dry crucible with sample at 100°C for 24 hours.

4. Allow sample to cool in desicator and weigh crucible + sample to an accuracy of 10^{-4} g.

5. Place crucible in furnace at 600°C for 20 minutes. This should incinerate all volatile material in the sample.

5. Allow crucible to cool in desicator and re-weigh crucible + incinerated sample to an accuracy of 10^{-4} g.

7. Difference in mass between the two weighings is equal to the mass of volatile material present in 100 mℓ of mixed liquor. Multiply the reading by 10 for MLVSS in mg/ℓ.

APPENDIX A4

DETERMINATION OF TOTAL PHOSPHATE PHOSPHORUS USING COLORIMETRIC MOLYBDATE-VANADATE TECHNIQUE

PRINCIPLE OF THE METHOD

In the presence of vanadates, phosphates react with molybdates to form yellow phosphovanadomolybdate. The intensity of this yellow colour is proportional to the amount of phosphate present and is determined by absorbance using a spectrophotometer. This system obeys Beer's Law at a wavelength of 470 μ to a concentration of 300 mg/ℓ.

The conversion of all the phosphate present takes place by the addition of anhydrous sodium carbonate and ashing. This process removes the major fraction of any natural colour due to the presence of organic material in the sample.

REAGENTS

1. Anhydrous sodium carbonate: (Check the bottle for percentage impurity. That for phosphate should not exceed 0,001%). Anhydrous sodium carbonate is available as a fine powder or as small flakes. The fine powder form is preferable, as the flaky form tends to splatter on heating in the crucible (see later).

2. Vanadomolybdate reagent:

Solution A: 20g of ammonium molybdate tetrahydrate dissolved in ± 250 mℓ distilled water.

Solution B: 1g ammonium metavanadate dissolved in 40 mℓ concentrated nitric acid (A.R.) and ± 200 mℓ distilled water.

Mix solutions A and B, add 100 mℓ concentrated nitric acid, and dilute to 1000 mℓ with distilled water (solution is stable for ± 12 months).

3. 1:1 HNO_3 Solution by volume

TECHNIQUE

1. 25 mℓ of the sample is pipetted into a platinum bowl and dried over a steam bath. This takes about 45 minutes.

2. Add ± 1g anhydrous sodium carbonate into the platinum bowl. Heat the bowl strongly and evenly over a Meaker Bunsen Burner. The Na_2CO_3 melts. Using tongs, turn the bowl while heating so that the molten carbonate comes into contact with all the inside surface of the bowl. The bowl should be turned and heated in this fashion for about 2-3 minutes. Remove and allow to cool.

3. Place a watch glass, with convex side down, on the bowl and slowly pipette ± 10 mℓ HNO_3 solution into the bowl through the spout of the bowl. Effervescence droplets are trapped by the watch glass. Once effervescence stops, rinse the bottom of the watch glass into the bowl with de-ionized distilled water and empty the bowl contents into a 25 mℓ volumetric flask. Rinse the bowl's inner surface twice into the flask using 3-4 mℓ de-ionized water each time.

4. Make up the volume of the flask to 25 mℓ using de-ionized water.

5. To a 20 mℓ test tube add 5 mℓ treated sample and 5 mℓ vanadomolybdate solution. Cover the test tube with "parafilm" plastic, shake and allow to stand for 10-15 minutes to allow colour to develop. A blank is made up using 5 mℓ de-ionized water and 5 mℓ vanadomolybdate solution. (Note: It was found that the colour did not fade after standing for 24 hours).

6. Set the spectrophotometer to a wavelength of 470 μ and zero using the blank from (5) above. Read the samples.

7. Correction for colour in treated sample

After ashing and redissolution of sample as in (4) and (5) above, it has been found that a slight colour is sometimes present in the test sample. The colour persists after the vanadomolybdate addition. To correct for this colour: a blank of de-ionized water only is inserted and the spectrophotometer is re-zeroed at 470 μ; the treated sample after (3) and (4) above is now inserted undiluted into the spectrophotometer and a reading taken (for colour correction). In order to allow for the dilution effect of the vanadomolybdate addition, subtract half the colour correction reading from the spectrophotometer reading obtained in the sample test. This gives the corrected test sample reading.

8. Standardisation of vanadomolybdate solution

Make up standard phosphorus solutions with phosphate concentrations in the expected range, e.g. 5, 10, 15, 20, 25 ppm PO_4-P and proceed as in (5) above. Plot the results, spectrophotometer reading versus standard phosphorus concentrations. The values should plot in a straight line passing through zero. The inverse slope of the line should represent a value in the range K = 100 - 110 mg/ℓ PO_4 - P/ spectrophotometer unit.

i.e. P(mg/ℓ) = K*spectrophotometer reading.

APPENDIX A5.

SETTLING RATE TEST

A settling rate test was carried out daily on mixed liquor from the aeration zone. The test was based on the method of White (1976) and served as a guide of the state of the sludge.

The testing apparatus was based on the design of White and is shown in Fig. 5.1. Because the volume of mixed liquor is limited in a laboratory scale process, the diameter of the testing unit was reduced from 100 mm to 80 mm. White states that the smaller diameter would give a slightly lower settling velocity than the regular unit, and hence the settling velocity would be conservative. The apparatus has a central shaft driven by a 220 v. AC motor at a rate of 2,4 r.p.m. Two 6,5 mm diameter perspex tubes, one near the shaft and the other near the inner edge of the unit are fixed parallel to the shaft by two perspex discs, one at each end of the unit. A rule, graduated in 0,2 cm units is stuck on the outside of the unit.

The required volume of mixed liquor (1500 ml) is poured into the top of the unit and the motor switched on. Readings of the level of the interface between the settled sludge and the supernatant are taken every minute for approximately 10 - 14 minutes. A plot of the settled sludge level versus time is made and the slope of the line drawn through the straight line portion of the curve gives an estimate of the mean settling rate.

The mean settling rate varied from 20 to 60 m/d. Good settling sludges had settling rates in the range 24 - 60 m/d. It was noted that poor settling sludges were associated with the use of sewage, as feed for the unit, that had been stored for periods greater than about 2 weeks at 4°C.

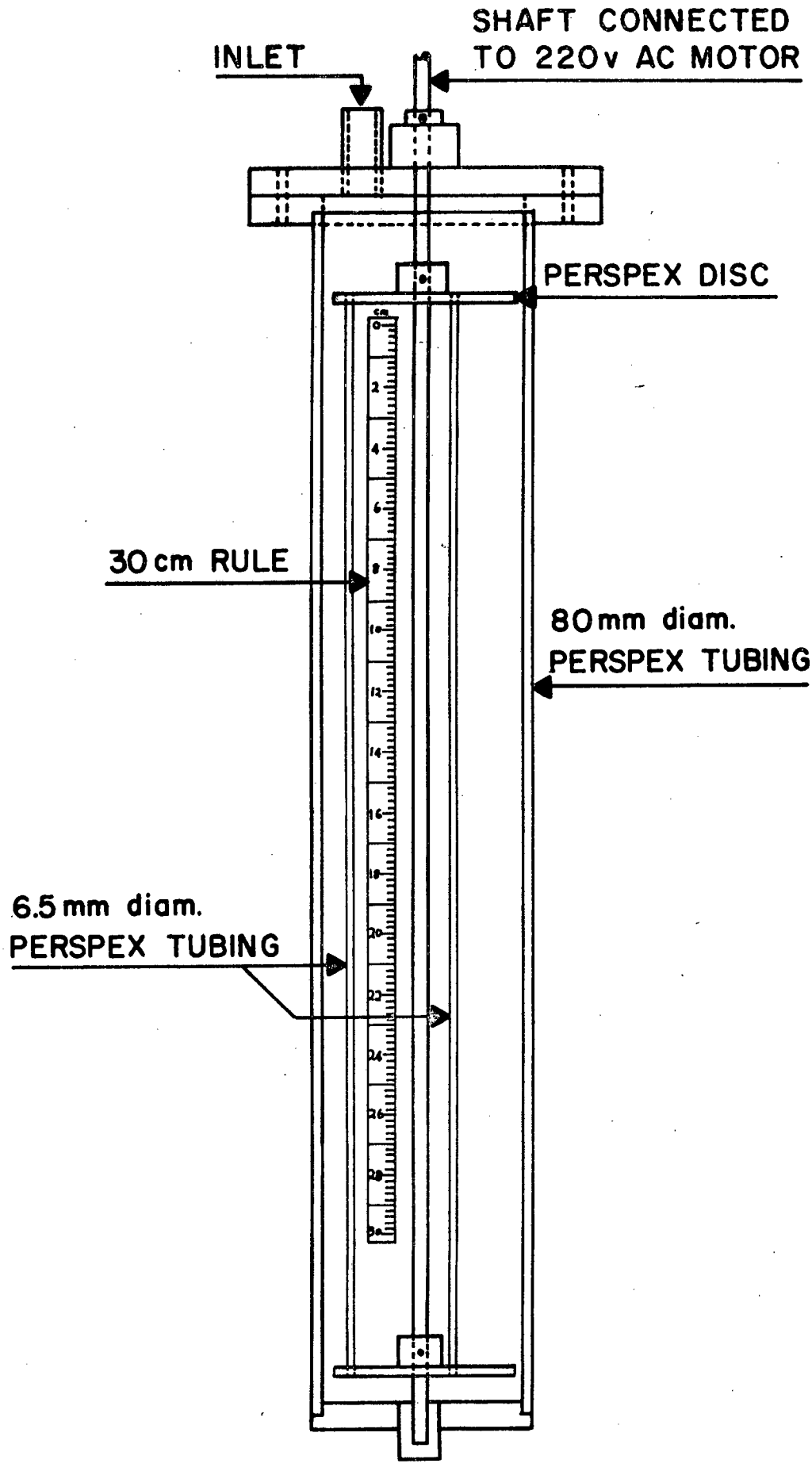


Fig. A5.1 Settling test apparatus

APPENDIX A 6

RAW DATA FROM EXPERIMENT 1.1

PHOSPHORUS (mg/l)

DAY	INF.	1	2	3	4	5	EFF.	FILT. EFF.
1	11,81	20,07	9,02	7,30	6,87	5,58	5,58	5,37
2	11,60	16,96	9,66	9,23	7,40	5,58	5,58	5,36
3	10,62	15,53	7,83	6,33	7,19	5,36	4,60	4,07
4	11,80	17,60	9,01	8,37	7,51	6,44	6,65	5,58
MEAN	11,46	17,54	8,88	7,81	7,24	5,74	5,60	5,10
5	11,80	17,17	9,98	8,80	7,51	6,01	6,11	5,90
6	11,80	18,99	10,08	8,15	6,76	6,11	6,11	5,68
7	11,63	16,64	9,24	6,63	7,83	6,52	7,18	5,98
8	11,53	16,53	6,31	6,74	6,85	5,76	6,85	6,20
9	12,62	13,81	9,25	8,38	8,38	8,27	7,07	7,61
10	10,33	11,42	7,72	4,13	7,83	6,31	7,18	7,18
11	10,99	7,29	7,18	7,61	6,63	6,85	6,96	6,09
12	11,64	-	-	-	-	-	-	7,18
13	10,66	10,66	6,74	5,55	6,09	6,31	8,81	5,22
14	11,09	10,77	7,94	5,98	5,98	3,92	4,57	3,92
15	11,42	7,61	7,18	6,31	6,09	5,66	5,76	5,66
MEAN	11,40	13,20	8,30	6,90	6,97	6,20	6,65	5,42

	COD(mg/l)		TKN(mg/l)		VSS(mg/l)
DAY	INF.	EFF.	INF.	EFF.	5
1	448	33	49,1	1,4	3444
2	487	39	50,0	1,4	3498
3	589	36	52,3	1,0	3504
4	573	33	50,0	1,4	3510
MEAN	524	35	50,4	1,3	3487
5	500	25	50,8	0,7	3553
6	502	36	51,7	0,0	3553
7	558	31	50,8	4,4	3349
8	505	30	49,1	0,0	3614
9	479	40	53,1	1,7	3360
10	519	39	51,7	1,3	3436
11	632	53	50,8	0,0	3358
12	-	-	-	-	-
13	483	46	47,1	4,0	3185
14	487	52	45,1	3,0	3456
15	505	38	50,8	1,6	3242
MEAN	504	39	50,4	1,5	3411

	pH							O_2 DEMAND (mg/l/h)		
DAY	INF.	1	2	3	4	5	EFF.	3	4	5
1	7,12	7,16	7,12	7,05	6,98	7,10	7,20	71,0	49,0	21,0
2	7,20	7,18	7,20	7,05	7,10	7,05	7,28	-	-	-
3	7,10	7,20	7,10	6,95	6,95	7,10	7,20	60,0	25,5	11,0
4	7,10	7,20	7,15	7,00	6,90	7,10	7,20	-	-	-
5	7,10	7,10	7,10	7,10	6,98	7,10	7,30	72,0	52,0	17,0
6	7,10	7,10	7,10	7,02	6,95	7,00	7,25	69,0	48,5	17,5
7	7,20	7,18	7,20	7,12	7,0	7,10	7,20	69,5	52,0	20,5
8	7,18	7,20	7,20	7,15	7,0	6,92	7,15	62,0	46,5	26,5
9	7,15	7,20	7,13	7,10	6,90	7,10	7,18	59,5	40,5	17,0
10	7,10	7,18	7,12	7,14	7,00	6,95	7,10	59,0	47,5	18,5
11	7,10	7,10	7,00	7,01	7,10	7,10	7,10	55,0	24,5	13,0
12	-	-	-	-	-	-	-	-	-	-
13	7,20	7,10	6,90	6,90	6,88	6,90	7,00	61,5	43,0	19,5
14	7,20	7,20	7,10	7,00	7,10	7,15	7,20	57,0	41,5	41,5
15	7,30	7,12	7,15	7,15	7,08	6,80	7,05	60,0	43,0	22,5
MEDIAN	7,15	7,15	7,15	7,05	7,00	7,10	7,20			
							MEAN	63,0	42,0	18,0

