BIOLOGICAL EXCESS PHOSPHORUS REMOVAL IN SHORT SLUDGE AGE ACTIVATED SLUDGE SYSTEMS

by

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DECLARATION BY CANDIDATE

I hereby declare that this thesis is my own work and has not been submitted for a degree at any other University.

Signed by candidate

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SYNOPSIS

The objective of this investigation was to test, at laboratory-scale, the behaviour of short sludge age biological excess P removal systems, to assess the response of the systems under non-nitrifying and nitrifying conditions, to determine the optimal system configuration(s) and operational parameters, and to check the settling characteristics of the mixed liquor produced in the systems. A secondary objective was to use the observed response data to test the predictive qualities of both the general activated sludge model of Dold, Ekama and Marais (1985) and the semi-empirical biological excess P removal model of Wentzel, Dold, Ekama and Marais (1984).

The objectives were fulfilled by operating a number of laboratory scale anaerobic/aerobic and anaerobic/anoxic/aerobic systems with varying sludge ages, anaerobic, anoxic and aerobic mass fractions, mixed liquor recycle ratios and COD loading rates.

Almost all of the limited literature available on biological excess P removal at short sludge ages deals with the non-nitrifying Phoredox or A/O system (see Fig S.1). Accordingly, this system was selected as the starting configuration. The system was operated at a 4 day sludge age with a 50 percent anaerobic mass fraction and a 1:1 underflow recycle ratio. It was assumed that the short aerobic sludge age of 2 days would prevent nitrification. The influent to the system was unsettled municipal waste flow from Mitchell's Plain with a COD of approximately 500 mgCOD/ℓ and a TKN/COD ratio of approximately 0,1 mgN/mgCOD. The system provided good excess P removal (P removal per influent COD ~ 0,03 mgP/mgCOD), excellent settleability (DSVI ~ 70 mℓ/g) and adequate COD removal (approximately 90 percent) but, against expectations, the system nitrified partially. To eliminate nitrification, the system sludge age was reduced to 3 days while leaving all other process parameters unchanged. The system was operated at a 3 day sludge age on two separate occasions. On the first occasion, the nitrification slowly decreased to about 2 mgN/ℓ and very good P removal was attained (ΔP/influent COD = 0,03 mgP/mgCOD). On the second occasion, the

system nitrified partially and produced a lower P removal (ΔP/influent COD = 0,02 mgP/mgCOD). The reduction in P removal was consistent with the hypothesis that nitrate, discharged to the anaerobic reactor, has a detrimental effect on the excess P removal. The results also indicated that it is possible to obtain nitrification at sludge ages as low as 3 days with a 50 percent unaerated mass fraction, i.e. with an aerobic sludge age of 1,5 days. At 3 days sludge age, both Phoredox systems produced turbid effluents with high COD concentrations (about 14 percent of the COD in the influent). Furthermore the settleability of the sludges was very poor (DSVI ~ 150 mℓ/g) due to the presence of *S.natans*.

In an attempt to inhibit the growth of *S.natans*, two modifications of the 3 day sludge age Phoredox system were set up. In the first, two-thirds of the influent was fed into the first unaerated reactor and the remainder was fed into the first aerated reactor (see Fig S.2). In the second version a selector was introduced before the first aerobic reactor and the one-third feed fraction to the aerobic zone was fed into the selector (see Fig S.3). The Split-feed/selector modifications were implemented following the work of Ekama and Marais (1985) which indicated that, in long sludge age systems, a split-feed discharging to a selector reactor upstream of the main aeration zone reduces bulking. Both variations of this configuration were operated at a sludge age of 3 days, with an anaerobic mass fraction of 50 percent and an underflow recycle ratio of 1:1. Splitting the feed did not appear to inhibit the growth of *S.natans* and, in fact, appeared to favour it. Incorporation of the selector also had no apparent inhibitory effect on the growth of *S.natans*; the DSVI of the sludge reached 688 mℓ/g before the test was aborted. The P removal of both the Split-feed systems was poor relative to the 3 day sludge age Phoredox systems, possibly because only two-thirds of the influent flow was directed to the anaerobic reactor.

As a consequence of the inability to prevent nitrification by lowering the aerobic sludge age to 1,5 days, it was decided to accept nitrification and to study systems, such as the 3-stage Bardenpho and UCT systems, that provide a measure of control over the nitrate concentration in the recycles to the anaerobic reactor. However, to retain the short sludge age character, an upper limit of 6 days was imposed on the sludge age of the systems. The first system tested was the 3-stage Bardenpho system (see Fig S.4) with a sludge age of 6 days, an anaerobic mass fraction of 25 percent, an anoxic mass fraction of 25 percent and an underflow recycle ratio of 1:1. The a-recycle ratio was initially set at 2:1 but, when the nitrate concentration in the anoxic reactor was measured to be zero, the a-recycle ratio was increased to 4:1; a positive nitrate concentration leaving the anoxic reactor then indicated that the system was operating at its full denitrification potential. The system nitrified completely but the denitrification fluctuated, thereby causing a variation in the nitrate concentration in the underflow to the anaerobic reactor. Concomitantly, the excess P removal was variable; the mean removal was about 8 mgP/ℓ which is significantly less than that achieved in the 3 and 4 day sludge age Phoredox systems. The reason for this was that the wastewater used in the investigation had a TKN/COD ratio of approximately 0,1 mgN/mgCOD; with complete nitrification despite having a large anoxic mass fraction operating at its full denitrification potential, a significant amount of nitrate (± 13 mgN/ℓ) was recycled to the anaerobic reactor via the underflow recycle - the nitrate discharged to the anaerobic reactor was the cause of the reduction in P removal. However, the system produced a high COD removal (± 92 percent), a good settling sludge (± 100 mℓ/g) and a clear effluent.

A UCT system (see Fig S.5) was operated with a 6 day sludge age, a 14 percent anaerobic mass fraction, a 29 percent anoxic mass fraction, an underflow recycle ratio of 1:1 and an r-recycle ratio of 1:1. The a-recycle ratio was initially set at 2:1 but later reduced to 1:1 when it was found that the anoxic reactor was overloaded with nitrate. With the influent wastewater utilised, the system nitrified completely throughout its period of operation. With an a-recycle ratio of 2:1, about 4 mgN/ℓ of nitrate was present in the r-recycle to the anaerobic zone and the system P removal was about 7 mgP/ℓ. On reducing the a-recycle ratio to 1:1, the nitrate in the r-recycle stream decreased to near zero and the excess P removal increased steadily until, by the time the experiment was terminated, the P removal was about 14 mgP/ℓ. This removal was achieved despite the high effluent nitrate concentration of about 10,5 mgN/ℓ. The sludge settleability was generally good (DSVI ~ 110 mℓ/g) and the COD removal was consistently high (± 93 percent).

The results from the 6 day sludge age UCT and 3-stage Bardenpho systems indicate that: In the UCT system, by appropriate selection of mixed liquor recycle ratios, the system can remove about 0,027 mgP/mg influent COD from wastewaters with TKN/COD ratios of 0,1 mgN/mgCOD and higher. In contrast, the 3-stage Bardenpho system can remove only about 0,016 mgP/mg influent COD. The reason for the higher efficiency of the UCT system is due to its ability to selectively remove nitrate from the recycle to the anaerobic reactor; in the 3-stage Bardenpho system, the effluent nitrate concentration is the same as that recycled to the anaerobic reactor. The sludge settleability and COD removal for both the UCT and 3-stage Bardenpho systems were good.

The third system operated to minimise the nitrate in the recycle to the anaerobic zone was the Johannesburg system (see Fig S.6). This system was initially operated at a 3 day sludge age with a 24 percent anaerobic mass fraction, 24 percent anoxic mass fraction and a 1:1 underflow recycle ratio. The system nitrified partially and the anoxic reactor successfully removed all the nitrate from the underflow recycle stream. An excess P removal of between 8 and 9 mgP/ℓ was consistently attained. This removal was lower than that attained in the 3 day sludge age Phoredox system, possibly due to the smaller anaerobic mass fraction in the Johannesburg system. The COD effluent quality was very similar to that of the other 3 day sludge systems.

The Johannesburg system was also operated at a 5 day sludge age with a 24 percent anaerobic mass fraction and a 36 percent anoxic mass fraction. The underflow recycle ratio was initially set at 0,5:1 and, in this mode of operation, the nitrate leaving the anoxic reactor proved to be zero and the excess P removal was about 13 mgP/ℓ. The underflow recycle ratio was later raised to 1:1; this caused the nitrate concentration in the anoxic reactor to vary between 1 and 5mgN/ℓ and the excess P removal to decrease to about 7 mgP/ℓ. The results of this experiment indicate that, by adopting the

Johannesburg configuration, the anaerobic reactor can be protected (by the anoxic reactor) from nitrate in the underflow recycle stream for wastewaters with TKN/COD ratios as least as high as 0,1 mgN/mgCOD, provided the settleability of the sludge is sufficiently good to allow underflow recycle ratios of about 0,5 to 0,7. The settleability of the 5 day sludge age Johannesburg system was good with a mean DSVI of approximately 130 mℓ/g and with only minor concentrations of *S.natans* present.

In all the short sludge age systems operated, good nitrogen recoveries of about 97 percent were obtained but the COD recoveries were very poor, between 70 and 87 percent. Four factors individually or cumulatively could have led to the low COD recoveries:

(1) The effluent COD sample was always filtered and therefore any particulate material carried over in the effluent was not accounted for.

(2) The sludge wastage procedure, used to control the sludge age, involved removing calculated volumes of mixed liquor at two set times during the day. Since large volumes of mixed liquor needed to be removed daily, this method of wastage may had led to errors in the mass balance.

(3) COD may have been lost as hydrogen gas in the acidogenesis process whereby acetate and hydrogen ions are formed from glucose-type molecules.

(4) A large build up of slime was observed in the aerobic reactors of most of the systems. The COD of this slime, which almost certainly was a polysaccharide, was not accounted for in the mass balance.

Research work in the UCT laboratory has indicated similar poor COD recoveries in anaerobic/aerobic and anaerobic/anoxic/aerobic systems, but good COD recoveries in purely aerobic systems. This suggests that there may be processes taking place in the unaerated zone which at present are not understood and which are responsible for the low COD recoveries. Further research in this direction is required.

The responses of the various experimental systems were simulated using the general activated sludge model of Dold and Marais (1986). Certain changes had to be made to the input parameters of the model in order to accurately simulate the observed results. The changes were as follows:

1. To account for the high effluent COD values obtained from the short sludge age systems, it was necessary to increase the value of the unbiodegradable soluble COD fraction of the influent wastewater.

2. To account for the low experimental COD recoveries, it was assumed that the entire COD loss was due to acidogenesis and the values of the total COD and the readily biodegradable COD in the influent, were adjusted accordingly.

3. It was assumed that there was conversion of slowly biodegradable to readily biodegradable COD in the anaerobic zone.

When the above factors were taken into account, the general activated sludge model generally produced accurate predictions of the observed response of short sludge age systems. However, as the modifications are tenuous in some measure, it is clear that future research will have to be focussed on the processes in the anaerobic reactor if any solution to the poor COD recoveries is to be found.

This study gives rise to the following conclusions with regard to selection of short sludge age P removal systems.

(i) Phoredox system - The Phoredox *cum* A/0 system is designed to operate under non-nitrifying conditions. The observation that this system can nitrify at aerobic sludge ages as short as 1,5 days at 20°C and that, whenever nitrifiction occurs, the P removal is adversely affected, implies that this system cannot be accepted as a reliable process to achieve high P removal consistently (particularly during the summer months when the probability increases for nitrification). At 3 days system sludge age and 1,5 days aerobic sludge age, the effluent quality is poor. The effluent is turbid and the dissolved

COD is significantly higher than at 4 to 6 days sludge age. Furthermore the laboratory-scale system is prone to bulking due to the proliferation of *S.natans*, a filament that is favoured by high F/M ratios, low dissolved oxygen concentrations and high surface area/volume ratios. It is not clear whether the growth of *S.natans* in the laboratory scale units would be duplicated in full-scale plants with low surface area/volume ratios.

(ii) 3-stage Bardenpho system - The 3-stage Bardenpho system was developed to reduce the effluent nitrate concentration to negligible quantities. However, at short sludge ages of about 6 days, this study showed that, for TKN/COD ratios of about 0,1 mgN/mgCOD, nitrate will be present in the effluent and hence will be recycled to the anaerobic reactor. Nitrate discharged to this reactor adversely affects the P removal. In these circumstances, the only operational procedure whereby the nitrate can be reduced is to lower the underflow recycle ratio. If the DSVI of the mixed liquor can be guaranteed to remain below about 100 mℓ/g, then the system can be designed to operate under recycle ratios of about 0,3:1, and the 3-stage Bardenpho system would be a viable alternative.

(iii) Johannesburg system - In this system, the anoxic zone of the 3-stage Bardenpho system is transferred from the reactor series to the underflow recycle. It selectively removes the nitrate in this recycle to produce a nitrate-free recycle stream to the anaerobic reactor. It would appear that, for TKN/COD ratios of about 0,07 mgN/mgCOD, the system will remove all the nitrate in the underflow recycle at recycle ratios of about 1:1. At TKN/COD ratios of about 0,1 mgN/mgCOD, the system will remove all the nitrate at recycle ratios of 0,5 to 0,7. Because of its selective nitrate removal characteristic, this system appears to have greater viability than the 3-stage Bardenpho system.

(iv) UCT system - The UCT system discharges the underflow recycle into the primary anoxic reactor and recycles from this reactor to the anaerobic reactor. The system makes full use of the denitrification potential of the anoxic reactor which has a higher denitrification potential than the equivalent anoxic reactor in the Johannesburg system. Although not verified in this series of tests, the anoxic zone in the underflow recycle appears to have all the potential for providing a nitrate-free recycle flow to the anaerobic reactor for TKN/COD ratios of 0,12 mgN/mgCOD and higher.

A general conclusion from this study is that P removal systems at 3 days sludge age give poor effluent COD quality and have a potential for producing bulking sludges (at least at laboratory scale). If the system does not nitrify at a 3 day sludge age, the Phoredox-A/0 system can produce P removals of up to 0,03 mgP/mg influent COD. Should the system nitrify, the P removal will become uncertain.

At 6 days sludge age with complete nitrification, all the P removal systems investigated gave excellent COD reductions and good settling sludges. With regard to P removal, the 3-stage Bardenpho system should be avoided as it is not always possible to obtain a nitrate-free underflow recycle to the anaerobic zone. The Johannesburg system appears to be able to produce a nitrate-free underflow recycle to the anaerobic zone for either recycle ratios of 1:1 with TKN/COD ratios greater than 0,07 mgN/mgCOD or for recycle ratios of 0,6:1 with TKN/COD ratios of 0,1 mgN/mgCOD. The UCT system appears to provide the best security for consistently high P removals (without the need to reduce the underflow recycle) for TKN/COD ratios up to 0,12 mgN/mgCOD. In all cases it would seem that the system sludge age should not be less than 6 days.

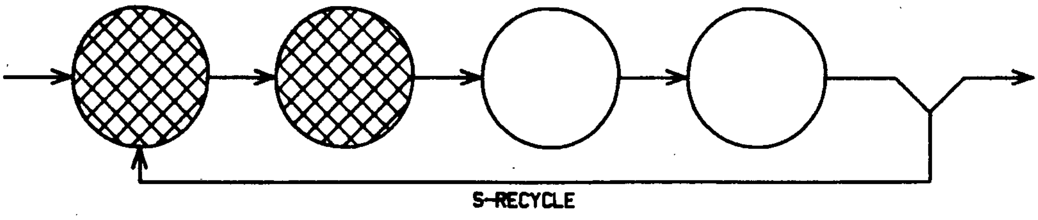

Fig S.1: Schematic diagram of the Phoredox-A/0 system.

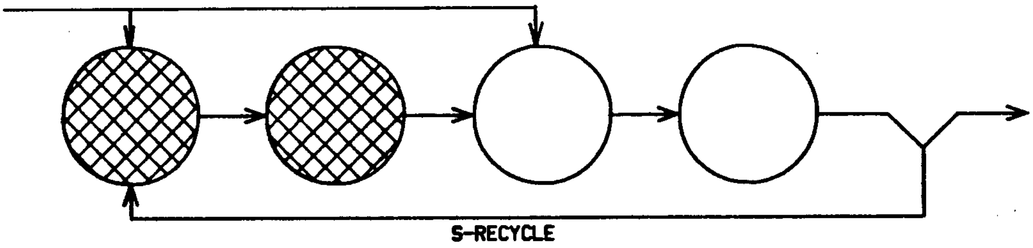

Fig S.2: Schematic diagram of the Split-feed system without the selector reactor.

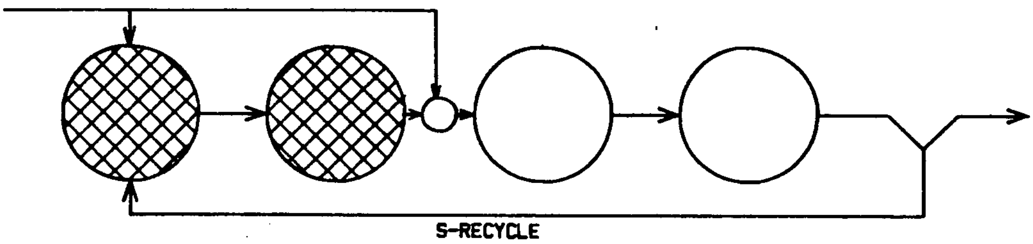

Fig S.3: Schematic diagram of the Split-feed system with the selector reactor.

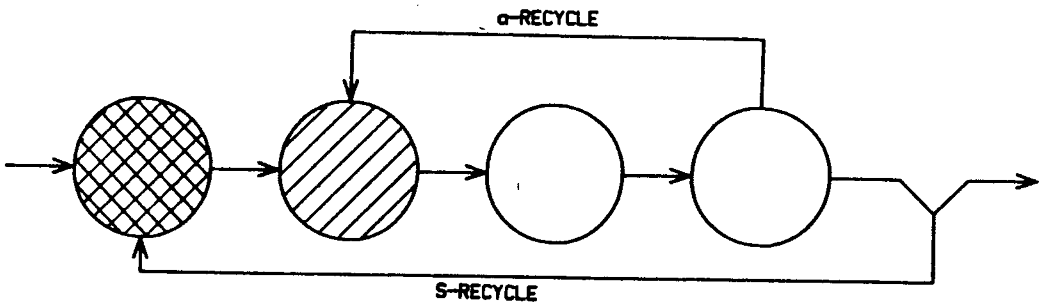

Fig S.4: Schematic diagram of the 3-stage Bardenpho system.

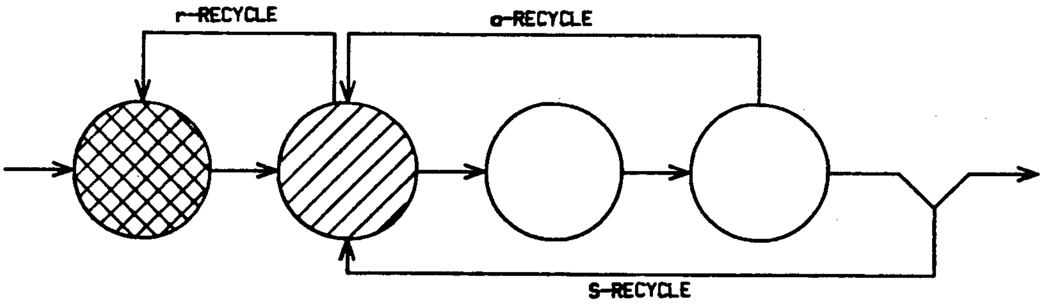

Fig S.5: Schematic diagram of the UCT system.

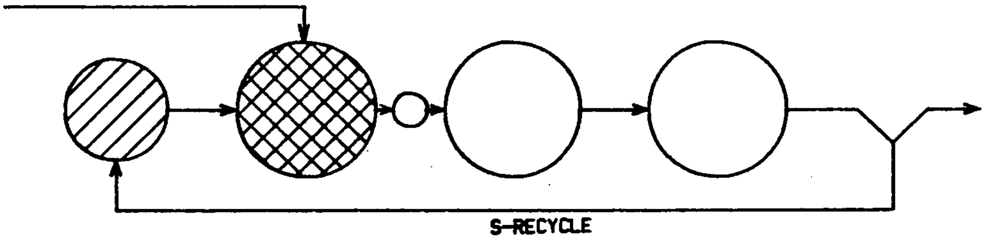

Fig S.6: Schematic diagram of the Johannesburg system.

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Symbol	Description
a	mixed liquor recycle ratio from aerobic to anoxic reactors
a'	constant, ranging from 1,145 for a sludge age of 20 days to 1,198 for a sludge age of 8 days, used to determine biological excess P removal from P release and metabolic P requirements
A/O	Anoxic/Oxic
AVSS	active volatile suspended solids (mgAVSS/ℓ)
b_a or b_n	nitrifier endogenous mass loss rate (/d)
b_h	heterotrophic endogenous mass loss rate (/d)
COD	chemical oxygen demand (mgCOD/ℓ)
COD_s	chemical oxygen demand of the sludge (mgCOD/ℓ)
C_{sp}	stoichiometric ratio ($\Delta P:\Delta S_{bs}$)
DO	dissolved oxygen concentration (mgO/ℓ)
DSVI	diluted sludge volume index (mℓ/g)
f	endogenous residue fraction in the steady state model of Marais and Ekama (1976) (mgVSS/mgVSS)
f_{av}	active fraction of the sludge mass with respect to volatile suspended solids
f_{bs}	readily biodegradable COD fraction with respect to the biodegradable COD ($f_{bs} = S_{bsi}/S_{bi}$) (mgCOD/mgCOD)
f_{cv}	COD to VSS ratio of the sludge mass (mgCOD/mgVSS)
f_e	unbiodegradable fraction of the heterotrophic cell mass (mgCOD/mgCOD)
f_n	nitrogen fraction of the sludge (mgN/mgVSS)
f_{na}	free and saline ammonia fraction of the influent TKN (mgN/mgN)

f_{nox}	fraction of the organic nitrogen that is particulate (mgN/mgN)
f_{nu}	soluble unbiodegradable fraction of the influent TKN (mgN/mgN)
f_{up}	unbiodegradable particulate COD fraction of the influent (mgCOD/mgCOD)
f_{us}	unbiodegradable soluble COD fraction of the influent (mgCOD/mgCOD)
f_{xa}	anaerobic mass fraction
f_{xbh}	fraction of the influent COD that is organisms (mgX_{bh}COD/mgCOD)
F/M	food to microorganism ratio (mgCOD/mgVSS)
i_{xb}	nitrogen fraction of the active volatile suspended solids (mgN/mgVSS)
i_{xa}	nitrogen fraction of the inert sludge mass (mgN/mgVSS)
K	first order rate constant for P release model of Wentzel *et al.* 1984 K' = equation constant K" = equation constant
K_h	maximum specific adsorbed COD utilisation rate under aerobic conditions (mgCOD/mgAVSS/d)
K_{ms}	maximum readily biodegradable substrate utilisation rate (mgCOD/mgAVSS/d)
K_{na}	Monod half saturation coefficient for ammonia for the heterotrophs (mgN/ℓ)
K_{nh}	Monod half saturation coefficient for ammonia for the autotrophs (mgN/ℓ)
K_{no}	Monod half saturation coefficient for nitrate for the heterotrophs (mgN/ℓ)
K_{oa}	Monod half saturation coefficient for oxygen for the autotrophs (mgO/ℓ)
K_{oh}	Monod half saturation coefficient for oxygen for the heterotrophs (mgO/ℓ)

K_r	organic nitrogen to ammonia conversion rate coefficient (ℓ/mgVSS/d)
K_s	half saturation coefficient for readily biodegradable COD utilization (mgCOD/ℓ)
K_x	half saturation coefficient for adsorbed COD utilization under aerobic and anoxic conditions (mgCOD/mgVSS)
LFA	lower fatty acid
m	number of data points used in a statistical analysis
$MCOD_{eff}$	mass of COD in the effluent per day (mgCOD/d)
$MCOD_{inf}$	mass of COD in the influent per day (mgCOD/d)
$MCOD_{ox}$	mass of COD oxidized per day (mgCOD/d)
$MCOD_{sl}$	mass of COD wasted in the sludge per day (mgCOD/d)
MLVSS	mixed liquor volatile suspended solids (mgVSS/ℓ)
$M(0_c)$	mass of oxygen for carbonaceous degradation per day (mg0/d)
$M0_e$	oxygen requirements for endogenous respiration (mg0)
$M0_n$	oxygen requirements for nitrification (mg0)
$M(0_n)$	mass of oxygen for nitrification per day (mg0/d)
$M0_s$	oxygen requirements for synthesis (mg0)
$M0_t$	total oxygen requirements, $M0_t = M0_s + M0_e + M0_n$ (mg0)
$M(0_t)$	total mass of oxygen per day, $M(0_t) = M(0_c) + M(0_n)$ (mg0/d)
MS_{ti}	mass of COD entering the system per day (mgCOD/d)
MX_{ah}	active mass of non-polyP organisms in system (mgVASS)
MX_v	mass of total volatile suspended solids in the system (mgVSS)
n	reactor number in a series of anaerobic reactors
N	number of anaerobic reactors of equal volume in series

N_n	reactor nitrate concentration in a single aerobic reactor system (mgN/ℓ)
N_{nanox}	nitrate concentration in the anoxic reactor (mgN/ℓ)
N_{ne}	effluent nitrate concentration (mgN/ℓ)
N_{ni}	nitrate concentration in the i^{th} reactor
N_{nr}	nitrate concentration in the recycle to the anaerobic reactor (mgN/ℓ)
N_s	nitrogen required for heterotrophic cell synthesis (mgN/ℓ)
N_{te}	unfiltered TKN concentration in the effluent (mgN/ℓ)
N_{ti}	unfiltered TKN concentration in the influent (mgN/ℓ)
NO_3	nitrate concentration (mgN/ℓ)
O_c	carbonaceous oxygen demand (mgO/ℓ/d)
O_t	total oxygen demand (mgO/ℓ/d)
OUR	oxygen utilization rate (mgO/ℓ/h)
P or PO_4	general symbols indicating phosphorus concentration (mgP/ℓ)
P(metabolic)	normal metabolic P requirement wasted daily in the sludge (mgP/ℓ)
P_{upt}	phosphorus uptake (mgP/ℓ) (a negative value indicates a phoshorus release)
P_{rem} or P(removal)	total system phosphorus removal per litre of influent (mgP/ℓ)
q	volume of mixed liquor wasted per day (ℓ/d)
Q	influent wastewater flow rate to system (ℓ/d)
r	mixed liquor recycle ratio from the anoxic to the anaerobic reactors reactors of a UCT system
R_s	system sludge age (d)
$R_{sm_{20}}$	minimum sludge age for nitrifiction at 20°C (d)

s	sludge underflow recycle ratio with respect to the feed flow rate
S	effluent soluble COD concentration (mgCOD/ℓ)
S_{bi}	influent biodegradable COD (mgCOD/ℓ)
S_{bs}	readily biodegradable COD concentration (mgCOD/ℓ)
S_{bsi}	influent readily biodegradable COD concentration (mgCOD/ℓ)
S'_{bsi}	influent readily biodegradable COD concentration available for use by the polyP organisms in the anaerobic reactor (mgCOD/ℓ)
S_{bsn}	readily biodegradable COD concentration leaving the last of a series of N anaerobic reactors (mgCOD/ℓ)
S_o	influent COD concentration (mgCOD/ℓ)
S_{te}	unfiltered effluent COD concentration (mgCOD/ℓ)
S_{ti}	total unfiltered influent wastewater COD concentration (mgCOD/ℓ)
SRT	solids retention time (d)
TKN	total Kjeldahl nitrogen (mgN/ℓ)
UCT	University of Cape Town
V_{aer}	volume of aerobic reactor (ℓ)
$V_{m\ell}$	volume of mixed liquor used in aerobic batch test (ℓ)
V_p	system volume (ℓ)
V_{ww}	volume of wastewater used in aerobic batch test (ℓ)
VSS	volatile suspended solids (mgVSS/ℓ)
x	fraction of the feed entering the anoxic reactor
$\bar{x}$	mean value
X_n	concentration of nitrifiers in aerobic batch test (mgX_n/ℓ)
X_v	volatile suspended solids concentration of the sludge (mgVSS/ℓ)

Y_a	yield coefficient for autotrophs (mgVSS/mgN)
Y_h	yield coefficient for active heterotrophic mass (mgVSS/mgCOD)
$\hat{\mu}_H$	maximum specific growth rate of the heterotrophs (/d)
$\hat{\mu}_N$	maximum specific growth rate of the autotrophs (nitrifiers) (/d)
$\mu_{nm_{20}}$	maximum specific growth rate of the nitrifiers at 20°C (/d)
Δ	symbol denoting change
ΔN_s	system nitrogen removal, through denitrification, per litre of influent (mgN/ℓ)
ΔP_n	phosphorus release in the n^{th} anaerobic reactor per litre of influent flow (mgP/ℓ)
η_G	fraction of the heterotrophic organism population that is capable of using nitrate as a terminal electron acceptor
η (growth)	see η_G
η_s or η(solubilization)	a factor that, when multiplied by the rate of hydrolysis in an aerobic environment, gives the rate of hydrolysis under anoxic conditions
σ	standard deviation of the sample
σ_m	standard deviation of the mean

Additional subscripts

in or inf.	refers to influent wastewater
out or eff.	refers to effluent from system
1	refers to reactor 1
2	refers to reactor 2
3	refers to reactor 3
4	refers to reactor 4
sel.	refers to selector reactor
20	refers to temperature (°C)

CHAPTER ONE

INTRODUCTION

Biological excess P removal activated sludge systems in South Africa have been developed to incorporate nitrification and denitrification. Nitrification has always been a requirement of South Africa because ammonia in the effluent has a toxic effect on higher aquatic life, particularly under the high temperatures experienced during the summer months. Once nitrification is achieved, denitrification not only reduces the nitrate in the effluent but has a stabilising effect on the pH changes and is essential in order to create the appropriate conditions for P removal.

Specifically, the conditions that these systems must satisfy are, (1) near complete nitrification, (2) a high level of denitrification, these two to be satisfied under the most adverse conditions, e.g. at the lowest yearly temperature and cyclic flow and load conditions, and (3) optimal biological excess P removal. To satisfy these conditions, the system must provide aerobic, anoxic and anaerobic zones to bring about nitrification, denitrification and phosphorus removal respectively. Research and full-scale application have indicated that the mass fractions of sludge allocated to the different zones in the system should be approximately 40 to 60 percent aerobic, 30 to 40 percent anoxic, and 15 to 20 percent anaerobic and that the sludge ages should lie in the range 15 to 25 days for the temperature conditions in South Africa.

In so far as future wastewater treatment plants are concerned, the nutrient removal activated sludge plants have been shown to have the capability of producing effluents of such good quality that, in most situations, the quality criteria set for the effluents can be achieved. Unfortunately, the vast majority of wastewater treatment plants in South Africa were built before any requirements on effluent P quality were considered necessary. Most of these plants were based on the trickling filter system of wastewater treatment; the plants were designed to nitrify but the trickling filter system inherently does not possess the capability to remove significant amounts of nitrate or phosphorus.

Up to 1985, the existing trickling filter systems for wastewater treatment were exempted from satisfying the effluent phosphorus quality regulations. Since 1985 these regulations have been applied also to trickling filter effluents. Removal of phosphorus from these effluents can be achieved only by addition of iron and aluminium salts. Research at Boksburg (Brodisch, Louw, Thirion and Wiechers, 1985) and NIWR (Brodisch, 1983) has provided guidelines for P removal from trickling filter effluents so that the problem has found a practical solution. However, removal of phosphorus by chemical addition has the disadvantages that the chloride and sulphate concentrations of the discharge are increased and the cost of chemicals is high and continuous.

An alternative approach to deal with P removal in trickling filter installations is the removal of phosphorus biologically in short sludge age nutrient removal activated sludge plants that do not nitrify. The effluent, even if of a poor COD quality, then can be passed through the existing trickling filter plant where it will be nitrified and the COD quality improved to satisfy regulatory requirements. For this specific purpose a short sludge age non-nitrifying P removal activated sludge system was proposed by Barnard in 1976 and termed by him the "Phoredox" system (see Fig 2.4). However, since the time of his proposal, no concerted investigation into this system has been undertaken in South Africa so there is virtually no locally generated information on the behaviour of this system.

In the United States of America, biological excess P removal activated sludge systems at short sludge ages have received considerable attention and have been designated the Anoxic/Oxic (A/0) system. The basic A/0 system is virtually identical to the Phoredox system proposed by Barnard and is applicable where nitrification does not occur. Should nitrification take place at the short sludge ages, a modified version of the A/0 system has been proposed which is identical to the 3-stage Modified Bardenpho system first proposed by Barnard (1976).

In America, the Phoredox-A/0 system has been investigated at laboratory, pilot and full scale for sludge ages as low as 2 days while the Modified Bardenpho-A/0 system has been investigated at sludge ages around 5 days. The American experience indicates that the phosphorus concentrations can be reduced to low values in both the nitrifying and non-nitrifying systems and that the settleability of the sludges is very good, all the reported SVI's being less than 100 mℓ/g. A feature of the operation of these plants has been the extremely low underflow recycle ratios (0,2:1 with respect to the influent flow rate) compared with those employed in biological P removal plants in South Africa, (usually 1:1). With such low recycle ratios the adverse influence on the P removal of nitrate returned in the recycle to the anaerobic zone is relatively small and this is probably a contributory reason why the American investigators obtained good P removal in Phoredox systems even when partial nitrification occurred. To operate full scale systems at such low recycle ratios, it is an essential requirement that the settling characteristics of the sludge remain very good. Any deterioration will demand either higher recycle ratios or settling tanks that are considerably larger. In South Africa, experience with long sludge age nutrient removal plants has shown that sludge settleability tends to be poor and it would be unwise to design the plants with underflow recycle ratios less than 1:1 (even if the settling tank was made sufficiently large) because of problems of sludge loss due to denitrification of the accumulated sludge in the settling tank.