NITRATE(mg/l)

DAY	1	2	3	4	5	EFF.
1	0,00	0,00	4,90	9,60	11,20	11,70
2	0,00	0,00	5,20	7,00	11,20	6,40
3	0,00	2,10	9,80	11,00	11,40	10,80
4	0,00	2,20	9,00	10,80	11,40	11,00
MEAN	0,00	1,00	7,20	9,60	11,30	10,00
5	0,00	0,00	5,30	8,50	10,20	12,00
6	0,00	0,00	5,20	8,20	10,50	10,80
7	0,00	0,00	-	-	13,80	14,10
8	0,00	0,00	4,50	7,60	10,30	14,30
9	0,20	2,30	8,30	10,50	13,60	11,30
10	0,90	0,40	10,60	9,30	13,20	14,20
11	6,40	8,30	10,60	10,60	12,40	11,90
12	-	-	-	-	-	-
13	4,30	7,50	13,20	14,70	16,50	14,70
14	0,00	0,00	1,80	4,40	12,30	12,30
15	0,00	1,50	2,70	4,60	5,00	14,10
MEAN	0,00	2,10	6,30	9,00	12,00	13,00

APPENDIX A 7

RAW DATA FROM EXPERIMENT 1.2

PHOSPHORUS (mg/l)

DAY	INF.	1	2	3	4	5	EFF.	FILT. EFF.
1	11,86	9,79	9,57	9,35	8,59	9,14	8,81	8,48
2	13,22	11,09	8,92	8,59	6,31	7,16	9,25	8,27
3	13,16	13,05	11,31	10,01	8,27	9,14	9,57	9,14
4	11,86	9,46	6,09	8,27	6,85	8,05	8,48	8,05
5	12,73	9,46	7,83	9,14	8,27	8,92	9,25	9,03
6	12,73	9,90	10,33	9,46	9,68	8,92	8,70	8,48
7	12,73	10,88	8,16	6,42	6,53	4,79	8,92	7,51
8	12,94	11.31	9,79	7,83	10,33	8,59	9,79	9,79
9	12,83	10,55	9,46	9,46	9,03	9,35	9,79	9,79
10	13,49	11,09	10,01	10,01	9,35	10,55	10,66	10,55
11	-	12,51	8,92	-	10,44	10,22	10,77	8,92
12	13,16	10,55	8,70	9,90	9,03	8,48	10,77	9,79
13	15,34	12,62	10,88	12,51	6,53	10,66	10,55	8,38
14	12,75	11,86	11,42	10,55	10,88	10,77	12,07	11,09
MEAN	12,88	11,0	9,45	9,35	8,75	9,0	9,80	9,10

	COD(mg/l)		TKN(mg/l)		VSS(mg/l)
DAY	INF.	EFF.	INF.	EFF.	5
1	416	32	47,1	3,9	3149
2	487	35	46,3	3,1	3210
3	495	40	51,7	2,1	3098
4	495	37	49,1	0,0	3205
5	437	38	48,8	3,3	2998
6	478	36	46,3	1,3	2916
7	433	33	48,6	3,4	2912
8	466	33	47,1	3,3	2916
9	483	35	45,7	1,1	2908
10	416	38	44,8	0,0	2890
11	449	32	48,6	2,0	2656
12	528	35	47,7	0,7	3126
13	512	40	45,7	0,0	2787
14	412	-	33,0	0,0	2850
MEAN	470	35	47,4	2,0	2982

	pH							O_2 DEMAND(mg/l/h)		
DAY	INF.	1	2	3	4	5	EFF.	3	4	5
1	7,25	7,10	7,10	7,10	7,05	6,80	7,10	65,0	50,0	26,0
2	7,30	7,20	7,20	7,20	7,15	6,90	7,00	65,0	51,5	39,0
3	7,15	7,12	7,15	7,12	7,10	6,90	7,10	62,5	53,5	13,0
4	7,30	7,05	7,10	7,00	6,98	6,85	7,00	63,0	50,0	24,5
5	7,20	7,18	7,10	7,10	7,05	6,80	7,10	72,5	47,5	17,5
6	7,20	7,25	7,10	7,00	6,90	7,05	7,20	70,0	47,0	14,5
7	7,20	7,20	7,05	7,00	7,00	6,95	7,10	79,0	55,0	24,5
8	7,20	7,18	7,18	7,20	7,20	6,95	7,12	73,0	59,0	48,5
9	7,30	7,20	7,10	7,00	6,92	6,90	7,20	73,5	41,0	14,0
10	7,20	7,00	6,95	6,90	6,80	6,90	7,10	67,5	40,5	15,5
11	7,30	7,10	7,00	6,90	6,80	6,98	7,10	67,0	30,0	14,5
12	7,20	7,15	7,00	6,90	6,85	7,00	7,15	-	-	-
13	7,20	7,18	7,00	6,95	6,85	7,00	7,10	58,0	52,5	16,0
14	7,30	7,00	6,90	6,70	6,65	6,60	7,10	58,0	52,5	16,0
MEDIAN	7,20	7,15	7,00	7,00	6,95	6,90	7,10			
							MEAN	68,0	48,1	19,9

NITRATE (mg/l)

DAY	1	2	3	4	5	EFF.
1	1,00	1,10	2,90	5,60	14,10	14,60
2	0,50	0,50	2,40	5,00	14,30	14,30
3	0,50	0,30	2,20	5,10	11,50	12,70
4	0,00	0,00	4,90	7,50	14,50	12,00
5	0,50	3,30	5,30	8,00	18,00	15,90
6	0,60	5,20	8,40	11,50	13,40	14,10
7	0,90	4,30	7,10	9,90	14,00	11,30
8	0,00	0,00	0,90	2,90	10,80	12,70
9	0,70	4,30	7,70	9,70	14,00	14,30
10	2,80	6,10	9,60	12,00	14,50	14,10
11	4,20	8,00	11,20	13,90	14,50	14,10
12	1,30	6,80	11,40	13,20	14,70	15,10
13	0,70	5,50	9,10	12,30	14,00	14,20
14	1,00	5,20	9,30	12,00	16,00	14,90
MEAN	0,80	3,90	6,90	9,60	14,20	14,20

APPENDIX A 8

RAW DATA FROM EXPERIMENT 1.3

PHOSPHORUS (mg/l)

DAY	INF.	1	2	3	EFF.	FILT. EFF.
1	15,09	15,40	7,95	7,75	7,95	7,24
2	15,09	15,60	9,18	7,24	7,85	7,24
3	14,58	14,89	10,20	8,36	8,06	7,55
4	14,77	14,48	9,08	8,67	8,77	8,06
5	14,58	15,60	9,59	7,95	7,95	8,16
6	14,68	14,99	6,63	6,12	7,75	7,24
7	14,07	16,42	8,87	8,16	6,83	6,83
8	14,48	14,58	7,14	5,10	7,34	6,83
9	15,30	15,50	8,26	7,65	8,06	7,95
10	14,48	15,60	8,57	7,55	7,55	7,55
11	14,68	14,17	9,79	8,57	8,06	8,26
12	14,38	17,23	10,81	9,08	8,77	8,36
13	14,38	12,75	9,38	8,36	8,77	8,46
MEAN	14,64	15,20	9,00	7,95	7,95	7,70

	COD(mg/l)		TKN(mg/l)					VSS(mg/l)	
DAY	INF.	EFF.	INF.	1	2	LAST REACT.	EFF	1	LAST REACT.
1	527	34	47,4	21,4	1,4	0,3	0,0	1834	3424
2	476	33	49,7	22,1	5,9	1,6	0,4	1846	3456
3	489	44	51,4	24,9	5,0	1,4	0,4	1790	3358
4	527	36	49,4	25,0	0,0	0,0	0,0	1774	3342
5	487	37	53,7	25,7	7,1	2,6	1,0	1828	3406
6	514	37	57,7	27,6	8,9	1,7	1,4	1826	3399
7	458	32	54,6	24,9	8,9	1,6	1,6	1818	3428
8	556	30	54,6	25,1	9,3	4,4	2,1	1856	3407
9	512	59	57,4	28,9	9,4	2,6	2,3	1954	3506
10	509	26	57,4	23,1	9,6	2,1	1,5	1886	3433
11	-	-	-	25,9	11,1	4,0	3,6	1962	3572
12	440	36	54,6	25,6	10,6	3,7	2,6	-	-
13	482	34	48,8	19,6	6,3	1,6	1,4	-	-
MEAN	499	35	53,0	24,8	7,8	2,0	1,3	1852	3430

	pH					O_2 DEMAND (mg/l/h)
DAY	INF.	1	2	3	EFF.	3
1	7,10	7,20	7,10	7,00	7,20	35,0
2	7,10	7,20	7,10	7,00	7,20	35,5
3	7,30	7,30	7,10	6,90	7,20	41,0
4	7,30	7,30	7,10	6,95	7,20	39,0
5	7,30	7,30	7,10	7,00	7,25	39,0
6	7,40	7,40	7,20	7,05	7,30	39,0
7	7,30	7,40	7,25	7,10	7,35	38,0
8	7,30	7,30	7,20	7,10	7,40	39,0
9	7,30	7,40	7,20	7,10	7,50	40,0
10	7,50	7,40	7,20	7,10	7,50	38,5
11	7,30	7,40	7,20	7,10	7,40	39,5
12	7,40	7,40	7,30	7,20	7,40	40,5
13	7,40	7,40	7,20	7,15	7,40	38,0
MEDIAN	7,30	7,35	7,20	7,10	7,35	MEAN 38,6

NITRATE (mg/l)

DAY	1	2	3	EFF.
1	0,00	4,10	13,80	14,50
2	0,00	6,80	14,50	12,70
3	0,00	8,80	17,50	15,00
4	0,00	8,20	17,00	17,10
5	0,50	7,90	16,70	16,20
6	0,70	11,30	21,00	19,20
7	0,00	8,80	17,50	18,50
8	0,00	7,80	16,50	16,20
9	0,00	6,70	13,40	15,30
10	0,00	7,60	15,70	15,30
11	0,00	7,90	16,70	16,20
12	0,00	5,50	12,90	15,00
13	0,00	7,80	15,00	15,00
MEAN	0,00	7,63	16,02	15,86

APPENDIX A 9

RAW DATA FROM EXPERIMENT 2

PHOSPHORUS (mg/h)

DAY	INF.	FILT. INF.	1	2	3	4	5	EFF.	FILT. EFF.
1	9,79	7,85	4,09	3,87	3,66	3,44	2,37	3,12	2,74
2	10,44	8,18	4,19	3,77	3,77	3,66	3,33	3,77	3,33
3	10,43	8,28	4,52	4,19	3,87	3,55	3,76	3,87	3,12
4	10,43	8,28	4,19	3,87	3,87	3,66	3,55	3,87	3,50
5	-	7,96	3,98	3,55	3,44	3,55	3,01	4,30	3,33
6	10,76	8,18	3,23	3,23	3,12	3,61	2,69	3,66	2,74
7	11,19	8,39	4,20	3,87	3,77	3,55	3,23	4,20	3,44
8	11,30	9,14	4,41	3,87	3,77	3,87	3,87	4,95	4,14
MEAN	10,78		4,17	3,78	3,70	3,59	3,38	4,08	3,36