One difficulty with the published work is that, in all instances except one, the influent P/COD (or P/BOD) ratio is much smaller than that normally encountered in South Africa so that the P removal per influent COD (or BOD), to achieve a good quality effluent, is well below that required in South Africa.

From the remarks above it is evident that the results achieved with the short sludge age nitrogen and P removal systems in America do not provide a reliable basis for the design of similar plants in South Africa. It was decided therefore to inaugurate a study into these short sludge age P removal systems, to assess the response of the systems under non-nitrifying and nitrifying conditions, to determine the optimal system configuration(s) and operational parameters and to study the settling characteristics of the mixed liquor produced in the systems. Ancillary to such a study, the response data observed should also provide information against which the predictive qualities of the general activated sludge model by Dold, Ekama and Marais (1985) and the semi-empirical biological excess P removal model of Wentzel, Dold, Ekama and Marais (1984) can be evaluated.

CHAPTER TWO

LITERATURE SURVEY

1. BIOLOGICAL EXCESS PHOSPHORUS REMOVAL IN LONG SLUDGE AGE ACTIVATED SLUDGE SYSTEMS

Very little research has been published on biological excess phosphorus (P) removal systems at short sludge ages - the overwhelming mass of research has been on long sludge age systems, from 20 to 30 days. The reason for this imbalance is to be sought in the South African situation; it is here that P removal found its first and most urgent need and where the first practical system for biological excess P removal was developed. From the beginning, the system had to satisfy the requirement that the effluent must be nitrified; experimental enquiry showed that nitrate had an adverse effect on P removal processes so that denitrification became an essential addition to the system. To obtain nitrification, denitrification and excess P removal, the system sludge age had to be between 15 and 30 days.

The requirement that the effluent must be nitrified in many ways complicated the research into the phenomenon of biological excess P removal and the parallel development of treatment systems to achieve P removal. Nitrification demanded denitrification so that any effort to elucidate the P removal phenomena had to contend with the confounding effects of nitrification and denitrification, these latter two phenomena being quite complex in themselves.

Considering the excess P removal phenomena, an acceptable biochemical model is now available (Wentzel, Lotter, Loewenthal and Marais, 1986). The phenomena is an extremely complex one but the essential features can be described as follows:

(1) P removal is achieved through the action of a specific group of organisms - the polyP organisms - of which the *Acinetobacter* spp. are the most important.

(2) The polyP organisms have the propensity to sequester and store lower fatty acids (LFA) in the poly-β-hydroxybutyrate (PHB) form. This can happen only if the appropriate biochemical state is provided. One such state, amongst a number, is of particular interest to us: If the organism is contacted with LFA in a situation where there is no external electron acceptor (nitrate or oxygen) present (anaerobic phase), provided the polyP organism mass has a reservoir (pool or store) of polyphosphate chains, the organism breaks down some of the polyphosphate to orthophosphate and the energy thus released is employed to convert the LFA to PHB which is stored within the organism. The orthophosphate generated is released to the surrounding liquid.

(3) The polyP organisms with their pool of PHB, when brought into the presence of an external electron acceptor, nitrate or oxygen (anoxic or aerobic phase respectively) but principally oxygen, will utilise the PHB for growth and for replenishing the polyphosphate pool by synthesising and storing polyphosphate chains, the phosphorus for this purpose being taken from the orthophosphate in the liquid phase. Thus, by passing through phases (2) and (3), there is firstly, a release of P and uptake of LFA and secondly, an increase in the polyP organism mass and an uptake of P as polyphosphate. The increase in the mass of polyP organisms (with their store of polyphosphate), if wasted will remove an associated mass of phosphate from the liquid phase. In this manner there is a net reduction in the P content of the liquid.

With regard to the activated sludge treatment system in which the excess P removal takes place, the following must take place:

(1) A mixed liquor stream with its polyP organism mass and the influent wastewater stream are discharged into a reactor into which no oxygen or nitrate is allowed to enter (anaerobic reactor). The polyP organism mass (with a polyphosphate pool) sequesters LFA as described earlier and converts and stores it as PHB, releasing orthophosphate (from the breakdown of the polyphosphate) to the surrounding liquid, i.e. there is an increase in the soluble orthophosphate concentration in the anaerobic reactor. The mass of phosphate released is very closely proportional to the mass of LFA sequestered.

(2) Most municipal wastewaters have only a small concentration of LFA. However, due to the presence of the anaerobic reactor, non-polyP organisms (facultative anaerobic heterotrophs) develop within the system; these can break down the smaller "readily biodegradable" substrate molecules to LFA via the process of acidogenesis. Unsettled municipal wastewaters in South Africa usually have approximately 20 percent of the total influent COD in the readily biodegradable form. This fraction, converted to LFA via acidogenesis, forms the main supply of LFA for PHB formation by the polyP organisms. The acidogenic organisms therefore perform an essential function by supplying LFA to the polyP organisms. The conversion of biodegradable COD to LFA experimentally appears to be in accordance with a first order reaction (Wentzel, Dold, Ekama and Marais, 1984). The first order rate constant is relatively small and the acidogenic reaction is much slower than the sequestration rate. Consequently the conversion rate is the governing one; any LFA formed is immediately sequestered so that the mixed liquor in the anaerobic reactor usually does not show up any LFA.

Very little is known of what happens to the more complex (particulate-type) biodegradable substrate molecules in the anaerobic reactor but the indications at present are that the particulate (slowly biodegradable) COD fraction is relatively unaffected in the anaerobic zones of long sludge age plants. However, this is an area that is in urgent need of further research.

(3) Entry of nitrate or oxygen (but particularly nitrate) into the anaerobic zone acts adversely on the mass of LFA sequestered by the polyP organisms for the following reason: Nitrate and oxygen are very rapidly used by heterotrophic organisms as electron acceptors in their usual metabolic action and readily biodegradable COD is preferentially used as an electron donor. This metabolic reaction is an order of magnitude faster than the conversion of readily biodegradable COD to LFA. Consequently, the store of readily biodegradable COD for LFA production is effectively reduced. The net result is that biological excess P removal is correspondingly reduced. The relative effects of nitrate and oxygen are as follows: 1 mg of nitrate (as nitrogen)

removes approximately 8,6 mg of readily biodegradable COD whereas 1 mg of oxygen removes only about 3 mgCOD. Normally the oxygen concentration in the recycle flow to the anaerobic reactor will not be more than 2 mg/ℓ, that is, 2 x 3 = 6 mg/ℓ of readily biodegradable COD is removed per litre of influent flow if the recycle ratio is 1:1. In nitrification/denitrification plants treating influents with high TKN/COD ratios (0,09 mgN/mgCOD or greater), the nitrate in the recycle may exceed 5 mgN/ℓ, that is, the nitrate will remove 5 x 8,6 = 43 mgCOD. This example shows that in nitrifying plants the nitrate can have a dominating effect on P removal if allowed to discharge to the anaerobic reactor.

(4) After the PHB has been stored by the polyP organisms in the anaerobic reactor, the mixed liquor passes to a reactor where an external electron acceptor (either nitrate only or oxygen plus nitrate) is added. Both the polyP and non-polyP organisms use these acceptors for energy generation to perform their respective biological functions: the polyP organisms for growth and polyphosphate storage using the stored PHB as an electron donor; the non-polyP organisms for growth using readily biodegradable COD (remaining after sequestration) and slowly biodegradable COD. Only a fraction of the polyP organisms can utilise nitrate so that, in a reactor where nitrate is the only electron acceptor available (anoxic reactor), relatively little phosphorus is taken up. However, in the anoxic reactor, the non-polyP organisms utilise the nitrate, usually at quite a rapid rate. The mixed liquor flow then passes from the anoxic reactor to one that is aerated, (or passes directly from the anaerobic reactor to the aerated reactor). In the aerobic reactor, the oxygen supply will be used by the polyP organisms for growth and polyphosphate accumulation using the stored PHB as an energy source; the non-polyP organisms grow normally from the biode-gradable material still remaining from the influent and generated by death of the organisms.

(5) Nitrifying organisms are obligate aerobes and these will develop in the aerobic zone to convert ammonia to nitrate, provided the aerobic organism retention time (or sludge age) is long enough.

Once one appreciates the behavioural patterns described above, it is understandable why in South Africa the research has been so greatly occupied in devising systems that would:

(a) have adequate aerobic sludge age to give continuously high efficiency of conversion of organic nitrogen and free and saline ammonia to nitrate under the most adverse conditions to be encountered, i.e. low temperatures, cyclic flow and load conditions and low maximum specific nitrifier growth rates,

(b) ensure, as effectively as possible, that no nitrate or oxygen enters the anaerobic zone.

Nitrification always can be assured by increasing the aerobic sludge age and accordingly system sludge ages of 30 days with aerobic sludge ages of about 15 days have been required in some plants.

Devising a system to provide a nitrate free discharge of mixed liquor to the anaerobic zone has been much more difficult; either the nitrate in the whole system has to be reduced to very low concentrations or the nitrate in the recycle to the anaerobic zone has to be selectively reduced. These two options directed much of the system development that took place:

(1) The 5-stage Bardenpho system in effect constitutes the outcome of an attempt to reduce the nitrate concentration in the whole system to negligibly small concentrations. The system (see Fig 2.1) has two anoxic zones with a recycle from the aerobic to the first or primary anoxic zone (a-recycle). The major fraction of nitrate formed in the aerobic zone is recycled and denitrified in the primary anoxic zone. The balance is denitrified when passing through the secondary anoxic zone leaving a substantially nitrate-free liquid to be discharged in the effluent or recycled, via the settling tank underflow, to the anaerobic reactor.

Experimental enquiry into the denitrification capacities of the anoxic zones soon showed that, if the TKN/COD ratio in the unsettled influent exceeded about 0,09 mgN/mgCOD, it was not possible to proportion the anoxic zones such that all the nitrate could be removed, in which event nitrate was recycled to the anaerobic reactor bringing about a reduction in excess P removal. The mass of nitrate recycled to the anaerobic zone could be decreased by reducing the underflow recycle flow with respect to the mean influent flow. Unfortunately, in nutrient removal activated sludge plants, it was found not to be possible to have low recycle ratios of say 0,25:1 for the following reasons:

> Nutrient removal plants tend to give rise to bulking sludges, often with Diluted Sludge Volume Indices (DSVI's) of 150 mℓ/g or higher. With such high DSVI's, sludge accumulation in the settler can be large and, if nitrate is present, denitrification develops in the accumulated sludge mass causing the sludge to rise in the settler and to discharge in the overflow. To minimise sludge accumulation and its associated effects, it has been necessary to use relatively high underflow recycle ratios - ratios of 1:1 are very common. These high recycle ratios have had important implications on the use of the Modified Bardenpho system - once the TKN/COD ratio exceeds about 0,09 mgN/mgCOD, it is no longer possible to have zero nitrate in the underflow; in effect the system is no longer viable for removing phosphorus.

An improvement on the 5-stage Bardenpho system, which retains the high underflow recycle ratio but makes use of selective removal of nitrate in the underflow stream, has been proposed by the Johannesburg City Council Research Group: the secondary anoxic zone in the Bardenpho system is removed and positioned in the underflow recycle stream (see Fig 2.2). By doing this, the mass of nitrate that needs to be reduced to give zero nitrate discharge to the anaerobic reactor is half of that required to be reduced in the anoxic zone of the normal 5-stage Bardenpho system because, in the latter, twice the flow (and hence twice the nitrate mass) passes through the secondary anoxic zone. In the Johannesburg modification, only the nitrate in the recycle stream needs to be reduced. This modification is of recent origin and the implications have not been fully investigated. However, an existing

Bardenpho system has been altered to operate with a Johannesburg modification, and the results show a promising improvement in P removal.

(2) The UCT system was developed specifically to remove nitrate selectively from the recycle flow to the anaerobic reactor (see Fig 2.3). The secondary anoxic zone in the 5-stage Bardenpho system is omitted and the anoxic mass fraction of this zone is added to the first anoxic zone. The nitrate in the underflow recycle is directed to the first anoxic zone. By controlling the internal recycle (a-recycle) from the aerobic to the anoxic zone, the anoxic zone can be loaded just to its denitrification capacity so that the nitrate in this reactor is maintained near zero. An additional recycle is incorporated conveying mixed liquor from the anoxic to the anaerobic reactor (r-recycle). In this manner, zero nitrate discharge to the anaerobic zone can be assured for TKN/COD ratios as high as 0,12 to 0,14 mgN/mgCOD for raw sewage influents. The system has the disadvantage of an extra recycle and, because the mixed liquor concentration in the r-recycle will be half of that in the underflow of the 5-stage Bardenpho system for the same recycle ratio, to obtain the same anaerobic mass fraction the volume of the anaerobic reactor needs to be twice as large as that in the Modified Bardenpho system.

The systems described above are the main ones that have been developed to achieve biological excess P removal in plants that are required to deliver nitrified effluents. It is clear that the principal problem in the development of P removal systems has been to find effective means of minimising or completely eliminating nitrate discharge to the anaerobic reactor.

2.1 Modelling of the response of long sludge age biological excess P removal systems

Modelling the response of nutrient removal activated sludge plants has proceeded along two parallel paths. The first path was to model the response of the heterotrophic mass with respect to oxygen utilization, organism growth, endogenous decay etc., assuming the polyP organism mass behaves identically to the normal heterotrophic organism mass. Dold, Ekama and Marais (1980), Van Haandel, Dold and Marais (1982) and Dold and Marais (1985) contributed to the development of a general model describing the behaviour of the heterotrophic and autotrophic organism masses in activated sludge systems containing anaerobic, anoxic and aerobic zones. Applying this model to the Bardenpho and UCT systems has, in the past, given acceptably close correspondence between predicted and observed behaviour. The reason why the model can be applied to these systems is that the fraction of polyP organisms is relatively small compared with that of the non-polyP organisms so that the sludge production, oxygen utilization and other heterotrophic behavioural responses are dominated by the non-polyP organism mass. However, this approach does not allow estimation of the P removal behaviour.

The second path was to model the P removal behaviour semi-empirically, from the understanding of the P removal processes, and to graft these behavioural patterns onto the behavioural patterns described by the general model. This required calibration of the P removal model using the data on P removal observed on long sludge age P and nitrogen removal plants. Within the range of sludge ages investigated, the P removal model (Wentzel *et al*, 1984) appeared to work very satisfactorily and it is still used for designing the P removal aspect of nutrient removal plants. It is important to remember however that the P removal model should be applied only within the range of sludge ages within which the model has been tested, that is, sludge ages greater than 8 days.

2. BIOLOGICAL EXCESS PHOSPHORUS REMOVAL IN SHORT SLUDGE AGE ACTIVATED SLUDGE SYSTEMS

In Section 1 it was shown that the system configurations developed for biological excess P removal have been strongly influenced by nitrification. If nitrification is not required, the need for anoxic zones (to denitrify) and for long sludge ages to ensure nitrification falls away. These aspects were recognised by Barnard (1976) who suggested that, if the system sludge age is shortened sufficiently to prevent nitrification taking place, the system configuration reduces to an anaerobic reactor, receiving the influent and underflow recycle, followed by an aerobic reactor (see Fig 2.4). He named this system the Phoredox system. Although proposed conceptually in 1976, no experimental units have been set up in South Africa to test the viability of the system.

Timmerman (1979) proposed a system, essentially the same as the Phoredox system, which she designated the Anoxic/Oxic or A/O system. The basic A/O configuration is identical to that of the Phoredox but, with the A/O, it is specifically proposed that the anaerobic and aerobic zones are partitioned to give a series reactor configuration that approaches plug-flow conditions.

Timmerman operated a laboratory scale A/O system with an anaerobic mass fraction of 0,375 (5 stages), an aerobic mass fraction of 0,625 (5 stages), and an underflow recycle ratio of 0,3 with respect to the influent flow rate. The system sludge age was not reported but, since the system apparently did not nitrify, the sludge age must have been "short". The influent to the system was primary clarifier effluent from the Allentown (Pennsylvania) sewage treatment plant.

The information in the paper regarding the influent characteristics and the operational procedures is incomplete. In addition, the parameters on which the performance of the system is assessed differ from those used by South African researchers which makes parallel assessment impossible. For example the readily biodegradable COD fraction in the influent, which forms a vital part of the theories of both polyP and non-polyP organism growth, receives no attention. There is also clearly an error in the influent COD and/or BOD reported so that it is not possible to determine the P/COD ratio of the influent.

Notwithstanding the deficiencies noted above, there is some interesting qualitative information in the paper: COD, BOD and soluble P profiles were taken along the flow axis of the reactor series. These indicate a "soluble" COD/BOD reduction in the anaerobic reactor with a concomitant increase in the soluble phosphorus content. The P release appears to show first order kinetic behaviour. In the aerobic zone there is a rapid reduction of the soluble phosphorus to virtually zero by the third of the five stages. Bot the P release and P uptake processes appeared to be fairly rapid. The system was started with no seed sludge and the P release and uptake phenomena developed gradually, finally achieving stability after about 12 weeks. The author found that, if nitrate was introduced into the anaerobic zone, the magnitude of the P release and the subsequent P uptake decreased. The sludge settleability was excellent with SVI's averaging below 50 mℓ/g.

The paper by Timmerman is significant in that it indicates, however qualitatively, that biological excess P removal is achievable in short sludge age plants. Furthermore, the observations also confirm the earlier findings in South Africa (Barnard, 1976) that nitrate has a detrimental effect on the P removal processes.

Subsequent to Timmerman's work, pilot scale investigations were conducted by various researchers at Air Products and Chemicals, Inc. (the same company that supported Timmerman's study). On-site, trailer-mounted A/O units were tested using wastewaters from treatment plants in Baltimore by Deakyne, Patel and Krichten (1984), in Largo by Hong, Krichten, Kiesnbauer and Sell (1982) and in Bath and Rochester by Hong, Spector, Galdieri and Seebohm (1983). All the pilot plant tests were run in a non-nitrifying mode with reported sludge ages ranging from 2,0 to 2,4 days. At Rochester, the system was also run in a nitrifying mode at a sludge age of 4,9 days. The influent characteristics, system parameters and effluent characteristics are summarised in Table 2.1. The procedures used for setting up and maintaining the reported sludge ages are not described. It appears that the sludge was withdrawn from the underflow recycle stream and apparently hydraulic control procedures were not followed. The wastewater strength was measured in terms of BOD_5.

In order to find some comparative measure with the South African research work, the influent BOD was converted to COD by accepting the following approximations:

$$\text{COD (unsettled)} = 2 \times \text{BOD (unsettled)}$$

$$\text{COD (settled)} = 1{,}8 \times \text{BOD (settled)}$$

This allowed the P/COD ratios of the influent to be determined (see Table 2.1). Compared with municipal flows in South Africa, the P/COD ratios of the Rochester and Baltimore flows were low and that of Bath extremely high. In South Africa, the P/COD ratio of the influent will range between 0,015 to 0,020 mgP/mgCOD for unsettled municipal effluents and 0,020 to 0,025 mgP/mgCOD for settled effluents. The South African experience with regard to P removal is that for anaerobic mass fractions of 0,15 and greater, ΔP/influent COD ranges from about 0,015 mgP/mgCOD with unsettled influent COD's of 200 mgCOD/ℓ to 0,020 mgP/mgCOD with unsettled influent COD's of 1000 mgCOD/ℓ. Experience has also indicated that with shorter sludge ages, the ΔP/influent COD tends to be higher. In the light of these observations and examining Table 2.1, it would seem that, except for the Bath study, the P/COD ratios of the influent flows were too low to test the P removal potential of these systems - the low effluent P concentrations obtained are not unexpected.

The Bath pilot plant study appears to be the most valuable in terms of the P removal capacity of a short sludge age A/O system. The unit was fed with wastewater from the Municipality of Bath containing a significant portion of industrial waste which was high in phosphorus. Accordingly, the influent to the unit contained 20 mgP/ℓ (total P) and 13 mgP/ℓ (soluble P). The system, while operating under non-nitrifying conditions with a 33 percent anaerobic mass fraction, was able to remove 8,6 mgP/ℓ (soluble P). In terms of P removal per influent COD, the unit removed 0,028 mgP/mgCOD which is high compared with the more usual value of 0,015 to 0,020 mgP/mgCOD achieved in long sludge age plants in South Africa. At the Patapsco wastewater treatment plant in the City of Baltimore, studies were conducted on the effect of cyclic flow conditions. The pilot plant was operated under two modes of diurnal flow variation; the first was to simulate the average flow conditions with daily fluctuations of 79 to 130 percent and the second was to simulate the flow variations obtained in the month with the maximum flow, i.e. flows from 104 to 173 percent. The system was run with a low underflow recycle ratio (0,32 and 0,42) for the two modes respectively. The sludge accumulated in the settler during the high flow period so that there was a variation of MLVSS concentration in the system and because the BOD concentration of the wastewater during the high flow period was higher than during the low flow period, an even larger variation in the F/M ratio of the sludge in the reactors. To equalise the F/M ratio, the underflow recycle ratio was increased during the period of high flow and reduced during the period of low flow. Without going into detail, the P and BOD removals appeared to have about the same efficiencies under constant and cyclic flow and load conditions.

The effect of low temperatures on biological excess P removal using automated batch fill and draw units is reported by Hong *et al.* (1982). The principal point of interest here is that P removal was not adversely affected by low temperatures, indeed, the authors note that the P removal improved when the temperature decreased from 10 to 5°C. Whether the same behavioural pattern would be exhibited in continuous feed systems is a matter for speculation.

Based on the results of pilot plant studies, large scale plant investigations were conducted at Largo (Krichten and Hong, 1981) and Pontiac (Kang, Horvatin and Briscoe, 1985) by converting sections of existing plants. The investigation included operation under non-nitrifying and nitrifying/denitrifying conditions.

The Largo plant configuration consisted of a 5-stage unaerated section and a 5-stage aerobic section. To obtain denitrification, 3 unaerated zones were made anaerobic (anaerobic mass fraction of 0,19), the remaining two were made anoxic (anoxic mass fraction of 0,19) and an inter reactor recycle was introduced from the last aerobic reactor to the first anoxic reactor. No information is supplied on the underflow or inter reactor recycles or on the system sludge age. The study is very poorly reported. Because of the incomplete nature of the information, there is little comment, of a quantitative nature, that can be made. Qualitatively, under both non-nitrifying and nitrifying/denitrifying conditions, the plant removed the phosphorus in the influent effectively and produced good settling sludges.

A full-scale demonstration of a nitrifying A/O system was conducted by Kang *et al.* (1985) at Pontiac (Michigan) for two purposes; firstly, to determine the effect on P removal of nitrate in the recycle, and secondly, to investigate full scale operation in a cold climate. The plant was first run under nitrifying conditions and then under non-nitrifying conditions. The performance of both modes of operation are summarised in Table 2.2. Kang *et al.* maintain that, under nitrifying and non-nitrifying conditions, the P removal of the system was good, the nitrate in the recycle stream had no effect on the P removal and that the cold climate had no evident detrimental effects on the system behaviour. It is difficult to assess whether the nitrate did in fact effect the P removal because; (i) influent wastewater had a low TKN/COD ratio (approximately 0,075 mgN/mgCOD) and a low P/COD ratio (approximately 0,016 mgP/mgCOD), (ii) no recycle ratios are reported, and (iii) under nitrifying and non-nitrifying conditions, the P removal per influent COD was low (0,013 and 0,012 mgP/mgCOD respectively).

2.1 General discussion and conclusions

From a review of the literature on short sludge age Phoredox-A/0 systems, the following points merit comment:

(1) The A/0 system operating in the non-nitrifying mode appears to give adequate P removal at sludge ages as low as 2 days with approximately 25 percent anaerobic and 75 percent aerobic mass fractions. At these low sludge ages, the anaerobic and aerobic mass fractions appear to be adequate to allow all the P release possible in the anaerobic phase and all the P uptake possible in the aerobic phase. These response patterns imply that the rates of the biochemical reactions in these processes are fairly rapid.

(2) In all the systems the sludge settleability appeared to have been excellent, the mean SVI's reported ranging from 38 to 75 mℓ/g.

(3) The underflow recycle ratios were all very much smaller than those employed in South Africa, ranging from 0,15 minimum to 0,42 maximum whereas in South Africa a recycle ratio of 1 or higher is the norm. The reason why the low recycle ratios were successful undoubtedly must be ascribed to the good settleability of the sludge. In South Africa, Diluted Sludge Volume Indices of 150 mℓ/g and higher are not uncommon for long sludge age nutrient removal plants. With such poor settling

sludges in settling tanks designed to the normal IPC criteria, densification to the concentrations required with recycle ratios of say 0,2 is not likely to be achieved before the settled sludge builds up to the overflow level. The situation is relieved partially by having higher recycle ratios and deep settling tanks. With our present state of knowledge, it would seem rather risky to assume that these short sludge age plants always will produce good settling sludges.

(4) A further point that becomes evident in the study is the effect of low recycle ratios on the response of short sludge age plants under cyclic flow and load conditions. These plants may have nominal hydraulic retention times of 4 hours or less. Under cyclic flow conditions and with low underflow recycle ratios, there will be an appreciable shift of the sludge mass between the reactor system and the settling tank causing a possible loss of efficiency in P removal over parts of the cycle and putting undue load on the settling tank. It would seem that with low underflow recycle ratios, it is necessary to operate the system with different recycle ratios at different parts of the cycle in order to have greater equality in the loading on the sludge and on the settling tank. Once one accepts that greater recycle ratios are necessary over parts of the cycle, there is merit, from a practical aspect, in investigating the system under a continuous higher recycle ratio. Low recycle ratios would have the advantage in short sludge age nitrifying systems that less nitrate is transported to the anaerobic reactor and therefore the adverse effect of nitrate on the P removal would be reduced but again, the effect of cyclic loading is not so clear. The short sludge age studies reported here do not give sufficient information on the response behaviour to follow with confidence their views on low underflow recycle ratios.

In the long sludge age systems the nominal hydraulic retention time may be up to 20 hours; this, combined with the normal high underflow recycle ratios, greatly reduces the shift in loading on the sludge and also the mass of sludge to be stored in the settling tank. Thus, by shortening the sludge age, aspects that are of little consequence at long sludge ages become of significant importance at short sludge ages.

The general conclusion from this review is that short sludge age P removal systems have potential as a viable and practical system but that further study is required to obtain quantative and qualitative information on the following aspects: The effect of the anaerobic, anoxic and aerobic mass fractions on P removal, nitrification, denitrification, sludge settling and effluent COD quality over a range of short sludge ages from 6 days down to say 2 days; the response of the plants under higher recycle ratios and cyclic flow and load conditions.

Table 2.1: Summary of A/0 system pilot plant performances

	non-nitrifying					nitrifying
Location	Rochester	Largo	Bath	Baltimore (mode 1)	Baltimore (mode 2)	Rochester
Retention time (hours): anaerobic	0,50	0,48	0,87	0,64	0,48	1,00
anoxic	-	-	-	-	-	-
aerobic	1,50	1,63	1,73	1,97	1,48	3,00
Total sludge age (days)	2,34	2,03	2,43	-	-	4,90
Underflow recycle ratio	0,15	0,21	0,27	0,32	0,42	0,20
Reactor temperature (°C)	20,6	23,7	20,5	-	-	20,3
Influent characteristics: source	raw	settled	settled	settled	settled	raw
total BOD_5 (mg/ℓ)	186	144	172	200	194	184
total P (mg/ℓ)	4,9	-	20,0	8,4	8,2	4,9
soluble P (mg/ℓ)	2,2	5,8	13,0	6,2	6,2	4,1
NH_3-N (mg/ℓ)	16,7	-	-	-	-	16,9
TSS (mg/ℓ)	314	144	136	85	88	219
VSS (mg/ℓ)	269	109	108	-	-	185
P/COD (mgP/mgCOD)*	0,013	-	0,065	0,023	0,023	0,013
Effluent characteristics: total BOD_5 (mg/ℓ)	22,1	11,3	12,1	9,5	9,5	19,6
total P (mg/ℓ)	0,8	-	-	1,4	2,2	-
soluble P (mg/ℓ)	0,49	1,03	4,40	0,64	1,61	0,38
NH_3-N (mg/ℓ)	15,0	-	-	-	-	0,5
TSS (mg/ℓ)	40	16,3	16,1	14,5	13	26
MLVSS (mg/ℓ)	3850	2660	3030	3616	3488	4470
SVI (mℓ/g)	38	-	-	75	59	52

*estimated as described in text

Table 2.2: Summary of performance of full scale A/0 system at Pontiac, Michigan.

		nitrifying	non-nitrifying
Location		Pontiac	Pontiac
Influent characteristics			
source		settled	settled
temperature	(°C)	17	11
total BOD$_5$	(mg/ℓ)	110	143
total P	(mg/ℓ)	3,24	3,74
soluble P	(mg/ℓ)	1,86	2,18
TKN	(mg/ℓ)	15,2	16,1
nitrate	(mg/ℓ)	0,19	0,20
Effluent characteristics			
total BOD$_5$	(mg/ℓ)	6,2	12,9
total P	(mg/ℓ)	0,77	0,44
soluble P	(mg/ℓ)	0,69	0,28
TKN	(mg/ℓ)	0,93	5,93
nitrate	(mg/ℓ)	10,4	6,65

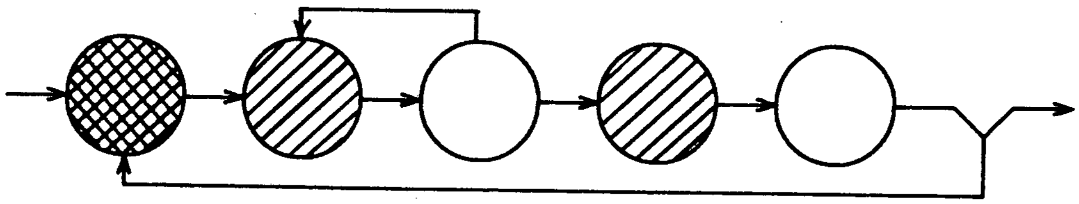


Fig 2.1: Schematic diagram of the 5-stage Bardenpho system.

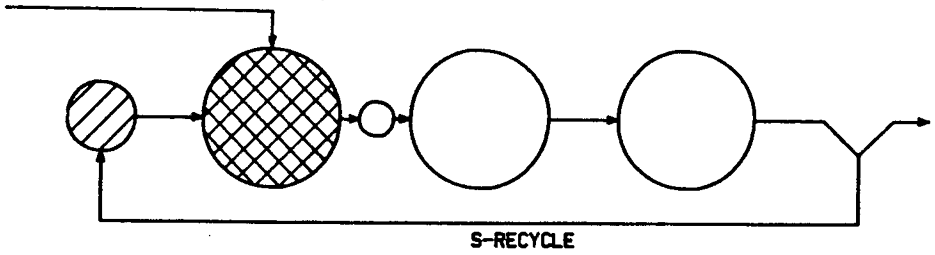


Fig 2.2: Schematic diagram of the Johannesburg system.

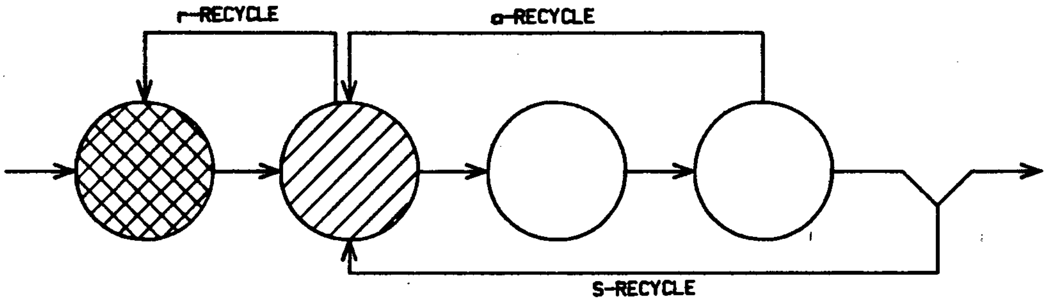


Fig 2.3: Schematic diagram of the UCT system.

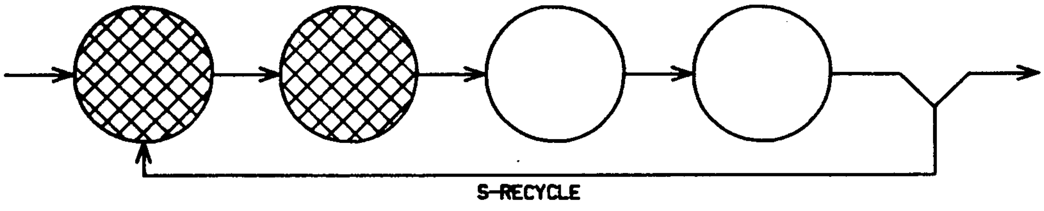


Fig 2.4: Schematic diagram of Phoredox-A/0 system.

CHAPTER THREE

EXPERIMENTAL PROCEDURES AND APPARATUS

1. INTRODUCTION

In this chapter, the experimental procedures, apparatus and analytical methods employed in the investigation are set out in some detail, particularly so because it may assist investigators doing further research in this area.

2. EXPERIMENTAL DESIGN

Prior to this investigation, very little work had been reported on excess P removal at short sludge ages and therefore, at the outset of the project, it was not possible to devise a detailed experimental design. Rather, it was decided, to commence with a simple system and from the observations and analysis of these, to modify the system accordingly.