	COD(mg/l)		TKN(mg/l)			VSS(mg/l)
DAY	INF.	EFF.	INF.	5	EFF.	5
1	451	39	43,3	4,0	4,6	2466
2	456	41	48,6	4,4	4,7	2472
3	541	-	51,9	4,0	3,6	-
4	-	42	59,3	3,9	3,9	2384
5	472	42	51,9	3,2	3,8	2389
6	500	44	51,6	5,0	4,8	2347
7	487	34	53,8	4,6	4,7	2301
8	448	40	48,6	3,4	-	2116
MEAN	474	41	51,2		4,10	2307

	pH							O_2 DEMAND (mg/l/h)		
DAY	INF.	1	2	3	4	5	EFF.	3	4	5
1	7,45	7,15	7,15	6,80	6,85	6,90	7,05	50,0	24,5	9,0
2	7,45	7,05	7,00	6,80	6,90	6,95	7,10	60,0	43,0	13,5
3	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	69,0	38,5	16,0
5	7,20	6,95	6,80	6,70	6,60	6,60	6,85	57,5	33,0	14,0
6	7,40	7,05	6,90	6,75	6,65	6,70	6,90	68,0	44,0	14,5
7	7,50	7,05	6,95	6,90	6,85	6,75	7,00	60,0	50,0	18,0
8	-	-	-	-	-	-	-	-	-	-
MEDIAN	7,40	7,05	6,90	6,75	6,65	6,70	6,90			
								MEAN 63,6	41,4	15,6

NITRATE (mg/l)

DAY	1	2	3	4	5	EFF.
1	7,84	12,04	14,50	16,58	16,96	19,50
2	8,06	9,54	15,05	16,96	16,03	16,54
3	2,33	7,12	11,62	12,72	13,78	15,77
4	0,85	4,58	8,48	10,18	10,85	13,56
5	1,70	7,21	11,79	12,08	12,72	11,66
6	0,68	6,28	10,60	11,79	12,55	13,19
7	2,04	5,09	8,31	10,81	12,30	12,89
8	-	-	-	-	-	-
MEAN	3,80	7,50	11,70	13,60	14,10	14,80

APPENDIX A 10

RAW DATA FROM EXPERIMENT 3.1

PHOSPHORUS (mg/l)

DAY	INF.	FILT. INF.	1	2	3	4	5	EFF.	FILT. EFF.
1	9,79	7,72	3,92	4,13	4,24	3,59	3,48	3,70	3,59
2	9,46	7,07	2,50	2,94	2,61	2,61	2,28	2,18	1,90
3	9,79	7,94	3,15	-	2,94	2,50	1,63	2,72	2,07
4	10,33	8,48	4,02	2,83	2,50	2,39	1,63	1,85	1,58
5	10,22	8,92	3,59	2,61	2,18	1,31	0,87	1,31	1,31
6	9,79	8,05	5,44	2,61	1,74	2,18	1,31	2,07	1,85
7	11,64	9,68	6,63	3,92	1,74	2,61	1,52	3,15	2,94
8	12,07	11,09	2,39	1,74	1,41	2,72	1,85	1,96	2,94
9	13,60	12,07	3,15	2,39	1,96	1,52	0,76	0,98	0,98
MEAN	10,55		3,60	2,85	2,20	2,42	1,63	2,20	2,10

	COD(mg/l)		TKN(mg/l)			VSS(mg/l)
DAY	INF.	EFF.	INF.	5	EFF.	5
1	490	22	32,0	4,3	2,6	2165
2	494	26	35,6	3,7	-	2090
3	462	31	34,3	4,9	4,3	2168
4	520	23	39,4	4,4	4,3	2214
5	471	22	36,8	4,1	3,6	2218
6	429	23	36,0	3,8	4,1	2262
7	446	26	42.27	4.7	4,0	2353
8	442	37	45,7	3,7	3,0	2472
9	-	29	44,8	1,9	2,0	2320
MEAN	462	25	38,50		3,6	2210

	pH							O_2 DEMAND (mg/l/h)		
DAY	INF.	1	2	3	4	5	EFF.	3	4	5
1	8,75	7,85	7,45	7,20	7,25	7,25	7,35	46,5	13,0	9,50
2	8,55	8,00	7,65	7,40	7,45	7,45	7,50	50,0	1,25	8,50
3	8,45	7,75	7,50	7,30	7,30	7,35	7,45	55,0	23,0	8,50
4	-	-	-	-	-	-	-	-	-	-
5	8,65	7,85	7,60	7,35	7,45	7,35	7,50	-	-	-
6	8,55	7,90	7,55	7,35	7,35	7,40	7,60	52,5	24,5	12,00
7	-	-	-	-	-	-	-	-	-	-
8	8,85	8,15	7,85	7,65	7,75	7,70	8,05	53,5	21,0	14,00
9	8,85	8,05	7,70	7,50	7,55	7,50	7,85	54,0	24,5	14,00
MEDIAN	8,65	7,90	7,60	7,35	7,45	7,40	7,50			
							MEAN	51,92	19,75	11,08

NITRATE (mg/l)

DAY	1	2	3	4	5	EFF.
1	1,10	4,20	7,70	7,60	7,90	5,70
2	0,70	5,60	7,20	10,80	9,40	10,20
3	0,80	2,60	4,50	6,70	7,40	6,80
4	0,70	0,60	3,90	5,20	5,20	3,50
5	0,90	0,90	3,20	5,40	6,40	5,20
6	0,80	2,20	3,50	7,50	6,90	8,90
7	1,20	1,50	2,50	3,80	6,30	3,60
8	1,10	2,70	4,50	7,90	7,80	6,70
9	1,50	6,60	8,50	13,40	13,20	9,70
MEAN	1,00	3,00	6,90	7,60	7,90	6,70

APPENDIX A 11

RAW DATA FROM EXPERIMENT 3.2

PHOSPHORUS (mg/l)

DAY	INF.	FILT. INF.	1	2	3	4	5	EFF.	FILT. EFF.
1	9,79	7,07	1,95	1,08	1,63	1,41	0,98	0,98	0,98
2	9,25	6,74	2,72	2,61	2,18	2,07	1,20	1,74	1,80
3	11,52	-	-	-	-	-	-	1,63	-
4	10,33	7,94	3,15	2,18	1,96	1,31	0,98	0,76	0,87
5	10,44	7,82	1,95	1,83	1,83	1,83	0,65	0,87	0,98
6	10,33	8,70	3,37	3,15	1,96	1,74	1,52	1,41	1,52
7	10,76	8,15	2,50	2,28	2,07	1,74	1,08	1,20	0,92
8	10,88	8,59	3,59	2,28	1,85	1,85	0,76	0,76	0,76
9	-	-	-	-	-	-	-	-	-
10	11,75	9,68	4,24	3,48	3,15	2,94	1,52	2,07	1,96
11	11,42	9,46	3,81	3,26	2,61	2,61	1,31	1,74	1,69
12	-	9,57	4,46	3,26	2,18	3,05	1,85	-	2,50
13	10,84	8,16	1,85	2,61	2,72	2,72	1,41	-	1,50
14	11,38	-	-	-	-	-	-	-	1,07
15	-	-	5,15	4,19	2,79	3,22	1,93	1,82	1,82
16	10,73	7,94	4,83	3,86	3,65	3,11	1,93	1,93	1,82
17	11,81	9,88	3,86	3,43	3,22	1,93	2,25	1,82	1,77
18	12,45	-	5,15	3,76	3,43	3,22	1,82	2,36	2,04
19	12,24	8,91	3,86	3,22	2,68	2,58	1,61	1,50	1,40
MEAN	11,00		3,55	2,95	2,43	2,32	1,42	1,50	1,48

	COD(mg/l)		TKN(mg/l)			VSS(mg/l)
DAY	INF.	EFF.	INF.	5	EFF.	5
1	571	28	33,7	1,9	1,4	3458
2	490	31	28,8	1,1	1,6	3374
3	-	-	-	-	-	-
4	506	33	34,0	1,9	0,0	3576
5	515	34	34,8	2,0	-	3282
6	522	35	36,0	1,8	1,7	3396
7	497	15	38,0	0,0	1,7	3333
8	524	26	31,7	1,7	-	3192
9	486	-	-	-	-	-
10	502	32	27,4	2,9	0,0	3151
11	523	31	33,7	2,4	2,3	3267
12	511	22	34,6	1,9	1,6	3206
13	-	-	32,3	3,0	0,0	-
14	466	14	32,4	-	1,4	-
15	-	16	42,8	0,0	0,0	3334
16	499	16	42,3	2,7	2,4	3480
17	444	27	37,4	0,0	0,0	3541
18	487	28	41,1	3,9	2,5	-
19	499	31	38,0	3,1	3,6	3556
MEAN	503	28	35,2		1,3	3367

pH — O_2 DEMAND (mg/l/h)

DAY	INF.	1	2	3	4	5	EFF.	3	4	5
1	6,90	7,90	7,60	7,55	7,48	7,25	7,50	61,5	46,5	38,5
2	6,95	7,75	7,40	7,35	7,30	7,18	7,40	60,0	43,0	25,0
3	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	60,0	39,0	25,5
6	-	-	-	-	-	-	-	-	-	-
7	7,00	8,20	7,65	7,40	7,35	7,20	7,30	60,0	30,0	13,5
8	6,90	8,25	7,70	7,45	7,35	7,35	7,45	45,0	36,0	16,0
9	-	-	-	-	-	-	-	-	-	-
10	7,05	8,10	7,85	7,60	7,50	7,55	7,70	50,0	33,0	19,0
11	6,95	8,20	7,75	7,50	7,40	7,40	7,55	48,5	33,5	18,0
12	6,95	8,10	7,65	7,45	7,35	7,35	7,55	53,0	33,5	18,0
13	6,95	8,25	7,70	7,50	7,45	7,40	7,65	50,0	28,0	18,5
14	-	-	-	-	-	-	-	-	-	-
15	7,00	7,85	7,60	7,45	7,35	7,30	7,55	53,0	39,0	20,5
16	7,00	8,00	7,60	7,50	7,40	7,35	7,50	55,0	39,0	22,5
17	7,15	8,10	7,65	7,50	7,45	7,50	7,65	55,5	30,0	18,0
18	7,10	8,05	7,65	7,50	7,40	7,45	7,65	61,5	40,0	18,0
19	7,10	8,10	7,65	7,45	7,45	7,45	7,65	62,5	31,5	19,0
MEDIAN	7,00	8,10	7,65	7,50	7,40	7,50	7,50			
							MEAN	55,3	35,8	20,7

NITRATE (mg/l)

DAY	1	2	3	4	5	EFF.
1	0,00	0,00	1,40	3,10	8,70	9,50
2	0,00	0,00	1,50	2,90	5,90	5,90
3	-	-	-	-	-	-
4	0,00	0,00	1,90	4,00	4,30	4,80
5	0,00	0,80	2,70	4,00	7,00	5,00
6	0,00	0,00	2,10	4,30	4,80	4,30
7	0,00	0,00	3,80	5,50	8,40	5,90
8	0,00	0,00	2,50	3,90	4,40	4,80
9	-	-	-	-	-	-
10	0,00	0,00	1,90	3,80	3,20	4,80
11	0,00	0,00	2,00	4,80	6,90	0,00
12	0,00	0,00	2,30	3,80	3,20	3,40
13	0,00	0,00	2,30	3,60	3,80	3,80
14	-	-	-	-	-	-
15	0,00	0,00	2,40	3,30	3,60	3,90
16	0,80	0,90	1,70	3,70	3,40	3,70
17	0,80	1,10	2,40	4,10	4,00	3,40
18	1,30	1,50	2,60	4,40	4,20	4,40
19	1,20	1,10	3,40	4,60	4,90	4,80
MEAN	0,00	0,00	2,30	4,00	5,00	4,80

APPENDIX A 12

RAW DATA FROM EXPERIMENT 3.3

PHOSPHORUS (mg/l)

DAY	INF.	FILT. INF.	1	2	3	4	5	EFF.	FILT. EFF.
1	11,59	8,80	11,59	6,87	5,47	4,51	2,25	3,11	2,42
2	11,38	9,77	12,13	7,84	3,86	3,97	1,61	3,01	2,79
3	11,49	9,98	13,31	4,19	5,26	4,51	2,68	3,54	3,22
4	11,81	10,73	8,69	3,22	6,23	3,86	3,11	3,01	2,90
5	12,31	10,84	9,55	6,23	4,72	4,08	3,22	3,01	3,01
6	12,02	10,73	13,42	4,29	5,26	4,51	3,33	3,54	3,43
MEAN	11.74		11.90	5.50	5.20	4.24	2.77	3.19	2.97

	COD(mg/l)		TKN(mg/l)			VSS(mg/l)
DAY	INF.	EFF.	INF.	5	EFF.	5
1	514	42	40,0	2,1	1,3	3024
2	489	35	41,4	1,6	3,0	3113
3	536	42	47,7	1,1	1,4	3175
4	580	31	53,2	2,6	3,6	3164
5	566	35	46,3	3,6	3,4	3300
6	-	-	49,2	1,9	1,7	3371
MEAN	537	37	46,3		2,4	3191

	pH							O_2 DEMAND (mg/l/h)		
DAY	INF.	1	2	3	4	5	EFF.	3	4	5
1	7,35	7,50	7,50	7,35	7,45	7,55	7,65			
2	7,30	7,35	7,45	7,25	7,40	7,45	7,65	77,5	25,0	20,5
3	7,40	7,45	7,45	7,30	7,40	7,50	7,65	85,0	29,0	21,5
4	7,45	7,50	7,55	7,35	7,45	7,60	7,75	93,0	38,0	23,0
5	7,40	7,40	7,45	7,35	7,40	7,50	7,65	78,5	29,0	22,5
6	7,35	7,45	7,45	7,35	7,45	7,55	7,75	85,0	33,5	24,0
MEDIAN	7,40	7,45	7,45	7,35	7,45	7,55	7,65			
							MEAN	83,8	30,9	22,3