Due to the initial paucity of understanding of process behaviour at short sludge ages, it was decided to have a comprehensive testing program that also included parameters not overtly associated with excess biological P removal. With further understanding of the processes, these parameters may be found to be of importance.

3. EXPERIMENTAL APPARATUS

In the design of all the equipment, emphasis was placed on simplicity, durability and ease of dismantling for cleaning and maintenance.

3.1 Reactors

Reactors were constructed from 115 mm diameter perspex tubes with a maximum volume of 3ℓ. A typical design for a reactor is shown in Fig 3.1.

The mixed liquor in the reactor was kept thoroughly stirred by means of perspex paddles mounted along the length of a stainless steel shaft. The shaft was driven by an electric motor fixed to the lid of the reactor. The motor was a brushless 115V AC motor equipped with an integral gearbox to give an output of 30 r.p.m. The size and position of the paddles were chosen to give complete mixing, independent of the bubble aeration mixing effect in the aerobic reactors, without causing turbulence on the surface of the mixed liquor. Each reactor was fitted with two vertical baffle plates, mounted on the inside of the perspex tubes, to improve the mixing action by preventing the formation of a vortex.

The reactor cover plate was removable for cleaning purposes and was provided with a 40 mm diameter access port for sampling, cleaning and inserting dissolved oxygen or pH probes. When a reactor served as an anoxic or anaerobic zone, the access port was sealed with a rubber bung.

The inlet and outlet ports were located at the bottom of the reactor, and consisted of 10 mm internal diameter perspex glass tubes glued over 10 mm holes drilled through the base plate. The outlet port was connected to an inverted U-tube, the height of which could be adjusted to control the liquid volume in the reactor.

Aeration was through porous stones, of the type normally used in fish tanks, attached to a perspex tube passing through the top cover; it could be lowered or raised to any depth of immersion. Air to the airstone was from a low pressure line supplied by a large compressor. The flow rate to each reactor was controlled by a fine needle-valve to maintain the dissolved oxygen (D.O.) concentration greater than 3 mgO/ℓ.

In the latter part of the investigation, a selector reactor was added to the system. This was constructed from 60 millimetre diameter perspex tubing and had a volume of 350 mℓ. The inlet to the reactor was in the baseplate while the outlet pipe was at a fixed height in the sidewall of the reactor. Vigorous stirring was provided by a single paddle driven at approximately 120 r.p.m. by a 220V AC motor. An airstone was built into the base of the selector such that the top of the airstone was level with the bottom of the reactor.

The reactors were mounted on a vertical board which was held in a frame on roller wheels, thus allowing the unit to be moved to any convenient place in the laboratory. Each reactor was set with its overflow point higher than that of the receiving reactor so that the reactors discharged under gravity from one to the other. A large shallow galvanised metal tray, extending beyond the reactor installation, was positioned below the units in order to catch and retain any sludge spilled due to blockages, split pipes or broken connections. Any sludge spilled was aerated and returned to the system.

The units were operated in a temperature controlled laboratory at 20°C.

3.2 Settling tank

The settling tank was constructed from 80 mm diameter perspex tube, as shown in Fig 3.2. The settling tank was mounted on a wooden holder and set at an angle of 60° to the horizontal. The mixed liquor inlet and the underflow recycle outlet were located opposite each other at the bottom of the settler and were set at 90° to each other. The effluent outlet was located near the top of the settler tube.

To prevent sludge from adhering to the sides and bottom of the settler and to prevent the sludge from settling into a solid mass, two wiper blades were attached to a central shaft to sweep the sides and the bottom at any desired interval. The shaft was driven at a speed of 1,33 r.p.m. by a 220V AC electric motor and, by connecting the motor to an on/off electronic timer, the frequency of on and off times could be set as desired. The usual setting was one revolution of the wiper blades every 3 minutes.

3.3 Pumps and tubing

The feed and recycle pumps were of the peristaltic type developed in the University of Cape Town, Civil Engineering workshops: Four vertical rollers were driven by a 0,5 kW brushless 115V AC motor. The pumping action was provided by stretching tubes horizontally across the rollers. The pumps could accommodate up to eight channels and, by adjusting the tension on the tubing, it was possible to obtain the same flow rate in each channel. Experience had shown that, once set, the flows remained constant for a considerable time. The pump tubing was periodically checked and replaced. By driving the pump through an on/off electronic timer, the daily flow rates could be set very accurately.

For the connections between the reactors, settler, feed container and recycle pump, tubes of soft transparent plastic were used. Tube lengths were kept to a minimum to reduce the retention time in them, thereby minimizing any bacterial reaction occurring outside the reactors. The diameter of the tubes was chosen such that the mixed liquor flow rate was high enough to prevent sludge settlement. It was important to have soft tubing so that regular cleaning of wall growths could be carried out by squeezing the tubing.

3.4 Daily feed container

The daily feed container was made from a length of 310 mm diameter plastic pipe with a flat base glued to it. It had a maximum capacity of 35 litres. An outlet was located close to the bottom of the container. A 10 r.p.m. motor, mounted on a cross-member resting on top of the container, drove a paddle in the wastewater. By trial and error selection, the paddle size was found which kept the solids in the wastewater in suspension but provided no visible turbulence on the surface. To prevent oxygen entering the feed liquid, a cover of expanded styrene was floated on the container contents. Both the hole in the cover for the shaft and the gap between the cover and the container wall were kept as small as possible. To minimise biological degradation of the influent feed, the container was placed in a large chest refrigerator which maintained the temperature of the influent between 5 and 8°C. The feed container and the cover were washed daily with hot water to remove any growth adhering to the sides.

4. EXPERIMENTAL PROCEDURE

4.1 Wastewater collection and storage

The activated sludge was fed with raw (unsettled) sewage from the Mitchell's Plain Sewage Works near Cape Town. The wastewater to this plant is primarily of domestic orgin. A major advantage in using this wastewater was that the sewer network is new so that infiltration during the rainy season was negligible. Consequently, dilution of the influent wastewater during rainy periods was minimal. The unsettled wastewater was collected in a 1000 litre tanker every 10 to 14 days. It was collected between 12h00 and 14h00 in order to provide a COD concentration of approximately 1200 mgCOD/ℓ and a TKN/COD ratio of approximately 0,1 mgTKN/mgCOD. Experience had shown that in the early morning the TKN/COD ratio reached values as high as 0,185 mgTKN/mgCOD while in the late afternoon it dropped to 0,075 mgTKN/mgCOD.

It was found that the tanker must be thoroughly washed before collecting the wastewater; any sewage left in the tank fermented and innoculated the new batch so that there was accelerated loss of COD during storage in the cold room.

At the laboratory, the wastewater was gravity fed through a fine macerator into 400ℓ stainless steel tanks kept in a cold room at 4°C. In order to ensure the same constitution in each tank, the filling hose was moved from one tank to the next approximately every ten minutes.

The wastewater was collected a couple of days before the previous supply was exhausted. This enabled the COD and TKN concentrations of the new sewage to be analysed before use. Before any sample or daily feed was taken from a tank, the contents of the tank were thoroughly mixed with a mixer consisting of a large diameter wooden disc fixed at right angles to a long steel rod.

4.2 Feed preparation

At a set time each day, the contents of a chosen tank were thoroughly mixed and a calculated volume of wastewater was drawn off through a tap at the base of the tank. The wastewater was sieved through a coarse wire mesh to remove any large solid objects and then diluted to the required COD by the addition of tap water.

Sodium bicarbonate was added for pH control; the amount of bicarbonate was determined by trial and error and ranged between zero and two flat teaspoons per 25ℓ of feed.

The Mitchell's Plain wastewater contained insufficient phosphorus for the nature of the experimental work. The wastewater was therefore supplemented with a solution of di-potassium hydrogen orthophosphate (32 g/ℓ). The volume added varied with the system under investigation but ranged from 20 to 50 mℓ per 25ℓ of feed.

The contents of the feed solution were thoroughly mixed and a 200 mℓ sample was extracted from the middle of the bucket. Two drops of 8,6 g/ℓ mercuric chloride were added to the sample to halt all bacterial action. The sample was then stored in the refrigerator for testing the following day. The feed itself was transferred to the feed container.

4.3 Sampling

The effluent from the laboratory unit was collected in an open bucket. Before sampling, the contents of the bucket were stirred with a wooden rod to give a representative effluent sample. A 200 mℓ sample was extracted from the middle of the bucket and filtered through Whatman's No.1 filter paper. Two drops of mercuric chloride were added to the filtrate.

At the outset of the investigation, mixed liquor samples were pipetted directly from the reactors. The pipette tips were filed down in order to widen the entrance thereby eliminating filtering effects. In all previous work carried out in the Water Research laboratory, no problems were encountered with this procedure. However, with the first system under investigation, poor consistency was obtained with volatile suspended solids (VSS) measurements. An alternative sampling procedure was tried whereby the sample was collected from the inverted U-tube (for details see below). This procedure resulted in more consistent and slightly higher values in the VSS determination and therefore was adopted for the remainder the investigation.

The detailed reactor sampling procedure was as follows: A centrifuge tube was brushed and rinsed with water. Two drops of 8,6 g/ℓ mercuric chloride solution were added to the tube. About a quarter of the mixed liquor in a particular reactor was allowed to flow out through the level controller into a storage container in order to clear the tubes of any settled sludge. The centrifuge tube was then filled, through the level controller, to a mark indicating 100 mℓ of sample. The sludge discharge in the storage container (to clear the tube) was then returned to the reactor and the level in the reactor was made up with effluent. The sequence of sampling of the reactors was from the downstream reactor in an upstream direction. After samples from all the reactors had been taken, the centrifuge tubes were centrifuged at 2000 r.p.m. for a minimum of 20 minutes. The supernatant was drawn off, vacuum filtered through Whatman's No.1 filter paper and stored for testing. The compacted solids in the centrifuge tube were washed into a porcelain crucible with distilled water from a squeeze bottle in preparation for the MLVSS test.

4.4 Experimental tests

The samples extracted from the reactors and the effluent bucket, together with the influent sample taken the previous day and stored overnight at about 5°C, were tested for the parameters listed in Table 3.1.

All the tests, except the DSVI, were performed daily. The frequency of the DSVI test depended on the settling behaviour of the sludge but ranged from once a day to once a week.

Determinations of the COD, TKN and MLVSS concentrations were in accordance with the procedures laid down in "Standard Methods for the Examination of Water and Wastewater", 16th Edition (1985). Nitrate concentrations were determined by auto-analyser in accordance with the Industrial Methods 33,68 and 35,69 W test techniques as set out in the Technicon Auto-analyser methodology. Mixed liquor pH was measured with a Radiometer type 80 pH meter. Dissolved oxygen concentrations and oxygen utilization rates (OUR) were measured with a Yellow Springs Instrument Co. probe and meter connected to a Phillips chart recorder. The OUR's were measured in the aerobic reactors as follows: With the feed rate continuing as normal, the dissolved

Table 3.1: Parameters measured in influent, reactor and effluent samples.

Parameter	Samples			
	Unfiltered Influent	Unaerated reactor	Aerated reactor	Filtered effluent
COD	✓			✓
TKN	✓			✓
MLVSS		✓	✓	
Total phosphorus	✓	✓	✓	✓
OUR			✓	
pH		✓	✓	
NO_3		✓	✓	✓
DSVI			✓	

oxygen (D.O.) concentration in the reactor was raised from 2 to 6 mgO/ℓ. Aeration was then stopped and the chart recorder plotted the change in dissolved oxygen concentration with time. It is important to note that during the measurement of the OUR, stirring and feeding were maintained. Aeration was restarted when the dissolved oxygen concentration reached a lower level of 2 mgO/ℓ. The slope of the line plotted by the chart recorder provided the rate of oxygen consumption in mgO/ℓ/h. Under normal operation, the oxygen concentration in the aerobic reactors was maintained around 4 mgO/P.

Total phosphorus determinations only were made during the investigation. Orthophosphate determinations were not possible as the natural colour of the effluent from the Western Cape causes gross inaccuracies when using colorimetric methods. The total phosphorus test requires the conversion of all the phosphorus to the orthophosphate form whereupon, in this investigation, the concentration was measured by the molybdate vanadate technique. The technique for converting to orthophosphate and for removal of natural colour is described in detail in Appendix B.

Sludge settleability tests were conducted on the mixed liquor from the first aerobic reactor using the Diluted Sludge Volume Index test (DSVI) proposed by Stobbe (1964). In this test, the sludge is diluted such that the 30 minute settled volume (SV_{30}) is less than 200 mℓ in a 1ℓ cylinder. The DSVI is given by the SV_{30} divided by the diluted sludge concentration in the cylinder.

4.5 Control of sludge age

The sludge age was established by "hydraulic control". To maintain a specific sludge age, a fraction of the total reactor volume was wasted every day. When wasting, due cognisance was taken of the volume of mixed liquor already abstracted for testing. For example, for a 4 days sludge age, 1/4 of the total volume was wasted per day. Assume 1/8 of the total mixed liquor volume was removed for testing, then a further 1/8 of the mixed liquor volume had to be removed to maintain the sludge age at 4 days. Sludge was wasted only from the aerobic reactors. The sampling of the reactor contents took place at approximately 08h30 and the balance, to maintain the sludge age, was removed at about 15h30. The disadvantages of hydraulic control in short sludge age systems are discussed in Chapter 4, Section 2.4.1.

4.6 Cleaning

In laboratory-scale activated sludge plant operation, the surface/volume ratio is very large and particularly so at short sludge ages. It is important therefore that attached growth is continuously removed. At leat twice a day, the walls of the reactors were brushed to remove the adhering sludge. Periodically through the day, the interconnecting soft plastic tubing was squeezed to free the film of sludge that formed on the tube walls. Once every 2 days, the feed container and the feed line to the pump were thoroughly scrubbed and rinsed with hot water. At the same time, the effluent bucket was scrubbed and rinsed. Despite this cleaning procedure, some adhering growths developed on the reactor walls and brushing apparently did not dislodge them. After brushing, although the walls appeared to be clean, growths were visibly reestablished within an hour. To remove these growths, the reactors and tubing had to be washed in hot water and sodium hypochlorite every two weeks. During this operation, the sludge from the unit was stored in a plastic bucket and aerated. Before returning it to the unit, the sludge was sieved through a wire mesh to break up sludge lumps and to remove large solid objects.

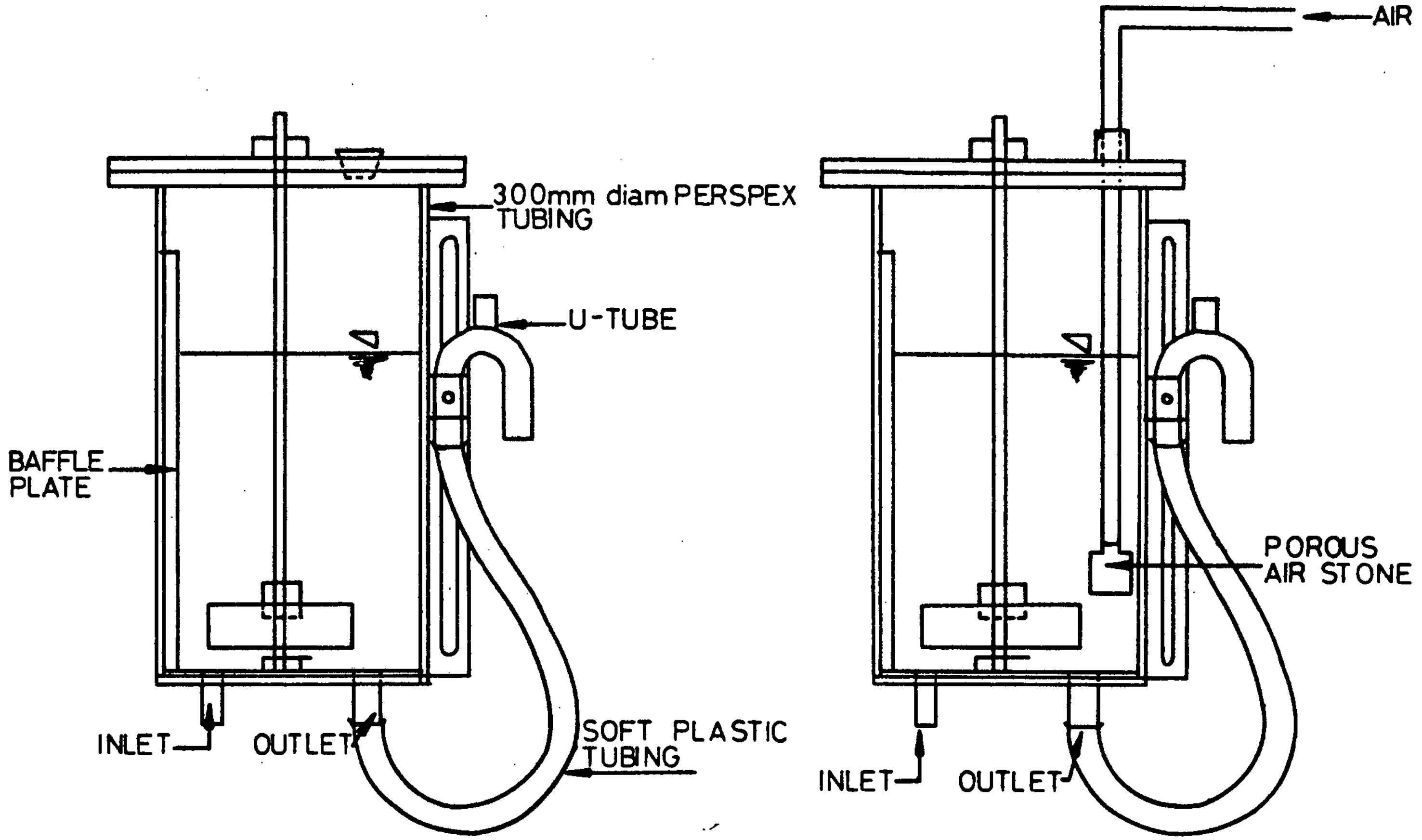


Fig 3.1: Details of the construction of the anaerobic/anoxic and aerobic reactors.

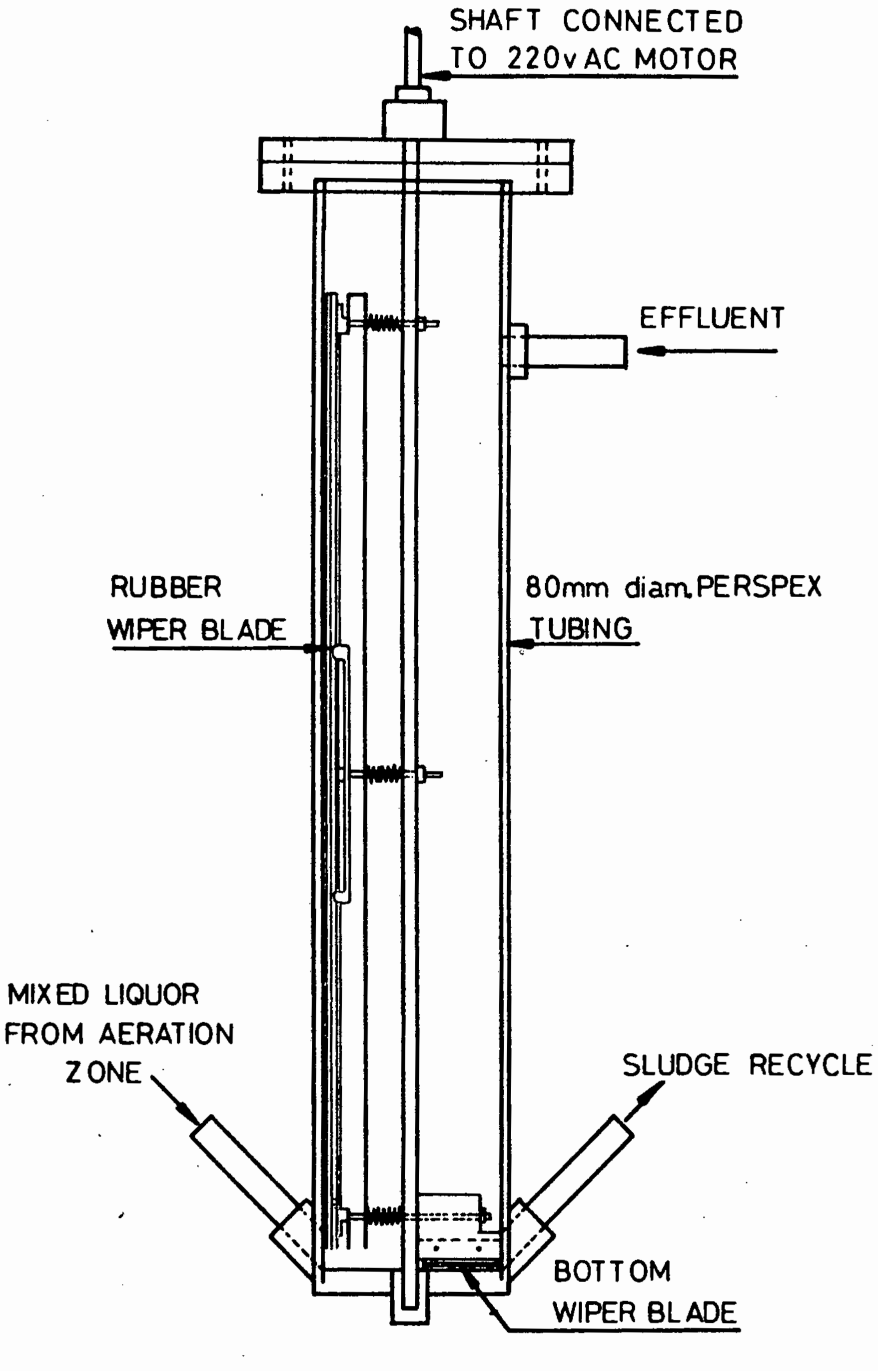


Fig 3.2: Details of the construction of the settling tank.

CHAPTER FOUR

SYSTEM INVESTIGATION AND ANALYSIS

1. INTRODUCTION

This chapter systematically describes the progress of each of the various experiments by firstly, discussing the choice of the system configuration, then describing the system response and any problems that came to light and finally, formulating conclusions from each particular experiment.

2. PHOREDOX SYSTEM AT FOUR DAY SLUDGE AGE

2.1 System Selection

The limited literature available on excess P removal at short sludge ages indicated that most research had been carried out on the Phoredox system (known in the USA as the A/O system). Accordingly, a "regular" Phoredox system was selected as the first configuration (see Fig 4.1).

The system sludge age was selected at 4 days with an anaerobic mass fraction of 0,5. With these two parameter selections, the expectation was that the 2 day "aerobic sludge age" would be less than the minimum sludge age for nitrification at 20°C ($R_{sm_{20}}$), i.e. nitrification would not occur. The 0,5 anaerobic mass fraction should provide sufficient anaerobic mass to break down the readily biodegradable COD to lower fatty acids which, in turn, would be sequestered by the polyP organisms.

A series configuration of reactors was selected for the following reasons; firstly, it would provide additional information on the kinetics of the various processes within the system, and secondly, the anaerobic zone, if subdivided in a series system of reactors, would improve the efficiency of conversion of readily biodegrdable COD (S_{bs}) to lower fatty acids, because this conversion takes place as a first order kinetic reaction with respect to the readily biodegradable COD (Wentzel *et al.*, 1984). Accordingly, a series of 2 unaerated (anaerobic) and 2 aerated reactors were set up, each reactor providing a liquid volume of 2ℓ, giving a total process volume of 8ℓ.

The concentration of MLVSS in the system was selected at about 2100 mgVSS/ℓ which, for the system volume of 8ℓ stated above, would give a total sludge mass of 16800 mgVSS. To provide this mass of VSS it is necessary to estimate the COD mass loading rate on the system. For this purpose, the characteristics of the wastewater have to be known. The wastewater used in the investigation was that from the satellite town of Mitchell's Plain (Cape Town) consisting virtually totally of domestic effluent. From past experience with this unsettled wastewater, the COD can be subdivided into the following fractions; approximately 8 percent unbiodegradable soluble COD (f_{us} = 0,08), 8 percent unbiodegradable particulate COD (f_{up} = 0,08), giving a biodegradable fraction of $(1-f_{us} - f_{up}) = 0,84$.

For the purpose of design, it is accepted that all the biodegradable COD is metabolised. Using the activated sludge theory under steady state operation by Marais and Ekama (1976), the mass of volatile solids (MX_v) is expressed as:

$$MX_v = MS_{ti}.R_s \left\{ \frac{(1-f_{us}-f_{up}).Y_h}{(1+b_h.R_s)} (1+f.b_h.R_s) + \frac{f_{up}}{f_{cv}} \right\} \qquad (4.1)$$

where MX_v = mass of VSS in the system (mgVSS)
MS_{ti} = mass of COD entering the system (mgCOD/d)
b_h = endogenous respiration rate (0,24/d)
Y_h = yield coefficient (0,45 mgVSS/mgCOD utilised)
f = endogenous residue (0,20 mgVSS/mgVSS)
f_{cv} = COD/VSS ratio (1,48 mgCOD/mgVSS)
R_s = sludge age (d)

Substitution for MX_v = 16800 mgVSS and R_s = 4 days and solving for MS_{ti} gives a COD mass loading rate of 14792 mgCOD/d. This calculated value was rounded off to 15000 mgCOD/d which should produce a VSS concentration of 2129 mgVSS/ℓ. The wastewater COD concentration was selected at 500 mgCOD/ℓ and hence a rate of 30 ℓ/d was required in order to produce the loading rate of 15000 mgCOD/d.

The underflow recycle ratio was selected at s = 1, i.e. a flow rate of 1:1 with respect to the feed flow rate. Theoretically, if the system does not nitrify, this ratio could have a range of values without influencing the excess P removal. Indeed, in some Phoredox plants, the s-recycle ratio has been as low as 0,15 (Hong *et al.*, 1982). However a higher ratio of s = 1 has the advantage that, with a poor settling sludge, it allows higher loads on the settling tank before failure of the tank or, from a different point of view, provides greater security against tank failure.

A schematic diagram of the Phoredox configuration is shown in Fig 4.1 and the specificiations for the system are presented in Table 4.1.

2.2 System Operation

Details of the daily operation, control and experimental procedures followed in running the system have been set out in Chapter 3.

The system was operated for 65 days from 6/2/85 to 14/4/85. After allowing 13 days for the system to stabilise, daily measurements of process parameters were taken for 51 days (18/2/85 to 10/4/85).

2.2.1 Influent characteristics

The measured influent characteristics, COD (S_{ti}), readily biodegradable COD (S_{bsi}), unfiltered TKN and total phosphorus over the experimental period are shown in Figs 4.2 to 4.5.

Over this period, 7 different batches of wastewater were fed to the sludge. Some of the wastewater characteristics, such as TKN/COD ratio, differed substantially from one batch to another so that it is not desirable to present mean influent characteristics over the entire period. The mean influent characteristics for each batch are presented separately in Table 4.2. These mean values are not calculated but estimated by visual investigation of the plots of the daily values.

2.3 System Response

Figures 4.2 to 4.22 show the measured responses of the various parameters in the reactors and the effluent, i.e. COD, soluble TKN, OUR, VSS, P, nitrate and DSVI. The detailed results for the system are tabulated in Appendix A.

(i) COD

A plot of the influent and effluent COD values is shown in Fig 4.2. The COD removal showed little fluctuation throughout the period of operation of the system despite the short aerobic sludge age. The influent COD, of approximately 500 mgCOD/ℓ, was reduced to an effluent value of approximately 50 mgCOD/ℓ, i.e. a 90 percent removal or 10 percent remaining.

(ii) Nitrogen behaviour

The TKN concentrations of the infuent and filtered effluent are plotted in Fig 4.4. The nitrate concentration in the effluent is plotted in Fig 4.6.

Initially the nitrate concentration in the effluent was zero, i.e. no nitrification occurred, but gradually during the course of the experiment nitrification developed (see Fig 4.6). Once nitrate was present, denitrification took place due to the recycle of the nitrified underflow (s-recycle) to the unaerated zone. With an s-recycle ratio of 1, the concentration of nitrate removed would be equal to that present in the effluent, provided the anaerobic reactors were not overloaded with nitrate, which they were not.

If one accepts that the nitrogen content of the volatile solids is 0,10 mgN/mgVSS, as suggested by the WRC (1984), the nitrogen removal through sludge wastage (N_s) should be

$$N_s = \frac{0,1.MX_v}{Q.R_s} = \frac{0,1.16800}{30.4}$$

$$\sim 14 \text{ mgN}/\ell \text{ influent}$$

This calculated nitrogen removal is very near the observed mean reduction in TKN (influent TKN - filtered effluent TKN) when no nitrification took place. When nitrification took place cognisance must be taken of the nitrification/denitrification effect as follows:

$$N_s = TKN_{in} - \left[TKN_{out} + 2\ NO_{3\,eff}\right]$$

where all values are in mgN/ℓ influent. During the periods of nitrification, the nitrate in the effluent was approximately 4 mgN/ℓ and, substituting this and the values of the TKN_{in} and TKN_{out} into the above equation, the nitrogen removal through sludge wastage is 13 mgN/ℓ influent which is close to the value when no nitrification took place.

(iii) Volatile Suspended Solids (VSS)

The VSS concentrations in the 4 reactors are plotted against time in Figs 4.7 to 4.10. The VSS's in all the reactors were stable over the period of operation. The VSS's in both the unaerated reactors were approximately 2000 mgVSS/ℓ, and in both the aerated reactors approximately 2200 mgVSS/ℓ. No further comment on the volatile solids will be made at this stage. The measure in which the concentrations correspond to those theoretically expected is considered in greater detail when discussing the applicability of the general activated sludge model to short sludge age anaerobic/anoxic-/aerobic systems in Chapter 5.

(iv) Oxygen Utilization Rate (OUR)

The plot of OUR versus time for the 2 aerated reactors, is presented in Fig 4.11.

In each reactor the OUR showed considerable fluctuation. Furthermore the fluctuations in the 2 reactors appeared to be in step. There was always a higher OUR in the first reactor than in the second. Although the magnitude of the OUR in the 2 reactors tended to show wide fluctuations, because these fluctuations tended to be in step, the difference in the rates between the two remained relatively stable.

(v) P release, uptake and removal

The concentrations of phosphorus in the effluent and the 4 reactors are plotted versus time in Figs 4.12 to 4.16. The plots of P release, uptake and removal are shown in Figs 4.17 to 4.21.

The excess P removal was initially erratic but after 29 days the fluctuations reduced considerably. Although the excess P removal changed from one batch of sewage to the next, it was consistent within each batch with average values of approximately 16 to 17 mg(PO_4-P)/ℓ influent removed in the sytem.

(vi) Settleability

The plot of Diluted Sludge Volume Index (DSVI) versus time is presented in Fig 4.22. The Phoredox system was started with sludge from a laboratory scale Modified UCT system operating at a 21 day sludge age with a DSVI of 168 mℓ/g. Over the first 30 days of operation, the DSVI decreased to between 65 and 80 mℓ/d and remained at this low level throughout the experimental period. Unfortunately, at the time these experiments were performed, the techniques for identifying and evaluating the filamentous organisms in the mixed liquor were not yet available so that no information can be given on the types of filaments present and their relative frequency of occurrence.

(vii) Running problems

The system presented few difficulties as regards maintenance. During the operation of the system, one particular batch of sewage caused the excess P removal to drop precipitously from 17 mg(PO_4-P)/ℓ to below 10 mg(PO_4-P)/ℓ. Similar reductions in P removal were observed in two long sludge age modified UCT systems, using the same sewage as influent; evidently the sewage batch contained some toxicity. As soon as this situation was identified, the batch was discarded for another batch, whereupon the systems recovered. The toxic agent in the sewage was not identified.

2.4 Analysis of Phoredox system at 4 days sludge age

2.4.1 Statistical Analysis

The experimental data obtained on the Phoredox system generally showed some dispersion. To obtain values representative of the average behaviour, it is necessary to analyse the data by some statistical procedure. In this investigation, a graphical procedure was adopted for the following reasons;

1. Possible outlyers, that is data points that appear to fall outside the group behaviour and probably arose from errors in the sampling or chemical analyses, can be identified visually and such suspect data then can be tested for rejection (Laubscher, undated).

2. Usually one expects the distribution of data to be approximately normal. The graphical statistical analysis procedure adopted gives a rapid visual assessment as to whether this is so or whether biomodial distributions have arisen due to some substantive change in the process

behaviour over the period of the investigation. Only if data approximates normality can the mean value have any significance. With normally distributed data, it is also possible to determine graphically the standard deviation and hence a confidence interval (at some selected probability, say 95 percent) for the mean, i.e. there is a 95 percent probability that the interval spans the true mean value. In the absence of normality, neither the mean nor the standard deviation can be determined graphically. In this event the best measure of central tendency is the median but a confidence interval for the median cannot be determined by the normal distribution theory.

The procedure for graphical analysis of the data is given in Appendix D.

For each set of data, the plots showed strong normal characteristics. Therefore, the mean values and the standard deviations for the means were determined from the statistical plot. This procedure was followed for every set of experiments in this investigation.

For the Phoredox system, the set of mean values and standard deviations for the various parameters are set out in Table 4.3. These values form the basic input data for any numerical process analysis.

2.4.2 Acceptability of data

Before analysing the behaviour of the system it is essential to establish if the data observed can be accepted with confidence. A powerful means for establishing acceptability is to perform mass balances on appropriate parameters. There are 2 mass balances significant to this work;

(i) Carbonaceous organic material (COD)
(ii) Nitrogenous material.

Mass balance equations to determine the COD and nitrogen recoveries were derived for a general nitrification/denitrification activated sludge system in Appendix E. The equations used in analysing the non-nitrifying Phoredox system are presented below.