NITRATE (mg/l)

DAY	1	2	3	4	5	EFF.
1	1,00	0,50	7,80	9,40	9,60	8,00
2	0,00	0,00	6,70	7,20	7,50	7,50
3	0,00	0,50	5,20	6,80	7,40	7,50
4	0,00	0,00	5,70	8,20	8,00	6,90
5	0,00	0,00	4,20	5,90	6,20	7,30
6	0,00	0,00	4,20	4,50	4,40	5,20
MEAN	0,00	0,00	5,60	7,00	7,20	7,10

APPENDIX A 13

RAW DATA FROM EXPERIMENT 3,4

PHOSPHORUS (mg/l)

DAY	INF.	FILT. INF.	1	2	3	4	5	EFF.	FILT. EFF.
1	11,31	10,99	7,51	6,42	5,33	5,22	4,57	5,33	4,35
2	-	-	-	-	-	-	-	-	-
3	13,27	9,68	11,20	3,92	2,72	2,83	2,83	3,15	2,83
4	11,96	9,46	5,66	4,13	2,07	1,20	0,44	3,05	2,66
5	12,94	10,66	8,05	3,48	3,48	0,65	1,85	1,41	1,74
6	11,42	8,81	8,38	4,02	4,57	2,72	2,39	2,50	2,18
7	11,31	9,57	9,46	5,22	3,59	3,70	2,39	2,50	1,47
8	12,18	10,33	11,31	4,79	2,50	2,50	1,96	2,18	2,39
9	-	9,14	12,73	-	3,13	3,05	1,74	2,15	1,93
10	11,70	10,20	12,24	4,72	3,33	1,07	1,82	1,72	1,93
11	-	9,98	10,73	5,15	3,11	2,79	0,97	2,36	1,93
MEAN	12,02		10,20	4,48	3,13	2,18	1,95	2,50	2,12

	COD (mg/l)		TKN (mg/l)			VSS (mg/l)
DAY	INF.	EFF.	INF.	5	EFF.	5
1	555	27	43,4	2,4	2,1	3222
2	520	37	-	-	-	-
3	515	-	46,5	6,6	3,4	3129
4	488	29	41,7	2,6	1,6	3177
5	557	21	39,4	2,9	2,7	3093
6	522	35	37,1	2,6	1,6	3203
7	545	41	39,7	1,6	1,7	3092
8	510	29	40,3	3,3	2,6	3194
9	510	42	40,3	3,2	2,3	3060
10	490	35	41,4	1,7	2,1	3147
11	473	30	41,4	1,1	1,1	3163
MEAN	515	33	41,0		2,1	3148

	pH							O_2 DEMAND (mg/l/h)		
DAY	INF.	1	2	3	4	5	EFF.	3	4	5
1	7,15	7,40	7,35	7,25	7,35	7,40	7,50	74,50	21,50	18,00
2	-	-	-	-	-	-	-	-	-	-
3	7,25	7,45	7,45	7,30	7,40	7,50	7,80	-	-	-
4	7,20	7,35	7,40	7,30	7,50	7,50	7,70	-	-	-
5	7,20	7,40	7,45	7,35	7,40	7,50	7,70	79,00	25,00	25,00
6	7,35	7,40	7,45	7,30	7,40	7,50	7,70	-	-	-
7	7,30	7,40	7,45	7,40	7,40	7,50	7,75	77,00	25,00	20,50
8	7,25	7,35	7,40	7,30	7,35	7,45	7,70	81,00	27,00	20,00
9	7,20	7,35	7,35	7,30	7,35	7,50	7,70	75,00	24,50	22,00
10	7,35	7,40	7,45	7,30	7,40	7,50	7,65	81,00	26,50	22,00
11	7,35	7,45	7,50	7,35	7,45	7,55	7,75	84,00	29,50	22,00
MEDIAN	7,25	7,40	7,45	7,30	7,40	7,50	7,70			
							MEAN	78,80	25,60	21,40

NITRATE (mg/l)

DAY	1	2	3	4	5	EFF.
1	0,00	6,20	10,20	9,80	12,30	21,20
2	-	-	-	-	-	-
3	0,00	1,00	6,10	6,40	7,60	8,20
4	0,00	1,20	5,90	5,80	6,80	7,40
5	0,00	0,00	5,00	5,00	6,00	6,40
6	0,00	0,00	7,00	7,10	7,00	6,60
7	0,00	0,90	5,60	5,80	7,00	6,70
8	0,00	1,80	6,70	7,00	8,30	7,50
9	0,00	1,80	6,90	7,30	8,50	8,40
10	0,00	0,70	5,70	6,40	7,60	8,20
11	0,00	0,80	7,80	9,20	10,00	8,80
MEAN	0,00	1,20	6,50	6,70	7,50	7,60

APPENDIX A 14

RAW DATA FROM EXPERIMENT 4.1

PHOSPHORUS (mg/l)

DAY	INF.	FILT. INF.	1	2	3	4	5	EFF.	FILT. EFF.
1	9,98	7,19	3,22	2,25	1,82	1,61	1,50	1,29	1,07
2	9,77	8,16	3,43	1,18	1,72	2,04	1,40	1,18	0,91
3	10,63	6,27	2,90	2,15	1,50	2,04	1,40	0,86	0,48
4	9,98	7,62	2,79	2,25	1,72	1,82	1,40	1,29	1,18
5	10,41	7,84	2,04	1,72	1,07	0,97	1,29	1,18	1,18
6	-	8,16	3,11	1,82	1,29	1,18	0,97	0,86	0,59
7	10,20	6,66	1,07	0,86	1,50	1,50	0,75	1,07	0,91
8	11,86	9,25	3,37	2,72	2,18	0,54	1,31	1,52	1,09
9	11,75	9,35	3,92	2,94	2,50	1,96	1,63	0,87	1,09
10	12,18	9,57	3,26	2,61	2,18	1,96	1,31	1,63	1,41
11	10,88	9,14	3,15	2,94	2,28	2,07	1,85	1,85	1,47
12	12,07	9,46	3,48	3,15	3,48	2,18	1,09	2,39	2,18
MEAN	10,70	8,50	2,98	2,34	1,94	1,94	1,33	1,27	1,11
13	9,79	-	4,35	3,05	2,07	1,74	1,74	1,96	1,52
14	10,66	-	3,59	2,50	0,87	1,31	0,44	1,52	0,98
15	10,77	7,18	3,26	1,85	1,31	1,31	0,76	1,20	0,87
16	9,90	7,72	3,37	1,63	1,20	0,98	0,44	1,20	0,65
17	9,90	6,96	2,83	1,63	1,31	0,33	0,98	1,09	0,54
18	10,33	8,27	1,96	1.96	1,41	1,20	0,76	0,54	0,60
19	11,09	8,48	4,02	2.18	1,41	1,41	0,54	0,87	0,76
20	11,64	8,16	2,83	1.52	1,52	1,20	0,65	1,09	0,76
21	11,57	9,14	4,13	2.18	1,31	0,65	0,54	0,76	0,71
22	11,09	9,03	4,79	2.39	1,74	1,41	1,09	0,87	0,82
23	10,77	8,48	1,41	1.96	1,31	0,98	0,65	0,98	0,76
24	11,31	6,85	4,87	2,28	1.52	1,41	0.98	0,98	0,92
MEAN	10,80		3,45	2,09	1,42	1,24	0,80	1,04	0,78
25	11,09	8,70	5,33	2,61	1,63	1,52	1,31	1,31	0,98
26	11,75	9,46	5,66	2,72	1,74	1,09	1,07	1,20	0,87
27	11,42	8,48	1,31	0,65	0,76	0,33	0,44	0,87	0,76
28	11,96	9,68	6,53	2,83	1,96	1,52	1,20	0,76	0,82
29	11,09	7,51	4,02	2,83	2,07	1,09	0,87	0,87	0,65
30	11,53	5,22	6,31	3.26	2,07	1,74	1,20	0,78	0,82
MEAN	11,48		4,86	2,48	1,69	1,22	1,02	0,97	0,82

	COD (mg/l)		TKN (mg/l)			VSS (mg/l)
DAY	INF.	EFF.	INF.	5	EFF.	5
1	497	28	36,6	0,0	0,0	3296
2	470	20	32,8	0,0	0,0	3516
3	491	21	40,8	0,0	0,0	3276
4	521	24	38,6	0,0	0,0	3128
5	419	31	34,0	0,0	0,0	2982
6	487	39	35,7	0,0	0,0	3220
7	465	43	34,0	1,6	4,7	3030
8	501	31	33,3	0,0	0,0	3240
9	466	26	35,7	0,0	0,0	3281
10	499	33	56,3	0,0	0,0	3472
11	487	-	36,0	0,0	0,0	3328
12	509	36	36,0	1,3	0,0	3420
MEAN	494	30	35,0		0,0	3266
13	494	31	-	0,0	0,0	3367
14	523	33	45,4	2,7	1,7	3420
15	489	47	41,7	1,7	1,7	3422
16	489	-	44,3	1,7	1,6	3373
17	491	22	50,3	1,9	1,0	-
18	465	30	52,6	2,1	0,0	3418
19	535	-	46,3	1,6	1,7	3365
20	548	44	48,3	2,3	0,7	3427
21	504	39	52,0	2,0	0,0	3440
22	507	52	62,8	0,0	0,0	3552
23	472	36	41,7	2,6	3,0	3488
24	491	42	53,0	2,0	2,6	3421
MEAN	498	38	47,6		1,17	3427
25	523	38	-	1,4	1,0	3382
26	527	30	54,0	2,6	2,6	3354
27	537	26	52,0	1,9	1,7	3508
28	537	33	55,0	2,2	3,0	3513
29	511	26	52,0	0,7	0,9	3399
30	605	27	60,1	3,9	4,0	3524
MEAN	537	30	53,3	-	2,2	3407

DAY	pH INF.	1	2	3	4	5	EFF.	O_2 DEMAND (mg/l/h) 3	4	5
1	9,10	8,25	7,90	7,65	7,50	7,45	-	46,5/ 63,5	20,0/ 48,5	13,0/ 26,5
2	9,00	8,20	7,80	7,60	7,40	7,45	7,55	49,0/ 65,0	14,0/ 48,0	14,5/ 21,0
3	8,90	8,25	7,80	7,55	7,40	7,45	7,55	- / 68,0	- / 53,0	- / 26,5
4	9,00	8,20	7,75	7,50	7,30	7,40	7,60	- / 65,5	- / 49,0	- / 24,0
5	8,95	7,95	7,55	7,35	7,40	7,45	7,55	- / -	- / -	- / -
6	9,05	8,40	7,90	7,60	7,45	7,60	7,80	- / 72,0	- / 65,0	- / 23,0
7	8,30	7,90	7,60	7,40	7,55	7,80	9,10	53,0/ -	14,5/ -	16,0/ -
8	9,00	8,35	7,90	7,65	7,50	7,60	7,85	- / 52,0	- / 20,0	- / 16,5
9	-	-	-	-	-	-	-	67,0/ -	46,0/ -	24,5/ -
10	8,85	8,15	7,70	7,45	7,35	7,50	7,75	51,0/ 76,0	18,5/ 52,0	15,0/ 20,0
11	8,95	8,30	7,80	7,55	7,40	7,55	7,80	- / 73,0	- / 61,5	- / 21,0
12	8,85	8,15	7,70	7,45	7,35	7,45	7,75	- / 74,0	- / 57,0	- / 22,0
13	8,85	8,15	7,80	7,50	7,40	7,55	7,85	- / -	- / -	- / -
14	8,95	8,20	7,85	7,55	7,45	7,55	7,80	- / - am	- / - am	- / - am
15	8,95	8,15	7,80	7,50	7,35	7,55	7,72	72,5	58,5	19,0
16	8,95	8,20	7,80	7,45	7,40	7,55	7,85	74,0	68,0	21,0
17	9,05	8,40	8,00	7,65	7,55	7,65	7,90	70,0	42,5	19,5
18	9,00	8,25	7,85	7,55	7,40	7,45	7,70	76,5	68,0	26,5
19	9,00	8,25	7,85	7,55	7,45	7,50	7,75	82,0	72,0	29,0
20	8,95	8,25	7,85	7,55	7,40	7,50	7,80	-	-	-
21	8,95	8,20	7,85	7,50	7,40	7,45	7,80	-	-	-
22	8,95	8,25	7,85	7,55	7,45	7,50	7,70	-	-	-
23	9,00	8,25	7,85	7,55	7,40	7,55	7,85	72,0	60,5	22,0
24	8,95	8,25	7,85	7,55	7,40	7,45	7,75	76,5	64,0	25,0
25	8,85	8,10	7,75	7,45	7,30	7,40	7,70	-	-	-
26	8,95	8,30	7,90	7,55	7,40	7,40	7,65	-	-	-
27	8,90	8,15	7,70	7,40	7,30	7,35	7,50	-	-	-
28	8,90	8,20	7,80	7,45	7,35	7,35	7,55	-	-	-
29	8,85	8,10	7,75	7,45	7,35	7,30	7,50	73,5	69,0	30,5
30	8,85	8,15	7,80	7,50	7,40	7,35	7,60	-	-	-
MEDIAN	8,95	8,15	7,75	7,50	7,35	7,45	7,75			
							MEAN			
							pm	53,0	18,3	16,1
							am	76,9	53,6	23,0