Carbonaceous organic material

$$Q.S_{ti} = Q.S_{te} + f_{cv}.X_{v}.q + O_{t}.V_{aer} - 4{,}57.N_{ne}.Q - 0{,}71.\Delta N_{s}.Q$$

$$\Delta N_{s} = s.N_{ne} - (s+1).N_{nanox} \qquad (4.2)$$

where Q = average influent flow rate (ℓ/d)

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

S_{te} = total unfiltered effluent COD concentration (mgCOD/ℓ)

f_{cv} = COD:VSS ratio (mgCOD/mgVSS)

X_{v} = mixed liquor volatile suspended solids concentration in the reactor from which the waste sludge is removed (mgVSS/ℓ)

q = average waste sludge flow rate (ℓ/d)

O_{t} = observed oxygen consumption rate (mgO/ℓ/d)

V_{aer} = aerobic reactor volume (ℓ)

N_{ne} = effluent nitrate concentration ($mgNO_3$-N/ℓ)

ΔN_{s} = system nitrogen removal (mgN/ℓ influent)

s = underflow mixed liquor recycle ratio

N_{nanox} = anoxic reactor nitrate concentration (mgN/ℓ)

Nitrogenous material

$$Q.N_{ti} = Q.N_{te} + Q.N_{ne} + f_{n}.X_{v}.q + Q.\Delta N_{s} \qquad (4.3)$$

where N_{ti} = unfiltered TKN concentration in influent (mgN/ℓ)

N_{te} = unfiltered TKN concentration in effluent (mgN/ℓ)

f_{n} = nitrogen fraction of the sludge (mgN/mgVSS)

The concentration of nitrate in the anoxic reactor was not measured but, since the effluent nitrate concentration never exceeded 6 $mgNO_3$-N/ℓ during the experimental period, it could be safely assumed that all the nitrate recycled in the underflow to the unaerated zone would have been denitrified, i.e. in Eqs (4.2 and 4.3) we can assume the $N_{nanox} = 0$.

The data from Table 4.3 was inserted in the mass balance equations and the percentage COD and nitrogen recoveries were calculated. Assuming a COD:VSS ratio of 1,48 mgCOD/mgVSS and a N:VSS ratio of 0,1 mgN/mgVSS for the sludge, the data provided a COD recovery of 87 percent and a nitrogen recovery of 97 percent. The COD recovery is low; values of about 92 to 97 percent are more usual (WRC, 1984).

These higher recoveries were obtained on short and long sludge age aerobic systems and on long sludge age (10 to 20 days) anaerobic/anoxic/aerobic systems. No information on the short sludge age version of these systems was available. The low COD recoveries, coupled with the satisfactorily high nitrogen recoveries would indicate that either the COD test was not correctly performed or that factors causing electron losses were present that were not recognised previously due to possible small effects in long sludge age anaerobic/anoxic/aerobic systems. It is unlikely that the COD test was incorrectly performed because COD mass balances on long sludge age and aerobic systems done at the same time as the short sludge age investigation gave acceptable recoveries. A review of the factors that could have led to the low COD recovery therefore is presented.

(i) Filtered effluent sample

The effluent sample for COD, TKN and nitrate measurement was always filtered and therefore any particulate material carried over was not accounted for in the mass balance equation. Since the sludge settled very well and a limited amount of nitrification occurred, it is unlikely that the error due to filtering would have been significat.

(ii) Hydraulic control of sludge age

The sludge wastage procedure used in this investigation was the hydraulic control method. This entails the daily abstraction of a calculated volume of mixed liquor directly from the aerobic reactors. The daily volume of mixed liquor to be abstracted (q) for a selected sludge age (R_s) is given by

$$q = V_p/R_s$$

Thus, if say a sludge age of 10 days is required, one tenth of the volume must be wasted every day. Theoretically, the hydraulic method of sludge age control demands that the mass of sludge in the secondary settling tank is negligible with respect to that in the process reactors, that the draw-off takes place over 24 hours and, if the wastage is from a single reactor in a series of reactors, then the VSS concentrations in all the reactors must be the same. At short sludge ages, the assumption of negligible sludge mass in the settler is not always valid as the settler may contain up to 10 percent of the sludge in the system, particularly if the settling is poor. However, in this test, the sludge settleability was excellent so that this effect could not have been significant.

With regard to the wastage procedure, the sludge was not drawn off continuously but at two fixed times during the day. The reason for not practising continuous draw-off was that the waste flow rate would need to be slow and experience has shown that thickening of sludge in the draw-off pipe occurs. The liquid tends to filter through the sludge without the sludge itself being wasted, giving the correct volume drawn off, but an incorrect mass. To guard against this, the compromise wastage scheme was adopted in which the wastage draw-off was divided equally between 2 sessions during the working day, approximately 7 hours apart; no sludge wastage was practised at night. The sludge age/sludge concentration of the system then possibly followed the pattern shown in Fig 4.23. Clearly, the selected times for wasting were not well chosen as the wasting did not correspond with the times giving the theoretical mean behaviour.

Intermittent draw-off always gives rise to errors; these are negligibly small in long sludge age systems but may be significant in short sludge age plants. In the system tested here with a 4 day sludge age, 1/8 of the sludge mass was wasted per draw-off which would have induced an appreciable transient state in the periods between the draw-offs.

A more acceptable approach to sludge age control, when having to waste a large fraction of the sludge mass, is to draw off the waste mixed liquor at intervals of about 4 hours by automatic pump control, i.e. 6 draw-offs per daily cycle. Each draw-off should take place over a short period so that the pumping rate is high and filtration effects are minimised. The draw-offs can be set to give slightly less than the required total daily waste volume and the additional mixed liquor volume withdrawn once a day.

(iii) Conversion of glucose to acetate

The activated sludge biomass in an anaerobic/aerobic system contains acidogenic organisms. Under anaerobic conditions, these facultative anaerobes convert glucose and glucose-type material (readily biodegradable COD) to short chain fatty acids, say acetate, in order to meet their energy requirements. Assuming that the readily biodegradable COD consists of glucose, it is possible to calculate the COD loss during acidogenesis by conversion of H^+ to H_2 gas.

COD of 1 mole glucose

$C_6H_{12}O_6 + 6\ H_2O \rightarrow 6\ CO_2 + 24\ H^+ + 24\ e^-$

1 e^- equivalent ≡ 8 mgO_2

i.e. 24 e^- ≡ 192 mgO_2

i.e. 1 mole glucose ≡ 192 mgO_2

i.e. 180 mg glucose ≡ 192 mgO_2

COD of 1 mole acetate

$CH_3COOH + 2\ H_2O \rightarrow 2\ CO_2 + 8\ H^+ + 8\ e^-$

8 e^- ≡ 64 mgO_2

i.e. 1 mole acetate ≡ 64 mgO_2

i.e. 60 mg acetate ≡ 64 mgO_2

COD lost in conversion of glucose to acetate

1 mole glucose → 2 mole acetate

i.e. 192 mgO_2 → 128 mgO_2

The remainder of the COD is lost as H_2

$$\text{i.e. COD lost} = \left(\frac{192-128}{192}\right)100$$

$$= 33\% \text{ of original COD}$$

Assuming 20 percent of the total COD is in the readily biodegradable (glucose-type) form, the COD lost from the total influent COD, is determined as follows:

$$\begin{aligned} &\text{Let influent COD} &&= S_{ti} \\ \text{i.e.}\quad &\text{readily biodegradable COD} &&\approx 0{,}2.S_{ti} \\ \text{i.e.}\quad &\text{COD loss through acidogenesis} &&\approx 0{,}333\ (0{,}2.S_{ti}) \\ & &&\approx 0{,}067.S_{ti} \end{aligned}$$

Therefore approximately 7 percent of the total influent COD can be lost in the conversion of glucose to acetate.

The conversion of readily biodegradable COD to short chain fatty acids in the anaerobic zone cannot be measured directly in P removal plants; in the anaerobic zone, the poly-P organisms take up the lower fatty acids by releasing phosphate to the liquid medium, so that usually no fatty acids are detected in this zone. Indirectly however, one can conclude that lower fatty acids were generated by observing the P release in this zone - 1 mole of P is released for one mole of acetic acid taken up. In many waste flows and in particular the waste flow from Mitchell's Plain, the short chain fatty acids constitute only a minor fraction of the readily biodegradable COD in the influent. Consequently, if P release is observed this indicates that conversion of readily biodegradable COD to a lower fatty acid must have taken place in the anaerobic zone. Since a P release of between 50 and 60 mgP/ℓ was obtained in the system, considerable acidogenic action must have taken place with the concomitant loss of COD as hydrogen gas. A word of caution is necessary however with this hypothesis: if the glucose is converted to propionate instead of aacetate, there will be no COD loss as H_2 is not generated.

2.5 Discussion

The objective of this experiment was to determine if a biological excess P removal system could be operated successfully at such a short sludge age that nitrification would not take place. To accomplish this objective, a Phoredox system (see Fig 4.1) was operated at a total sludge age of 4 days with a 50 percent unaerated (anaerobic) zone, i.e. with a 2 day aerobic sludge age. Such a system was not expected to nitrify if the mean specific growth rate of the nitrifiers was less than about 0,4/day. The influent COD was set at 500 mgCOD/ℓ with a mean readily biodegradable COD concentration of approximately 100 mgCOD/ℓ.

The experimental results indicate that:

(i) At a 4 day system sludge age with 2 days aerobic sludge age and with the influent wastewater utilised, the system nitrified partially, that is the system operated very near the minimum sludge age for nitrification.

(ii) The settleability of the sludge in the system was excellent with DSVI values of approximately 70mℓ/g. This supports the observations of Timmerman (1979) who noted that good settleability was a feature with the non-nitrifying A/0 (Phoredox) system.

(iii) The COD removal of the system ($COD_{in} - COD_{out}$) was consistent at a value of approximately 90 percent, i.e. the filtered effluent was about 10 percent of the unfiltered influent.

(iv) No maintenance problems were encountered while running the system.

(v) Excess P removal of approximately 16 mgP/ℓ was obtained, giving a ΔP/influent COD ratio of about 0,032 mgP/mgCOD. Compared with long sludge age UCT systems operating on the same influent, the removal achieved by the Phoredox system was about 50 percent higher.

(vi) The COD recovery of 87 percent was a most unsatisfactory aspect. One of the causes was attributed to electron (COD) loss in the formation of hydrogen gas during acidogenesis in the anaerobic reactor.

At a 4 day sludge age, despite the partial nitrification, the system gave such excellent P removal with good settleability and ease of operation, that it seemed worthwhile to investigate the system at sludge ages even shorter than 4 days in an effort to ensure no nitrification while maintaining the system's advantageous properties.

3. PHOREDOX SYSTEM AT 3 DAY SLUDGE AGE

3.1 System selection

The Phoredox system described in Section 2 was operated at a 4 days sludge age and at 20°C with the expectation that the sludge would not nitrify. Although there were periods of no nitrification, there were also periods when the system nitrified partially, i.e. the 2 day aerobic sludge age must have been very close to the minimum sludge age for nitrification. Since the objective of the project was to investigate excess P removal in short sludge age systems in the absence of nitrification, it was decided to reduce the system sludge age to 3 days (by changing the sludge wasting rate) in an effort to eliminate nitrification completely. For the sake of comparison, all other process parameters were left unchanged so that theconfiguration was the same as that presented in Fig 4.1. The detailed system specifications are tabulated in Table 4.4.

3.2 System operation

The system was operated for 72 days from 16/4/85 to 26/6/85. After allowing 8 days for the system to stabilise, daily measurements of process parameters were taken for 64 days (24/4/85 to 26/6/85). Details of the daily operation, control and experimental procedures followed in running the system have been set out in Chapter 3.

3.2.1 Influent characteristics

The measured influent characteristics, COD (S_{ti}), readily biodegradable COD (S_{bsi}), unfiltered TKN and total phosphorus over the experimental period are shown in Figs 4.24 to 4.27. Over this period, 6 different batches of wastewater were fed to the sludge. The mean influent charcteristics are presented separately for each batch in Table 4.5. These mean values were not calculated but estimated visually from the plots of the daily values.

3.3 System response

Figures 4.24 to 4.44 show the measured responses of the various parameters in the reactors and the effluent, i.e. COD, soluble TKN, OUR, VSS, P, nitrate and DSVI.

(i) COD

A plot of the influent and filtered effluent COD values is presented in Fig 4.24. The COD removal, based on the filtered effluent, showed little fluctuation throughout the period of operation of the system despite the short aerobic sludge age. The influent COD, of approximately 500 mgCOD/ℓ, was reduced to an effluent value of approximately 70 mgCOD/ℓ, i.e. 86 percent removal, or 14 percent remaining. The effluent was very turbid but unfortunately no COD values were determined for the unfiltered effluent.

(ii) Nitrogen behaviour

The TKN concentrations of the influent and filtered effluent are plotted in Fig 4.26. The nitrate concentration in the effluent is plotted in Fig 4.28.

Theoretically, accepting that the nitrogen content of the volatile solids is 0,10 mgN/mgVSS and using the experimentally observed volatile suspended solids concentration, the TKN reduction through sludge wastage should be about 13 mgN/ℓ influent.

The plot of effluent nitrate concentration (Fig 4.28) indicates that the system nitrification decreased to a reasonably consistent level after 28 days of operation (this includes the 8 day stabilisation period when no readings were taken). The concentration of nitrate in the effluent after the 28 days varied between 1 and 3 mgNO_3-N/ℓ which indicates that very little nitrification took place. This suggests that the system was operating virtually at the minimum sludge age for nitrification at 20°C ($R_{sm_{20}}$). If the 1,5 days aerobic sludge age was shorter than $R_{sm_{20}}$, then 99.9% of the nitrifiers should have been washed out within 3 sludge ages, i.e. 9 days. Since the nitrate concentration took more than three times this period to decline to its lowest value, the system sludge age must have been very close to $R_{sm_{20}}$.

(iii) Volatile Suspended Solids (VSS)

The VSS concentrations in the 4 reactors are plotted against time in Figs 4.29 to 4.32. The VSS in reactors 1, 3 and 4 showed a slow downward trend and by the time the system was closed down, the VSS's in all the reactors were approximately the same at 1300 mgVSS/ℓ.

(iv) Oxygen Utilisation Rate (OUR)

The plot of OUR versus time for the 2 aerated reactors is presented in Fig 4.33. The values in the 2 reactors were stable throughout the period of operation of the system, with the OUR in the first aerobic reactor always higher than that in the second aerobic reactor.

(v) P release, uptake and removal

The concentration of phosphorus in the effluent and the 4 reactors is plotted versus time in Figs 4.34 to 4.38. The plots of P release, uptake and removal are presented in Figs 4.39 to 4.43.

The excess P removal suffered an early setback when toxic sewage was fed to the system from day 9 to day 14 causing the removal to drop below 10 mgP/ℓ. Thereafter the removal attained a high level of between 13 and 17 mgP/ℓ, each sewage batch giving a slightly different removal.

(vi) Settleability

The settleability of the sludge in the 3 day sludge age system is shown as a plot of DSVI versus time in Fig 4.44. The DSVI tended to be unstable and was generally higher than the values found during the 4 day sludge age experiment (*cf.* Fig 4.22 and Fig 4.44). The DSVI never exceeded 170 mℓ/g but, for long periods, it was virtually impossible to take readings in the DSVI test because the turbidity of the supernatant was so high that the upper surface of the settling sludge could not be monitored closely. A microscope study of the sludge revealed the following microorganism populations present:

Thiothrix II - abundant
Thiothrix I - very common
S.natans - common
Type 0092 - some
Type 0914 - some

Thiothrix is usually associated with hydrogen sulphide in the sewage (Jenkins, Richard and Daigger, 1984); all the other activated sludge units in the laboratory showed similar bulking problems during this period of operation, suggesting that the cause of the poor settling lay with the batches of sewage rather than the system configuration.

(vii) Running problems

Throughout its operation, the 3 day sludge age Phoredox system provided problems with maintenance. The following difficulties were encountered;

(1) Pipes connecting reactors became blocked overnight and the sludge overflowed. This sludge was collected in overflow trays and replaced the following morning but of course the steady state of the unit was disturbed.

(2) Even when the pipes did not block, sludge tended to stick to the pipe surfaces and the mixed liquor was filtered through the sludge. Smaller diameter pipes were used to increase the flow velocity in the pipes but no substantial improvement was observed.

(3) The turbidity of the effluent and the poor settleability in the settling tank caused sludge to be carried over into the effluent bucket. Each day this sludge was returned to the reactors but this, in itself, created an uncertainty as to the exact mass that was withdrawn daily, i.e. there was a measure of uncertainty with regard to the actual sludge age.

3.4 Analysis of Phoredox system at 3 days sludge age

3.4.1 Statistical analysis

The experimental data obtained from the 3 day sludge age Phoredox system was analysed by the statistical procedure set out in Appendix D; the means and the associated standard deviations for the means are listed in Table 4.6. These values form the basic input data for all the numerical analyses of the system such as mass balances, P removal, etc..