NITRATE (mg/l)

DAY	1	2	3	4	5	EFF.
1	1,20	1,40	2,00	4,90	8,20	8,80
2	0,60	1,90	5,30	8,70	11,70	7,70
3	0,00	0,60	3,60	6,90	8,50	9,30
4	0,00	0,00	3,20	5,60	8,50	8,50
5	0,60	2,70	6,80	7,40	8,50	7,40
6	0,50	1,30	5,00	8,20	9,10	8,70
7	5,90	1,70	5,50	8,80	8,90	7,60
8	0,00	0,00	5,90	6,00	8,20	7,50
9	0,00	0,00	3,40	6,90	8,30	7,80
10	0,00	0,60	4,90	8,50	9,60	8,60
11	0,00	0,80	5,10	9,10	10,50	9,60
12	0,00	0,00	5,20	8,80	11,70	10,70
13	0,00	0,00	4,10	6,20	6,90	8,50
14	0,00	0,00	3,50	5,80	6,70	6,00
15	0,00	0,00	2,30	4,80	6,60	6,60
16	0,00	0,00	3,30	5,90	6,20	5,90
17	0,00	0,00	2,60	5,90	5,80	5,90
18	0,00	0,00	3,00	5,60	7,40	6,20
19	0,00	0,00	2,90	6,00	7,30	6,70
20	0,00	0,00	2,60	5,60	7,50	6,90
21	0,00	0,00	3,10	5,60	8,20	6,70
22	0,00	0,00	3,10	5,70	9,00	9,40
23	0,00	0,00	3,70	7,50	6,90	8,10
24	0,00	0,80	4,80	10,20	12,00	10,00
25	0,00	0,80	4,80	9,70	11,60	9,40
26	0,00	0,00	4,40	8,90	11,30	13,60
27	0,00	0,90	4,70	9,10	10,90	10,50
28	0,00	0,90	5,10	-	12,60	11,20
29	0,00	0,70	3,70	9,00	13,70	12,10
30	0,00	0,00	4,10	8,30	11,70	11,70
MEAN	0,00	0,00	4,20	7,40	9,30	8,90

APPENDIX A 15

RAW DATA FROM EXPERIMENT 4,2

PHOSPHORUS (mg/l)

DAY	INF.	FILT. INF.	1	2	3	4	5	EFF.	FILT. EFF.
1	11,09	7,94	11,31	4,79	3,59	4,02	3,37	2,28	1,96
2	12,40	11,86	12,07	3,26	4,35	3,26	2,72	2,18	1,58
MEAN	11,75							2,23	1,77
3	-	9,03	11,75	6,96	4,89	3,92	3,70	3,05	2,72
4	11,53	7,51	11,53	5,76	8,38	3,81	2,72	2,39	2,18
MEAN	11,53							2,72	2,45
5	10,12	7,18	10,66	5,98	4,13	3,81	1,96	2,39	2,07
6	10,66	6,53	11,42	5,87	5,33	3,92	2,50	1,85	1,58
7	11,42	8,27	7,62	5,22	3,59	3,05	2,50	2,94	2,94
8	11,86	9,35	2,28	5,87	2,94	4,35	2,72	2,28	1,85
9	11,31	8,59	13,27	5,44	4,46	3,81	1,20	2,61	2,61
MEAN	11,80		10,90	5,78	4,50	3,86	2,50	2,42	2,16

	COD (mg/l)		TKN (mg/l)			VSS(mg/l)
DAY	INF.	EFF.	INF.	5	EFF.	5
1	384	26	44,9	0,9	3,6	-
2	472	29	52,9	1,1	5,7	3471
3	306	43	53,5	4,9	3,9	3335
4	421	-	52,6	3,6	4,2	3277
5	538	34	52,0	3,0	3,3	3238
6	524	30	56,7	1,6	1,1	3205
7	472	26	54,0	3,0	2,3	3266
8	484	33	54,3	2,7	3,3	3170
9	516	41	51,4	2,9	2,1	3107
MEAN	454	33	52,5		3,3	3259

	pH							O_2 DEMAND(mg/l/h)		
DAY	INF.	1	2	3	4	5	EFF.	3	4	5
1	7,20	7,30	7,35	7,35	7,25	7,35	7,60	69,0	65,0	20,5
2	7,10	7,30	7,35	7,35	7,25	7,30	7,60	-	-	-
3	7,15	7,40	7,35	7,35	7,25	7,25	7,55	-	-	-
4	7,25	7,40	7,40	7,35	7,35	7,40	7,60	63,5	61,5	21
5	7,15	7,45	7,45	7,35	7,35	7,40	7,65	80,5	66,0	21,0
6	7,15	7,45	7,40	7,30	7,25	7,40	7,65	68,5	62,5	22,0
7	7,35	7,50	7,45	7,35	7,30	7,40	7,70	76,0	76,0	21,0
8	7,25	7,50	7,40	7,75	7,25	7,45	7,65	82,5	67,5	19,5
9	7,20	7,40	7,30	7,20	7,25	7,40	7,60	81,0	63,5	19,0
MEDIAN	7,20	7,40	7,35	7,35	7,25	7,40	7,65			
							MEAN	74,4	66,00	20,6

NITRATE (mg/l)

DAY	1	2	3	4	5	EFF.
1	0,00	0,60	4,80	8,70	10,40	10,90
2	0,00	1,60	5,30	9,40	15,40	11,40
3	0,00	1,80	5,40	9,60	15,50	13,60
4	0,00	3,20	6,70	12,90	15,70	13,00
5	0,00	3,00	7,50	12,60	15,20	13,20
6	0,00	2,80	6,50	12,00	13,50	14,00
7	0,00	3,10	7,90	13,00	16,00	14,00
8	0,00	3,80	9,50	15,00	16,20	14,40
9	0,00	4,10	8,90	15,20	16,20	14,80
MEAN	0,00	3,10	7,10	12,20	14,30	13,30

APPENDIX A 16

RAW DATA FROM EXPERIMENT 5.1

PHOSPHORUS (mg/l)

DAY	INF.	1	2	3	4	5	EFF.	FILT. EFF.
1	12,24	7,14	5,10	4,89	5,10	4,79	6,32	6,42
2	12,24	7,95	4,38	3,67	3,57	3,06	3,47	3,16
3	13,36	7,95	3,67	3,06	2,45	2,04	2,55	2,65
4	11,12	6,93	3,57	2,96	2,55	2,14	1,84	1,73
5	11,42	5,61	4,18	2,65	3,06	2,86	2,55	1,84
6	11,73	5,40	4,18	3,57	3,67	3,77	3,26	3,06
7	12,13	5,61	4,89	4,59	3,87	4,59	4,08	3,87
MEAN	11,98	6,70	4,30	3,58	3,35	3,30	3,20	2,90
8	16,21	5,22	5,87	6,09	5,00	5,00	4,89	4,79
9	15,77	7,72	6,53	6,63	5,98	5,44	5,98	5,44
10	13,27	6,09	5,76	6,09	6,31	5,76	6,09	5,87
11	14,79	5,66	5,66	5,44	5,00	5,76	5,87	5,33
12	13,92	7,61	7,40	6,20	5,33	4,57	5,98	5,76
13	-	7,51	6,74	5,85	5,98	5,98	5,76	5,33
14	13,92	11,53	10,66	8,59	7,18	5,87	5,55	5,55
15	12,94	6,85	5,66	5,00	4,68	3,81	4,68	4,35
16	12,40	5,44	5,33	5,33	5,22	4,35	4,89	5,11
17	14,14	6,53	6,20	5,00	5,98	5,33	6,09	6,09
18	13,60	6,96	5,66	5,76	6,63	5,66	6,09	5,87
MEAN	14,00	6,70	6,15	5,80	5,70	5,32	5,80	5,44

	COD(mg/l)		TKN(mg/l)		VSS(mg/l)
DAY	INF.	EFF.	INF.	EFF.	5
1	553	55	36,3	0,9	3208
2	553	24	33,4	0,0	3142
3	527	41	34,6	0,0	3030
4	461	40	38,3	0,0	3146
5	473	37	35,7	0,0	3096
6	507	41	-	0,0	3194
7	522	31	39,1	2,0	3196
MEAN	519	38	36,3	0,0	3196
8	605	32	44,0	3,6	3256
9	520	49	42,8	0,0	3150
10	477	42	44,8	0,0	3210
11	532	49	46,0	0,0	2966
12	429	37	46,3		2880
13	477	26	41,4	0,0	2862
14	524	55	39,1	2,7	2994
15	508	48	40,3	2,0	2926
16	458	30	42,3	0,0	3068
17	462	29	43,0	2,3	2976
18	570	26	43,4	2,1	3070
MEAN	502	38	43,2	1,3	3033

	pH						O_2 DEMAND (mg/l/h)		
DAY	INF.	1	2	3	4	5	EFF.	3	4	5
1	8,70	7,20	6,70	6,2	6,10	6,00	5,70	54,0	33,0	14,5
2	9,10	7,50	7,00	6,50	6,60	6,60	6,40	51,0	21,0	16,5
3	8,90	7,50	7,20	6,90	7,00	7,10	7,00	59,0	20,5	15,5
4	9,0	7,75	7,30	7,10	7,30	7,30	7,30	63,0	30,0	14,0
5	8,90	7,30	7,5	7,10	7,30	7,30	7,50	53,0	16,0	13,0
6	8,90	7,90	7,50	7,10	7,35	7,35	7,45	63,0	19,5	12,5
7	8,80	7,70	7,40	7,00	7,15	7,28	7,30	59,0	19,0	14,0
							MEAN	57,4	22,7	14,3
8	8,60	7,25	7,22	7,00	6,90	6,95	7,00	75,0	47,0	23,5
9	8,80	7,80	7,10	6,95	7,00	7,00	7,15	82,0	70,0	26,5
10	8,60	7,10	7,10	7,00	7,05	7,10	7,10	52,0	19,0	16,0
11	8,75	7,65	7,30	7,10	7,10	7,00	7,10	80,0	65,5	62,0
12	8,70	7,60	7,40	7,20	7,30	7,20	7,40	81,0	70,0	53,0
13	8,70	7,65	7,30	7,10	7,05	7,02	7,15	80,0	63,5	24,5
14	8,70	7,60	7,40	7,35	7,30	7,20	7,25	83,0	80,0	63,0
15	8,7	7,6	7,2	6,9	6,9	7,1	7,25	80,0	27,0	18,0
16	8,65	7,62	7,20	6,90	7,00	7,15	7,25	76,0	26,0	14,5
17	8,90	7,80	7,3	7,0	7,05	7,20	7,30	68,0	18,0	14,5
18	8,70	7,70	7,15	6,90	6,95	7,15	7,30	71,0	19,5	13,5
MEDIAN	8,70	7,65	7,20	7,00	7,05	7,5	7,25			
							MEAN	75,3	42,6	29,9

NITRATE (mg/l)

DAY	1	2	3	4	5	EFF.
1	0,00	1,30	4,90	6,60	7,10	7,70
2	0,00	1,80	5,00	5,80	6,00	6,30
3	0,00	2,30	5,10	5,40	9,30	5,60
4	0,00	0,50	5,00	5,50	5,80	5,80
5	0,00	1,20	5,30	5,40	5,60	5,50
6	0,00	1,30	5,30	5,30	5,60	5,80
7	0,00	0,50	4,30	4,40	5,00	5,10
8	3,20	1,60	4,70	5,30	6,40	9,20
9	1,30	2,50	6,30	9,00	9,20	8,50
10	5,20	4,70	6,70	7,00	7,70	9,00
11	0,00	0,00	1,20	1,70	6,60	8,00
12	0,00	0,00	1,10	2,20	6,60	9,20
13	0,00	0,00	1,10	2,20	6,60	9,20
14	0,00	0,00	0,00	0,00	3,70	6,50
15	0,00	0,00	4,00	4,80	6,50	9,40
16	0,00	1,60	7,00	7,80	8,30	7,90
17	0,00	0,80	5,10	5,40	6,40	7,60
18	0,00	3,00	8,70	9,40	9,80	8,50
MEAN	0,00	1,40	4,50	5,20	6,80	7,50

APPENDIX A 17

RAW DATA FROM EXPERIMENT 5.2

PHOSPHORUS (mg/l)

DAY	INF.	1	2	3	4	5	EFF.	FILT. EFF.
1	12,73	9,35	4,89	4,46	4,46	3,70	3,26	3,05
2	14,90	9,57	4,68	4,24	3,92	3,26	3,59	3,59
3	15,55	8,48	4,57	4,02	3,92	3,37	3,05	3,05
4	12,64	6,31	4,46	3,81	3,48	3,26	2,94	2,94
5	11,09	8,05	4,68	3,05	2,94	3,05	3,26	3,15
6	13,92	9,14	4,79	4,02	3,37	3,05	3,48	3,05
7	14,58	10,66	5,11	4,35	4,02	3,48	2,83	2,39
8	15,23	9,68	7,40	5,00	4,35	2,70	3,48	3,26
9	12,73	10,22	5,87	4,02	3,59	2,61	2,50	2,28
10	13,92	11,20	5,44	4,13	3,59	2,50	2,28	2,72
11	15,12	12,18	6,31	5,44	4,89	4,02	3,37	3,05
12	-	7,40	5,76	5,44	5,33	3,59	4,35	4,13
13	14,58	8,81	6,53	5,11	4,46	4,13	3,92	4,02
14	15,45	7,72	5,76	4,57	4,13	4,02	3,81	4,46
MEAN	14,50	9,20	5,35	4,35	4,00	3,35	3,30	3,10

	COD(mg/l)		TKN(mg/l)		VSS(mg/l)
DAY	INF.	EFF.	INF.	EFF.	5
1	543	23	44,0	0,0	3164
2	549	30	43,1	1,0	3184
3	531	21	50,0	5,0	3000
4	577	29	47,4	6,6	2994
5	525	36	48,0	5,6	3015
6	475	36	55,0	7,7	2999
7	489	27	47,0	3,0	2980
8	536	32	46,0	4,4	3162
9	513	32	-	-	3380
10	506	24	41,1	0,0	3544
11	476	30	38,6	0,0	3459
12	527	35	41,4	1,9	3313
13	541	28	40,8	4,0	3364
14	501	28	41,7	1,6	-
MEAN	522	29	44,60	3,0	3197

	pH						O_2 DEMAND (mg/l/h)		
DAY	INF.	1	2	3	4	5	EFF.	3	4	5
1	9,00	7,90	7,50	7,20	7,20	7,40	7,40	74,0	30,5	15,5
2	9,00	7,80	7,40	7,20	7,10	7,35	7,50	74,0	26,5	14,5
3	9,10	7.95	7,50	7,20	7,10	7,30	7,45	71,0	19,5	14,0
4	9,00	7,90	7,45	7,20	7,10	7,30	7,40	73,0	23,0	13,0
5	9,10	7,90	7,45	7,20	7,20	7,40	7,40	61,0	18,0	12,0
6	9,10	7,90	7,40	7,10	7,08	7,30	7,40	60,0	20,5	16,0
7	9,10	7,90	7,50	7,20	7,10	7,30	7,55	76,0	37,0	15,0
8	9,10	8,00	7,60	7,50	7,40	7,40	7,50	-	-	-
9	9,10	7,80	7,50	7,30	7,20	7,30	7,60	79,0	62,0	20,0
10	9,00	7,70	7,40	7,30	7,20	7,35	7,55	86,0	79,0	22,5
11	9,10	7,80	7,50	7,30	7,30	7,40	7,50	85,0	68,0	22,0
12	8,90	7,90	7,50	7,45	7,30	7,50	7,50	96,0	67,0	26,0
13	9,00	7,90	7,50	7,40	7,35	7,20	7,40	90,0	64,0	32,0
14	9,00	7,90	7,50	7,30	7,30	7,20	7,40	96,0	70,0	30,5
MEDIAN	9,10	7,90	7,50	7,25	7,20	7,35	7,50			
							MEAN	78,6	44,5	19,5

NITRATE (mg/l)

DAY	1	2	3	4	5	EFF.
1	0,00	0,70	3,40	5,00	5,90	6,20
2	0,00	0,00	2,30	4,60	5,20	5,60
3	0,00	1,60	4,10	6,20	7,00	6,50
4	0,00	1,60	4,00	6,30	6,50	6,70
5	0,00	1,50	4,10	5,20	5,80	6,20
6	0,00	1,90	4,50	6,20	6,50	6,00
7	0,00	0,00	1,90	4,40	5,00	5,70
8	0,00	0,00	0,80	1,80	4,80	6,60
9	0,00	0,00	1,30	2,70	5,40	5,60
10	0,00	0,00	1,80	3,60	5,90	6,10
11	0,50	0,00	2,00	3,70	6,10	5,10
12	0,70	0,00	1,50	3,30	8,70	6,40
13	0,50	0,00	0,90	1,20	8,40	7,20
14	0,50	0,00	1,60	2,30	8,80	8,60
MEAN	0,00	0,00	2,40	4,00	6,40	6,30

APPENDIX A 18

RAW DATA FROM EXPERIMENT 5.3

PHOSPHORUS (mg/l)

DAY	INF.	1	2	3	4	5	EFF.	FILT. EFF.
1	15,23	11,75	7,94	3,48	3,70	3,26	4,13	3,92
2	14,68	10,22	4,02	2,61	2,18	1,63	2,39	2,18
3	15,77	11,20	3,81	2,28	1,20	1,41	1,96	1,85
4	-	12,62	5,00	3,05	2,72	1,96	1,85	1,85
5	15,88	12,83	4,57	2,39	1,52	0,98	2,28	1,20
6	13,49	13,81	3,37	2,72	1,96	1,31	1,63	1,20
7	15,01	12,94	4,35	2,50	2,07	1,31	1,96	1,20
8	14,90	10,88	4,79	2,50	1,20	1,20	1,81	1,31
9	14,68	10,33	3,37	2,72	1,85	1,31	1,96	1,41
10	15,99	12,94	4,35	2,28	2,07	1,31	2,07	1,41
11	15,12	13,92	5,44	3,70	2,72	1,31	2,07	1,63
12	15,23	13,16	6,31	3,92	2,83	2,07	2,50	1,96
MEAN	15,10	12,35	4,55	2,72	2,15	1,31	2,10	1,60

	COD (mg/l)		TKN (mg/l)		VSS (mg/l)
DAY	INF.	EFF.	INF.	EFF.	5
1	536	38	43,1	1,7	3211
2	486	42	34,6	3,6	3377
3	520	40	34,6	3,6	3204
4	533	30	35,7	3,7	3252
5	524	29	38,3	0,0	3275
6	482	29	37,7	1,7	3320
7	494	39	38,8	1,4	-
8	454	54	36,3	1,4	3256
9	516	27	-	-	3088
10	563	34	41,7	0,0	3140
11	548	47	39,0	0,0	3268
12	510	4,3	41,1	1,7	3334
MEAN	516	37	38,3	1,7	3248

	pH						O_2 DEMAND (mg/l/h)		
DAY	INF.	1	2	3	4	5	EFF.	3	4	5
1	9,00	7,65	7,40	7,20	7,20	7,10	7,30	92,0	87,0	34,5
2	9,25	7,85	7,45	7,25	7,20	7,35	7,40	85,0	53,0	20,0
3	9,10	7,70	7,30	7,15	7,10	7,30	7,60	84,0	61,0	20,5
4	9,00	7,65	7,45	7,30	7,25	7,30	7,60	90,0	42,0	19,5
5	9,30	7,90	7,50	7,30	7,20	7,40	7,70	97,0	37,0	20,5
6	9,00	7,70	7,30	7,10	7,10	7,30	7,55	92,0	62,0	26,5
7	9,10	7,70	7,30	7,10	7,05	7,30	7,60	96,0	34,5	23,0
8	9,10	7,60	7,30	7,10	7,10	7,15	7,50	95,0	75,0	32,0
9	9,10	7,70	7,30	7,10	7,05	7,30	7,50	80,0	22,0	18,0
10	8,90	7,60	7,30	7,10	7,10	7,30	7,50	75,0	40,0	19,5
11	9,00	7,60	7,30	7,10	7,00	7,20	7,50	88,0	64,0	23,5
12	8,90	7,65	7,30	7,20	7,10	7,30	7,60	77,0	34,0	20,0
MEDIAN	9,10	7,55	7,30	7,10	7,10	7,30	7,50			
							MEAN	88,6	52,5	23,4

NITRATE (mg/l)

DAY	1	2	3	4	5	EFF.
1	0,00	0,00	1,10	0,80	6,20	5,90
2	0,00	0,00	1,60	3,60	4,00	3,00
3	0,00	0,00	1,70	2,50	3,90	3,40
4	0,00	0,00	1,40	2,40	3,90	2,70
5	0,00	0,00	2,10	2,80	3,70	3,40
6	0,00	0,00	2,30	2,10	2,80	3,60
7	0,00	0,00	2,60	1,90	3,30	3,80
8	0,00	0,00	1,60	1,90	5,60	5,40
9	0,00	0,00	2,50	3,50	4,80	4,60
10	0,00	0,00	1,50	3,20	4,00	3,30
11	0,00	0,00	1,40	3,10	5,20	4,20
12	0,00	0,00	1,90	3,40	4,80	5,20
MEAN	0,00	0,00	1,80	2,50	4,80	3,90

APPENDIX 19

RAW DATA FROM EXPERIMENT 5.4

PHOSPHORUS (mg/l)

DAY	INF.	1	2	3	4	5	EFF.	FILT. EFF.
1	14,90	6,53	3,48	2,61	2,72	3,05	2,94	2,72
2	14,90	7,07	4,79	4,35	4,57	4,79	3,92	3,48
3	14,90	7,61	4,24	2,61	3,37	3,92	4,57	3,92
4	14,79	5,87	4,35	3,48	3,48	3,81	4,68	4,57
5	14,90	14,03	9,14	5,55	4,35	2,94	4,35	3,26
6	14,90	5,00	4,24	3,26	3,15	-	3,48	2,50
7	14,68	6,09	4,68	3,26	3,26	3,81	3,92	3,48
8	14,79	5,87	4,35	3,05	3,59	3,70	3,81	3,37
9	15,77	4,13	4,02	3,81	3,48	3,81	4,24	3,81
10	15,42	5,11	5,22	5,44	5,98	5,98	4,89	4,68
11	14,68	6,42	3,92	3,70	3,70	3,70	4,13	3,81
12	14,36	3,37	2,94	2,94	3,70	4,02	3,37	3,70
13	14,90	3,70	3,37	3,59	3,92	4,02	4,24	3,92
MEAN	14,90	5,75	4,20	3.45	3,60	3,85	4,10	3,60

	COD(mg/l)		TKN(mg/l)		VSS (mg/l)
DAY	INF.	EFF.	INF.	EFF.	5
1	506	35	7,10	5,70	3500
2	553	38	66,8	12,14	3298
3	527	41	56,6	10,70	3319
4	470	41	55,4	4,10	3540
5	481	39	56,6	10,40	3510
6	505	37	55,7	11,10	3344
7	502	48	55,1	9,10	3266
8	473	38	53,7	10,10	3266
9	525	38	54,8	6,60	3330
10	513	31	57,7	2,10	3142
11	554	36	55,1	2,60	3142
12	521	23	57,4	0,00	3336
13	575	34	57,7	0,90	3282
MEAN	515	37	56,4	6,80	3329

DAY	pH							O_2 DEMAND (mg/l/h)		
	INF.	1	2	3	4	5	EFF.	3	4	5
1	9.00	7,60	7,20	7,00	6,90	6,80	7,20	84,0	64,0	62,0
2	8,80	7,70	7,30	7,10	7,00	6,80	6,90	78,0	63,0	65,0
3	8,90	7,60	7,20	7,10	7,00	6,80	7,40	92,0	72,0	68,0
4	8,90	7,60	7,20	7,00	6,95	6,50	6,70	100,0	76,0	64,0
5	9,0	7,50	7,30	7,20	7,20	7,00	7,10	-	-	-
6	8,80	7,30	7,10	7,00	7,00	6,70	6,90	92,0	74,0	70,0
7	8,90	7,90	7,45	7,30	7,20	7,00	7,00	90,0	86,0	80,0
8	8,90	7,75	7,35	7,20	7,10	6,90	7,10	75,0	88,0	70,0
9	9,00	7,80	7,10	6,70	6,65	6,70	6,70	80,0	37,0	18,0
10	8,80	7,40	6,80	6,40	6.65	6,20	6,40	65,0	49,0	16,5
11	8,70	7,40	7,00	6,70	6,70	6,80	6,80	64,0	28,5	16,0
12	8,80	7,50	6,90	6,50	6,40	6,50	6,60	74,0	46,0	16,0
13	8,70	7,20	6,60	6,20	6,00	6,00	6,30	70,0	40,0	17,5
								MEAN		
MEDIAN	8,90	7,60	7,20	7,00	7,00	6,90	6,90	80,1	58,3	44,9

NITRATE (mg/l)

DAY	1	2	3	4	5	EFF.
1	0,00	1,00	2,90	5,50	14,30	11,10
2	0,00	0,00	2,10	4,20	13,50	13,80
3	0,00	0,00	1,50	2,20	11,80	12,00
4	0,00	0,00	2,10	2,30	15,30	16,40
5	0,00	0,00	0,00	0,70	8,10	9,60
6	0,00	0,00	1,20	1,80	12,20	12,70
7	0,00	0,00	0,60	1,10	10,90	11,80
8	0,00	0,00	0,80	1,00	10,90	11,40
9	3,00	13,90	20,30	19,30	22,00	21,80
10	4,10	13,60	15,70	21,40	23,00	23,00
11	0,60	5,90	11,00	11,70	12,60	15,00
12	0,70	10,20	15,40	17,20	19,00	16,30
13	0,60	9,20	14,30	16,70	18,20	18,20
MEAN	0,00	4,20	16,90	8,40	14,80	14,90

APPENDIX A 20

RAW DATA FROM EXPERIMENT 6

PHOSPHORUS (mg/l)

DAY	INF.	1	2	3	4	5	EFF.	FILT. EFF.
1	14,33	6,50	3,75	2,32	2,54	1,98	1,98	1,87
2	14,55	6,06	2,87	2,20	2,43	2,09	2,20	2,09
3	14,99	5,95	2,76	3,09	2,32	2,09	2,65	1,76
4	15,21	8,05	3,86	3,31	3,09	2,87	2,98	2,65
5	15,10	5,51	2,54	1,55	1,22	1,33	1,87	1,44
6	14,33	5,29	2,65	1,32	1,98	1,54	2,32	1,76
7	14,66	7,50	2,98	2,54	2,32	1,98	2,43	2,09
8	15,65	10,14	4,52	4,08	3,75	3,20	3,09	2,65
9	14,77	3,20	2,65	2,54	2,20	2,20	2,65	1,98
10	-	-	-	-	-	-	-	-
11	12,90	5,07	3,20	2,76	2,76	1,98	4,41	3,20
12	15,21	7,06	2,20	2,65	2,65	2,20	2,43	2,32
13	14,66	5,86	2,06	1,54	1,54	1,43	1,54	1,65
14	14,77	7,72	2,76	2,09	1,76	1,21	1,43	1,10
15	14,66	8,06	2,98	1,98	1,65	1,21	1,32	1,21
16	15,87	12,13	3,98	3,31	2,65	1,87	1,76	1,54
MEAN	14,85	6,80	2,92	2,44	2,24	1,98	2,26	1,90

	COD(mg/l)		TKN(mg/l)		VSS(mg/l)
DAY	INF.	EFF.	INF.	EFF.	5 / 1
1	520	45	46,3	1,7	3318/1856
2	537	36	47,1	1,7	3261/1804
3	546	27	47,4	0,6	3260/1806
4	544	30	47,7	0,0	3334/1846
5	504	37	50,0	3,6	3232/1720
6	495	36	48,8	0,0	3358/1839
7	472	35	46,8	0,0	3203/1768
8	538	32	50,0	2,6	3228/1800
9	507	27	46,3	2,9	3317/1782
10	512	39	52,0	2,2	- / -
11	529	34	45,4	1,6	3417/1763
12	553	42	43,8	0,0	3449/1806
13	522	36	45,1	0,0	3451/1826
14	521	33	48,6	1,3	3492/1839
15	546	29	47,7	2,4	3418/1794
16	540	31	47,0	0,0	3478/1848
MEAN	528	33	50,7	1,4	3347/1807

	pH						O_2 DEMAND(mg/l/h)		
DAY	INF.	1	2	3	4	5	EFF.	3	4	5
1	9,30	8,00	7,20	6,80	6,90	7,00	7,20	67,00	21,00	14,50
2	9,00	8,00	7,20	6,90	6,90	7,00	7,10	80,00	22,50	16,00
3	8,80	7,70	7,00	6,70	6,70	6,80	7,10	84,00	26,00	16,00
4	8,90	7,90	7,20	6,90	7,00	7,00	7,10	78,00	27,00	18,00
5	9,00	8,00	7,40	7,00	7,00	7,10	7,30	90,00	34,50	18,00
6	9,10	7,80	7,20	7,00	7,00	7,10	7,30	96,00	39,00	18,50
7	9,10	8,00	7,00	7,00	7,00	7,10	7,30	84,00	40,00	17,00
8	9,00	8,00	7,40	7,20	7,10	7,20	7,30	120,00	50,00	17,50
9	9,10	8,30	7,30	6,95	6,90	6,95	7,30	82,00	34,00	10,50
10	-	-	-	-	-	-	-	-	-	-
11	9,00	8,00	7,25	7,00	7,00	7,00	7,30	90,00	49,00	15,00
12	9,00	7,70	7,20	7,00	7,00	7,12	7,30	83,00	33,00	14,00
13	9,10	7,80	7,20	7,00	6,95	7,10	7,20	70,00	36,50	14,00
14	9,00	8,10	7,30	7,10	7,00	7,05	7,10	92,00	92,00	16,50
15	9,20	8,20	7,40	7,15	7,00	7,10	7,30	98,00	63,00	14,00
16	9,50	8,55	7,60	7,20	7,20	7,30	7,45	78,00	31,00	14,00
MEDIAN	9,00	8,00	7,20	7,00	7,00	7,10	7,30			
							MEAN	86,10	34,10	15,60

NITRATE (mg/l)

DAY	1	2	3	4	5	EFF.
1	0,00	8,50	14,00	14,20	15,20	13,70
2	0,00	8,50	14,20	13,80	15,20	14,50
3	0,70	8,80	14,90	14,50	15,40	14,60
4	0,00	7,10	12,30	12,80	13,80	13,90
5	0,60	6,00	10,80	11,70	12,40	12,40
6	0,60	3,60	6,80	9,40	10,20	11,70
7	0,00	4,80	9,40	10,20	10,40	10,50
8	0,00	3,90	6,90	8,60	9,70	10,30
9	0,70	11,80	17,00	17,50	16,10	14,20
10	-	-	-	-	-	-
11	0,00	2,30	5,60	7,60	8,00	10,10
12	0,00	2,00	6,20	7,80	8,20	8,50
13	0,00	2,10	5,90	7,50	7,50	8,50
14	0,00	1,40	4,20	6,80	9,00	8,50
15	0,00	2,00	4,20	8,80	10,60	9,70
16	0,00	5,20	10,90	12,20	12,20	10,90
MEAN	0,00	4,70	9,00	10,40	11,30	11,30

EXAMINATIONS WRITTEN TO COMPLETE THE REQUIREMENTS FOR THE DEGREE

	Examination	Year passed	Credit rating	Symbol obtained
CE 522	Aquatic Chemistry	June 1978	7½	2-
CE 512	Wastewater Treatment	July 1978	7½	2-
CE 502	Low Cost Sanitation	December 1978	5	2-
CE 528	Advanced Aquatic Chemistry	August 1979	5	3
CE 527	Unit Processes in Water Treatment	November 1979	5	3
		SUB-TOTAL:	30	

THESIS: Chemical and Biological Phosphorus Removal in the Activated Sludge Process 20

TOTAL: 50

NUMBER OF CREDITS REQUIRED: 40

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY EXAMINATION : JUNE 1978

CE 522 : AQUATIC CHEMISTRY

Answer ALL questions.

1 (a).

$5{,}10^{-4}$ mole/l of NH_3 and 10^{-3} moles/l of CO_2 are added to pure water. ($pk_{NH_4^+} = 9{,}10$; $pk_{H_2CO_3} = 6{,}37$; $pk_{HCO_3^-} = 10{,}33$).

i. Determine the pH established in the mixture.

ii. Discuss (using appropriate sketches) the buffer capacity of this mixed system.

(b).

Write brief notes of not more than 100 words on the following topics :-

i. Alkalimetric titrations and buffer capacity.

ii. Equivalence points and equivalent solution.

iii. Mass parameters for weak acid systems in water.

iv. Stabilized water.

2 (a).

Analysis of a water gives Alkalinity 30 ppm (as $CaCO_3$), pH 6,2, $\mu = 0{,}005$ and temperature $20^{\circ}C$.

It is required to strip the carbonate species from the water by removing CO_2 under reduced pressures. Determine the pH of the water after CO_2 has been stripped. What mass concentration of CO_2 is removed ?

(b).

Waters from two sources are blended as in the table given below.

(Assume all these waters have the same conic strength and temperature i.e. 0,005 and $20^{\circ}C$ respectively).

i. Determine the condition of the blend.

ii. Is the blend stable ?

iii. If the blend is not stable, enumerate the alternative methods one could employ to obtain a stable blend.

WATER	SOURCE	pH	Alk. (ppm on $CaCO_3$) Ca	PARTS IN BLEND
A	Groundwater	6,4	70 75	2
B	Softened water	11,1	50 50	3

3. Analysis of a water from a dolomitic region gives :
Ca 300 ; Alk 200 ; Mg 100 (all in ppm expressed as $CaCO_3$) ;
pH 6,90 ; μ = 0,01 and temperature 20°C.

It is required that after softening and stabilization the magnesium and calcium concentrations are 20 and 140 ppm as $CaCO_3$ respectively.

i. Determine the mass concentrations of $Ca(OH)_2$ and Na_2CO_3 required in the softening process.

ii. Determine the mass concentrations of $Ca(OH)_2$ and CO_2 required to restabilize the water.

iii. Sketch the plant layout.

4 (a).

Analysis of a typical Cape water after colour removal gives :
Total Alkalinity 0,HCO_3 Acidity 12, Ca^{++}4(all in ppm as $CaCO_3$) and pH = 5,4.

i. Is this analysis in any way contradictory ?

ii. If so, what is the probable source of error and what is the most likely initial condition of the water ?

4 (b).

It is required to stabilize the water in (a) above using lime and CO_2, determine the required dosages of these chemicals. Comment critically on the pros and cons of the final condition of the water.

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY EXAMINATION - JULY 1978

CE 513 - WASTEWATER TREATMENT

To be collected after 09h00 on 28th July 1978 and returned before 17h00 on 31st July 1978. The attached affidavit to be signed by the student on receipt of the examination script.

ANSWER ALL QUESTIONS

QUESTION 1

An activated sludge plant is to be built for a town with a population of about 20 000 people. The data listed in the table below is available as representative of the flow and load conditions to be expected at the main sewer outfall of the town. At present the process is to be operated on the completely mixed principle including nitrification. The wastewater is well buffered and has a pH of about 7,2. As the wastewater principally is of domestic origin, assume a specific growth rate of nitrosomonas (μ_{nm}) of 0,50 per day.

RAW SEWAGE

TIME	FLOW (Mℓ/d)	COD (mgCOD/ℓ)	TKN (mgN/ℓ)
0600	1,10	248	30,2
0800	2,35	213	24,9
1000	4,60	412	55,1
1200	5,85	567	60,5
1400	5,70	625	54,9
1600	5,00	620	54,9
1800	4,50	576	51,8
2000	4,25	536	45,3
2200	3,95	480	42,8
2400	3,80	442	42,3
0200	3,40	389	35,8
0400	2,00	323	31,1
0600	1,10	248	30,2

a) Assuming steady state conditions :

i) Design the plant for summer conditions (20°C) at a sludge age of 15 days and an MLVSS concentration of 4000 mgVSS/ℓ.

ii) Check your design for winter conditions (12°C).

iii) Make a comparison, in tabular form, of the average effluent quality, oxygen demand and sludge concentration during summer and winter months.

iv) Estimate the minimum factor of safety with respect to nitrification.

b) Estimate from the influent loading variations given in the Table, the peak and minimum total oxygen requirements during summer and winter.

c) Assume that instead of a single reactor, three reactors of equal volume are built. Describe qualitatively with the aid of sketches, how the process variables such as oxygen demand, nitrate, TKN, filtered COD and MLVSS concentrations vary over the day through the plant at 20°C.

QUESTION 2

The waste sludge of the above plant is to be thickened by flotation to 4%, prior to aerobic digestion. Design the flotation system, presenting your final design in the form of sketches to scale on graph paper.

QUESTION 3

Design an aerobic digestor for the thickened sludge on the basis that the digested sludge may not be discharged to the drying beds unless the active fraction is less than 25%. The design may be based on steady state conditions at 20°C. Nitrification must be included in your design.

QUESTION 4

As an alternative scheme to that given in Questions 1,2 and 3 above, investigate a design of an activated sludge process at 20°C, operating at a very long sludge age, so that thickened waste sludge (also by flotation) may be directly cischarged to the drying beds (i.e. active fraction of the sludge less than 25%) without the use of aerobic digestion. Do not design the flotation system.

a) Assuming steady state conditions, determine ;

i) the required sludge age; and

ii) the reactor volume given that X_v is also 4 000 mgVSS/ℓ.

b)

i) Compare the oxygen and volume requirements of the two schemes (exclude the flotation plant in the comparison as both schemes require this unit process).

ii) Which of the two schemes is the better in terms of phosphorus removal ? Discuss with the aid of calculations.

c) Write down briefly your conclusions on the comparison of the two schemes.

QUESTION 5 ...../3

QUESTION 5

For an activated sludge plant, determine the average total power requirements of the aeration of the mixed liquor, for the following conditions. The volume of the aeration basin is 1,65 Mℓ and the average total oxygen demand is 48 mgO/ℓ/hr. Assuming that mechanical aerators are to be used with an oxygen transfer rate of 2,44 KgO/Kwh under standard conditions, what power, measured at the shaft, needs to be supplied for the following conditions?

At the proposed site :

Atmospheric pressure = 725 mm Hg ;

Temperature = 21°C ; an oxygen concentration in the reactor of 3 MgO/ℓ, (to ensure nitrification) is to be maintained.

The α and β values for the mixed liquor are estimated to be 0,8 and 0,9 respectively.

QUESTION 6

A cannery has an effluent flow of about 1 500 m^3/d during the main canning season. The daily averaged BOD is approximately 700 mg/ℓ; phosphorus and nitrogen concentrations are negligible. The cannery operates at peak production for about 4 months of the year during the summer when the flow and BOD given above are applicable. For the rest of the year the load and flow are less. An aerated lagoon system has been proposed to treat the waste stream. It is essential that the effluent from the system must have volatile solids and BOD concentrations as low as possible, but no settling rank or maturation pond system following the treatment works are envisaged.

With the objective of satisfying the conditions above, design and compare the following two solutions :

i) A single lagoon with a retention time of 10 days;

ii) A system of two lagoons in series, the first having a retention time of 2,5 days; the second a retention time of 7,5 days.

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

DECEMBER EXAMINATION 1978

CE 502 - LOW COST SANITATION

Do ALL Questions

QUESTION 1

a. Discuss the biochemical and feacal bacterial degradation kinetics in facultative ponds, with particular reference to wind, temperature and radiation effects and the influence of raw and anaerobic pretreated influents.

b. Discuss the design of a septic tank-french drain disposal system for waste waters from individual houses.

QUESTION 2

Write an essay on the problems associated with the provision of water supply and an acceptable form of sanitation for low cost housing areas. The discussion should include a comparison of the different forms of sanitation that have been used in Africa.

QUESTION 3

Discuss the approach you would take and the factors to be considered when investigating sub-soil conditions for a low cost high density housing project.

/2....

QUESTION 4

Design an oxidation pond system to treat the effluent from a low cost housing township in the lowveld of the Transvaal.

Present population	10 000
Estimated future population	15 000
Sanitation provision	Regular waterborne flush system to sewers
Estimated waste flow/capita/day	50 - 90ℓ
Estimated BOD_5 contribution per capita/day	0,04 kg

The pond system is to consist of (a) a grit channel
(b) Open anaerobic lagoons
(c) Primary, secondary and tertiary facultative ponds.

Design the system making your own estimates of the factors required in the design. Provision to minimize odours from the anaerobic lagoon is to be built into the design.

QUESTION 5

a. List the conditions that must be satisfied for data to be normal distributed.

b. Under what conditions do you expect data to be log-normal distributed ? Illustrate with at least 3 examples giving your evaluation of the causes in each case.

c. Give the various measures of central tendency of a distribution and discuss their efficiency.

A random sample of 20 apples was taken from all the apples picked from a single tree, listed below in ranked arbitrary mass units.

11, 14, 15, 18, 18, 20, 20, 22, 22, 22,
26, 26, 27, 30, 30, 32, 36, 38, 40, 70

If you would wish to compare this tree's production with another, what measure of central tendency would you select ? If you would wish to determine the average mass of the apples of this tree would you use the same measure ? Determine with the aid of graphical statistics the answers to your selected measures.

/3....

QUESTION 5 (continued)

d. The following two sets of data were obtained on the concentration of E.coli in the effluent from a facultative oxidation pond during the winter and summer season respectively.

Winter : < 300, 400, 17 000, 12 000, 2500,
1000, 700, > 20 000, 6000, 3500,
2500, 1400, 9000, 7000, 1400,
> 20 000, 4000.

Summer : 440, 800, 1000, 1260, 1600,
1800, 2400, 2800, 4000, 6000.

Test using graphical statistical techniques if the selected statistical mean values of these two distributions are significantly different at 96% level of significance.

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY EXAMINATION AUGUST 1979

CE 528 ADVANCED AQUATIC CHEMISTRY

To be collected after 09h00 on Friday, 3 August 1979 and returned before 17h00 on Monday, 6 August 1979. The attached affidavit to be signed by the student on receipt of the examination script.

ANSWER ALL QUESTIONS

1.

A. Write brief notes on the following:

(i) Interpretation of pH in high and low salinity waters using NBS buffer solutions as standards

(ii) Methods for expressing weak acid equilibrium constants. Outline the usefulness of each form.

(iii) pH-buffering capacity curves for a weak acid in water given that total weak acid species concentration is 10^{-3} mol/ℓ; $pK''_a = 7{,}00$; $pK'_a = 7{,}85$ and $pK_w = 13{,}0$

B. Analyses of a water in which complexing of weak acid species occurs gives $H_2CO_3^*$ Alk = 10^{-3} mol/ℓ and HCO_3 Acidity = 10^{-3} mol/ℓ; $pK'_1 = 6{,}2$; $pK''_1 = 5{,}9$; $pK'_2 = 10{,}0$ and $pK''_2 = 9{,}2$.

Determine free $CO_3^=$ species concentration if pH is adjusted to pH = 8,4.

2.

A.

(i) Draw up a table of analogy for pH-weak acid reactions and pe-redox reactions.

(ii) Briefly outline a thermodynamic basis for ordering strengths of acids and bases and oxidants and reductants.

B. Water contains 10^{-3} mol/ℓ of NH_3. Using redox reactions determine moles of Cl_2 required to denitrify the system completely (assume nitrogen species are lost from the system as N_2 gas)

C. Outline why chlorine is 'unstable' in water.

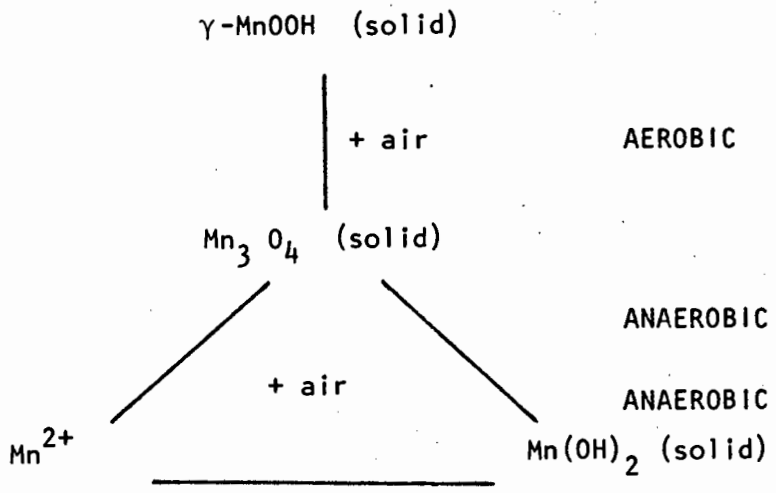
3.

A.

(i) Water has a pH of 9,0 and contains a total $SO_4^{=}$-HS^- species concentration of 10^{-4} mols/ℓ. Construct a diagram showing the dependence of species concentration on redox potential (i.e. pe).

(ii) If the pe of the water in (i) above had a value such that the sulphur species were predominantly in the HS^- form, briefly outline using redox theory how addition of HOCl to the water would effect the quality.

B. A pathway of reactions for precipitation of manganese minerals in aerobic and anaerobic environment is illustrated below:



(i) Construct a pH-pe diagram illustrating the field of stability for the various forms of manganese (assume $[Mn^{2+}] = 10^{-6}$ mole/ℓ).

(ii) What minimum partial pressure of O_2 is required to precipitate γ-MnOOH ?

(iii) How would the addition of chlorine affect the precipitation of γ-MnOOH ?

4.

A. In waste water treatment biologically mediated nitrification of NH_4^+ and NH_3 (aqueous) to NO_3^- and NO_2^- may be attained in the aerobic unit. Indicate graphically the chemical conditions favouring nitrification.

B. Graphically depict the conditions favouring biologically mediated denitrification of NO_3^- and NO_2^- to N_2 gas in an anoxic system. Assume a partial pressure of nitrogen equal to unity and the concentration of NO_3^- or NO_2^- equal to 10^{-5} mol/ℓ.

C. Based on the graphical work above, sketch a plant layout to effect nitrification and denitrification in waste water treatment.

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

DECEMBER EXAMINATION 1978

CE 502 - LOW COST SANITATION

Do ALL Questions

QUESTION 1

a. Discuss the biochemical and feacal bacterial degradation kinetics in facultative ponds, with particular reference to wind, temperature and radiation effects and the influence of raw and anaerobic pretreated influents.

b. Discuss the design of a septic tank-french drain disposal system for waste waters from individual houses.

QUESTION 2

Write an essay on the problems associated with the provision of water supply and an acceptable form of sanitation for low cost housing areas. The discussion should include a comparison of the different forms of sanitation that have been used in Africa.

QUESTION 3

Discuss the approach you would take and the factors to be considered when investigating sub-soil conditions for a low cost high density housing project.

/2....

UNIVERSITY OF CAPE TOWN

DEPARTMENT OF CIVIL ENGINEERING

UNIVERSITY EXAMINATION : NOVEMBER 1979

CE 527 : UNIT PROCESSES IN WATER TREATMENT

To be collected after 09h00 on 9 November 1979 and returned before 17h00 on 12 November 1979. The attached declaration is to be signed by the student when returning the examination script.

ANSWER ALL QUESTIONS

1. (a) Analyses of a ground water gives

Ca = 50 ppm (as $CaCo_3$)

Alkalinity = 60 ppm (as $CaCO_3$)

Fe^{2+} = 0,25 m.moles/ℓ

Mn^{2+} = 0,15 m.moles/ℓ

pH = 6,20 (before aeration)

Dissolved oxygen = 0

Ionic strength = 0,01

It is required to utilize this water for domestic purposes. Briefly outline a chemical treatment procedure to remove iron and manganese from the water taking due regard of the kinetics of oxidation of Fe^{2+} and Mn^{2+}. Estimate the chemical dosages (approximately) required for the above removal process and for final stabilization.

Molecular masses of Fe and Mn are 59 and 55 grams/mole respectively.

(b) Water is to be chlorinated to breakpoint

(i) Outline the factors which will affect the chlorine dosage;

(ii) Briefly outline the importance of pH in the treatment process.

2/....

2. Analysis of a water derived from Table Mountain Sandstone gives (after colour removal)

Alkalinity = 4 ppm

Ca = 2 ppm (both as $CaCO_3$)

pH = 6,0

ionic strength = 0,001

It is required to stabilize the water using a split treatment process as follows:

(a) The flow is divided into two fractions A and B where A:B as 1:3 .

(b) Fraction A is dosed with strong acid and passed slowly through finely ground solid $CaCO_3$. During this process the water comes to within 3 mg/ℓ of saturation with respect to $CaCO_3$. A small amount of $Ca(OH)_2$ is now added to adjust the saturation state to some desired value.

(c) Fractions A and B are now blended. Estimate the masses of strong acid and $Ca(OH)_2$ to be applied to fraction A to give a stable blend. If this is not possible, suggest what split should be used.

3. Estimate what is the maximum overflow rate of a suspension in an ideal settling tank to obtain a removal efficiency of 80 per cent. Assume an ideal settling tank with a depth of 2 m. Laboratory test on the suspension show the following results:

The uniform suspension settles in a 4 m settling tube. Samples are taken at depths of 0.75 ; 1,50 ; 2,25 ; and 3,00 m. The concentration of solids is determined as a function of settling time and depth. It is found that the concentration of solids can be expressed as:

$$C_{t,h} = C_o \left(1 - e^{-t/h} \right)$$

Where

C_o = initial concentration

t = settling time

h = settling depth

$C_{t,h}$ = solids concentration after settling time t and at depth h.

3/....

4. Design a single, completely mixed, mechanical flocculation unit with a hydraulic retention time of not more than 20 minutes based upon data for a batch flocculation test listed in Table 1.

Table 1 : Turbidity (as per cent of the original value) as a function of flocculation time for a velocity gradient of 50 s^{-1}.

TIME (S)	TURBIDITY %
0	100
50	0,63
100	0,40
200	0,18
300	0,10
400	0,07
500	0,06
750	0,05
1000	0,05

Assume a dead volume fraction of 20% in the flocculation unit.

Assume a flow of 3 Mℓ/d

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