3.4.2 Acceptability of data

The statistically determined mean values in Table 4.6 were used in the mass balance equations (Eqs. 4.2 and 4.3) to calculate the percentage COD and nitrogen recoveries. Assuming a COD:VSS ratio of 1,48 mgCOD/mgVSS and a N:VSS ratio of 0,1 mgN/mgVSS for the sludge, the data provided a COD recovery of 81 percent and a nitrogen recovery of 96 percent. As with the Phoredox system at a 4 day sludge age, the COD recovery was low. The factors discussed in Section 2.4.2 again could have been totally, or partially, responsible for the low recovery.

3.5 Discussion

The objective in this experimental series was to determine if the biological excess P removal Phoredox system could be operated successfully in the absence of nitrification. In the first experiment, a Phoredox system operated at a 4 day sludge age (2 day aerobic sludge age) had nitrified intermittently. Therefore, to accomplish the objective of no nitrification, the sludge age was reduced to 3 days and an anaerobic mass fraction of 0,5 was retained as before, i.e. the aerobic sludge age was reduced from 2 days to 1,5 days. The influent COD remained at 500 mgCOD/ℓ with a mean readily biodegradable COD concentration of approximately 100 mgCOD/ℓ.

The experimental results indicate the following:

(i) With the influent wastewater utilised, the system nitrification decreased gradually until an effluent nitrate concentration of between 1 and 3 mgN/ℓ was obtained. The slow decrease in nitrification indicates that the system was operating close to the minimum sludge age for nitrification at 20°C.

(ii) The settleability of the sludge was poor (DSVI ~ 150mℓ/g) due to the dominant presence of the filamentous organism *Thiothrix* and the minor presence of *S.natans*. The dominance of the *Thiothrix* is related virtually totally to the presence of high sulphide concentrations in the wastewater and cannot be ascribed to the system configuration.

(iii) The COD removal of the system, based on the unfiltered influent and filtered effluent, was consistent at a value of approximately 86 percent, i.e. 14 percent of the influent COD appeared in the filtered effluent. This percentage is significantly higher than that measured in the same system operated at a 4 day sludge age, viz. 10 percent. Furthermore, the unfiltered effluent was very turbid (unfortunately the COD was not measured). This latter observation would make the system entirely unsuitable as a final treatment facility, but adequate as a pretreatment one, provided of course, the settleability could be improved.

(iv) The system, as operated at laboratory scale, proved extremely difficult to maintain at steady state due to the sludge characteristics - the sludge settled poorly, often caused blockages in the connecting tubes and, by sticking to the tube walls, tended to filter out some of the mixed liquor from one reactor to another. The last effect is a problem peculiar to the laboratory scale at which the system was operated; it would not be a problem on large scale plants.

(v) The system produced excellent excess P removal of approximately 15 mgP/ℓ. The ΔP/influent COD ratio of 15/500 = 0,03 was much higher than that normally obtained on 20 day sludge age Bardenpho and UCT systems treating this wastewater, i.e. ΔP/influent COD = 0,02.

It was noted above that, when the experiment was terminated, the effluent nitrate concentration was between 1 and 3 mgN/ℓ. This suggests that the objective of operating a P removal system, in the absence of nitrification, had been achieved. However, on reducing the sludge age to 3 days (from 4 days in the previous experiment) it required 28 days before nitrification finally ceased, i.e. the system was still being operated very near the minimum sludge age for nitrification. For this wastewater, the aerobic sludge age in fact needed to be less than 1,5 days to ensure non-nitrifying conditions - it would indicate a maximum specific nitrifier growth rate of about 0,65/day. This rate is unusually high but it does indicate that, if a non-nitrifying Phoredox plant is contemplated, some experimental data on the nitrification rate should be obtained to establish the maximum aerobic sludge age that will not give rise to nitrification at the highest expected operating temperature. If the plant should nitrify, the biological excess P removal, which is sensitive to nitrate in the recycle stream, could be sharply lowered and the very objective for having a Phoredox system would be negated.

From the discussion above, it seems that, depending on the wastewater, it may not be practical to operate a stable Phoredox system at such a short sludge age that nitrification does not occur. It would seem more practical to design a system such that, should nitrification occur either continuously or at intervals, it would not fail in its P removal function.

4. PHOREDOX SYSTEM AT 3 DAY SLUDGE AGE - A REPEAT INVESTIGATION

During the short sludge age investigation in 1985, a Phoredox system was operated at a sludge age of 3 days (see Section 3). The laboratory-scale system provided excellent excess P removal but proved to be very difficult to maintain due to blockages of the tubes and poor settleability. The cause of the poor settleability was ascribed to the dominant presence of *Thiothrix*, with *S.natans* present as a minor filamentous organism. *Thiothrix* usually proliferates only when sulphide is present in the influent so that, in the experiment it was not certain whether improved settleability would have been obtained if the influent wastewater were free of sulphides. At the beginning of 1986, it was decided to repeat the 3 day sludge age experiments, to monitor the sulphide in the influent and, should it be present, to remove it prior to feeding the unit. Accordingly, the system was set up exactly as that for the previous 3 day sludge age Phoredox system (see Section 3), except that the influent flow was reduced from 30 to 25 ℓ/d in order to provide greater security against failure of the settling tank, should poor settleability again be encountered. The configuration is shown in Fig 4.1 and the system specifications are presented in Table 4.7.

4.1 System operation

The system was seeded with sludge from a Modified UCT system operated at a 21 day sludge age. After allowing 4 days for the system to stabilise, daily readings were taken for 23 days from 20/1/86 to 13/2/86. From commencement of the study, the settling properties deteriorated and, after 23 days, had deteriorated to such an extent that the sludge had to be discarded. Replacement sludge was again obtained from the 21 day sludge age Modified UCT system and the system was run for 12 days before testing recommenced. Thereafter, measurements were taken for 37 days. The settleability again deteriorated but not to the same degree as before.

Details of the daily operation, control and experimental procedures have been set out in Chapter 3.

4.1.1 Influent characteristics

The measured influent characteristics, COD (S_{ti}), readily biodegradable COD (S_{bsi}), unfiltered TKN and total phosphorus over the experimental period are shown in Figs 4.45 to 4.48.

Over this period, 7 different batches of wastewater were fed to the system; the mean influent characteristics are listed separately for each batch in Table 4.8. These mean values were not calculated but estimated visually from the plots of the daily values. It should be noted that during the initial period, up to 27 days, no measurements of S_{bsi} were taken due to a problem with the oxygen probes. Consequently, it is not possible to analyse effectively the data for the first 27 days.

4.2 System response

Figures 4.45 to 4.69 show the measured responses of the various parameters in the reactors and the effluent, i.e. COD, soluble TKN, OUR, VSS, P, nitrate and DSVI.

A plot of unfiltered influent and filtered effluent COD values is shown in Fig 4.45. The COD removal based on the filtered effluent COD showed little fluctuation throughout the period of operation of the system. The influent COD, of approximately 500 mgCOD/ℓ, was reduced to a filtered effluent value of approximately 70 mgCOD/ℓ, i.e. 86 percent removal, 14 percent remaining. This reduction was the same as that obtained with the previous 3 day sludge age Phoredox system. As in the previous 3 day sludge age Phoredox system, the unfiltered effluent was very turbid so that particulate COD escaped with the effluent.

The TKN concentrations of the influent and filtered effluent are plotted in Fig 4.47. The nitrate concentrations in the reactors and the effluent are plotted in Figs 4.49 to 4.53.

It is clear from the nitrate concentrations in the aerobic units over the first 20 days of monitoring that the aerobic sludge age was insufficient to cause nitrification. After the system was innoculated with the new sludge, nitrification occurred. The nitrate concentration in the effluent fluctuated between about 6 and 13 mgN/ℓ. During this period of nitrification, the measured readily biodegradable COD concentration was above normal, i.e. approximately 120 mgCOD/ℓ as against the more usual 100 mgCOD/ℓ for this wastewater. Thus, despite the rather high nitrate recycled to the anaerobic reactor, the excess P removal was about 10 mgP/ℓ. The removal in the previous 3 days sludge age investigation averaged about 15 mgP/ℓ but, in that investigation, the effluent nitrate concentration ranged from 1 to 3 mgN/ℓ. Taking the high nitrate concentrations in the present investigation into account, it would appear that the P removal was consistent with that in the previous 3 day sludge age test. The P removal per influent COD was $\Delta P/COD = 10/500 = 0,02$ mgP/mgCOD. This aspect is discussed in greater detail in Chapter 5.

With regard to the volatile suspended solids (VSS) concentrations (see Figs 4.54 to 4.57), the VSS's in all the reactors decreased for the first 5 days of monitoring. Thereafter, the values stabilised and remained steady for 35 days before dropping sharply. No reason could be found for this drop in VSS.

The plot of OUR versus time for the 2 aerated reactors is presented in Fig 4.58. From the limited number of OUR determinations, the OUR in the 2 reactors appeared to be stable with the OUR in the first aerobic reactor always being higher than that in the second. Again, these behavioural characteristics were close to those observed in the first 3 days sludge age investigation.

The settleability of the sludge is shown as a plot of Diluted Sludge Volume Index (DSVI) versus time in Fig 4.69. The settling deteriorated from a DSVI of 120 mℓ/g to 240 mℓ/g within 20 days and it was no longer possible to contain the sludge in the settling tank. A microscope study revealed the principal cause for the poor settling to be a dominant growth of the filamentous organism *S.natans*. After the sludge was replaced, the DSVI again rapidly increased from an initial DSVI of 80 mℓ/g to about 140 mℓ/g but thereafter remained stable around this value. *S.natans* was again the organism causing the poor settling but now it did not attain such high concentrations as in the first phase of the test.

Whilst cleaning the system, large jelly-like deposits were noticed on the walls, stirrers and airstones in the aerobic reactors. Although they did not appear to influence the process behaviour, on occasions they caused the airstones to become blocked, thereby reducing the dissolved oxygen concentration in the aerobic reactors from the normal 4 mgO/ℓ to about 2 mgO/ℓ. *S.natans* has been implicated as a short sludge age, low dissolved oxygen filament. The periodic decline in dissolved oxygen concentration may have been sufficient to create conditions favourable to the growth of *S.natans*.

4.3 Analysis of Phoredox system at 3 day sludge age - repeat investigation

The experimental data obtained for the repeat investigation was analysed by the graphical statistical procedure set out in Appendix D. The set of mean values and their standard deviations, for the period in which OUR and S_{bsi} readings were taken, is presented in Table 4.9.

The statistically determined mean values were used in the mass balance equations, derived in Appendix E, to calculate the percentage COD and nitrogen recoveries. Assuming a COD:VSS ratio of 1,48 mgCOD/mgVSS and a N:VSS ratio of 0,1 mgN/mgVSS for the sludge, the data provided a COD recovery of 86 percent and a nitrogen recovery of 109 percent. The factors discussed in Section 2.4.2 again could have been partially responsible for the low COD recovery. In addition, the generation of the slime observed in the aerobic reactors could have had an effect on the COD balance. It is generally accepted that, in systems with a high ratio of carbonaceous substrate to organisms and/or a nutrient deficiency, the substrate uptake rate exceeds the rate of metabolism. The excess substrate bypasses the energy yielding reactions and is secreted as an extracellular polymer, usually a polysaccharide. This polysaccharide is, to all intents and purposes, unbiodegradable. The generation of polysaccharides could have led to low COD recoveries because the polysaccharide slime that adhered to the paddles and aeration stones in the aerobic reactors was removed outside the reactors. Consequently the contribution of these masses to the COD was not included in the VSS measurement. In retrospect, the slime removal procedure was wrong because the amount of COD lost from the system through slime formation was unknown.

4.4 Conclusions

If the results of both 3 day sludge age Phoredox system investigations are analysed together, the following conclusions appear to be merited.

1. It is possible to obtain nitrification in these systems at system sludge ages as low as 3 days with a 50 percent unaerated mass fraction.

2. By comparing the P removal performance of the first and second 3 day sludge age Phoredox systems it is evident that the first system did not nitrify and an average P removal of about 15 mgP/ℓ was obtained whereas with the second system which did nitrify, the P removal fell to about 10 mgP/ℓ. This does not constitute proof of the detrimental effect of nitrate discharge to the anaerobic reactor but it is consistent with this hypothesis.

3. The settling of the sludge can be poor due to the growth of the filamentous organism *S.natans*.

4. Jelly-like, extracellular material can be generated in the aerobic zone, probably due to some imbalance between substrate and nutrient supply internal to the organism.

5. The effluent from the system is turbid and will not be suitable for discharge to the environment, even if no limitation is placed on TKN concentration.

6. The filtered effluent COD is higher than that of a UCT system treating the same influent at a sludge age of 21 days (14 percent versus 6 percent of the influent COD).

5. SPLIT-FEED SYSTEM

5.1 System selection

The data obtained from the two investigations into the 3 day sludge age Phoredox system indicated that the configuration had the potential to remove a large amount of phosphate 0,02 to 0,03 mgP per mgCOD in the influent. However, the system also appeared to have the potential for generating the filamentous organism *S.natans*, which causes severe bulking.

The bulking potential of a Phoredox configuration is an important factor in any proposal for using this system in full scale design. Some attention therefore was given to possible changes in the system configuration that might reduce this problem.

Ekama and Marais (1985) found that, in long sludge age Bardenpho plants, if a selector was installed ahead of the main aeration reactor and a fraction of the influent feed was discharged to the selector, the growth rate of the heterotrophs was increased. This, they concluded, allowed the heterotrophic organisms to gain a selective growth advantage over the filamentous organisms, causing the filament concentration to diminish substantially. The filamentous organisms in long sludge age plants are principally type 0092 and *M.parvicella*, organisms not observed in short sludge age plants. Nevertheless, it was hypothesized that, if a selector should be installed in a Phoredox system and the feed split between the anaerobic reactor and the selector, conditions might develop that reduce the concentration of *S.natans*. From the work of Ekama and Marais, a selector reactor volume of about 4 percent of the system volume was indicated, i.e. a selector volume of 350 mℓ.

The Split-feed operational mode was applied initially by discharging a fraction of the influent feed to the first aerobic reactor, see Fig 4.70, that is, a selector was not yet introduced. In order to maintain a high level of excess P removal, the larger fraction of the wastewater (2/3) was fed to the first anaerobic reactor with the remainder (1/3) fed to the first aerobic reactor. The actual ratio of 2/3 : 1/3 was chosen because of the pumping facilities available.

All other process parameters were left unchanged from the 3 day sludge age Phoredox system described in Section 4. The specifications are presented in Table 4.10.

The system was operated for 12 days. After allowing 1 day for the system to stabilise, daily measurements of process parameters were taken for 11 days. On the last day of the period, an aerobic batch test was carried out to determine the maximum specific growth rates of the heterotrophs and the nitrifiers. Also on the twelfth day the selector reactor was introduced into the system as shown in Fig 4.71. The specifications for this modified system are presented in brackets in Table 4.10. Daily process parameter readings were taken for a further 8 days. Another aerobic batch test was performed on day 20 when the experiment was terminated.

5.2 System operation

5.2.1 Influent characteristics

The measured influent characteristics, COD (S_{ti}), readily biodegradable COD (S_{bsi}), unfiltered TKN (N_{ti}) and total phosphorus over the experimental period are shown in Figs 4.72 to 4.75.

Over this period, 3 different batches of wastewater were fed to the sludge. The mean influent characteristics are presented separately for each batch in Table 4.11. The mean values were not calculated but estimated visually from the plots of the daily values.

5.3 System response

Figures 4.72 to 4.96 show the measured responses of the various parameters in the reactors and the effluent, i.e. COD, soluble TKN, OUR, VSS, P, nitrate and DSVI.

(i) COD

The influent and effluent COD values, presented in Fig 4.72, showed little fluctuation throughout the period of operation of the system. The influent COD, of approximately 500 mgCOD/ℓ, was reduced to an effluent value of approximately 60 mgCOD/ℓ, i.e. an 88 percent removal, or alternatively, 12 percent of the influent COD appeared in the filtered effluent.

(ii) Nitrogen behaviour

The TKN concentrations of the influent and filtered effluent are plotted in Fig 4.74. The nitrate concentrations in the reactors and the effluent are plotted in Figs 4.76 to 4.80.

The TKN and nitrate data indicated that partial nitrification took place throughout the period of steady state and that the incorporation of the selector reactor increased the amount of nitrification. The selector reactor increased the aerobic mass fraction and therefore the increase in nitrification was not unexpected. Nitrification was, however, never complete indicating that the system was operating slightly above the minimum sludge age for nitrification at 20°C.

(iii) Volatile Suspended Solids (VSS)

The VSS concentratios in the 4 reactors are plotted against time in Figs 4.81 to 4.84. The VSS's in all the reactors were stable over the period of operation and unaffected by the introduction of the selector reactor. The increase in the volume of the system due to the introduction of the selector would have had a marginal effect only as the selector volume was only 5 percent of the original volume.

(iv) Oxygen Utilisation Rate (OUR)

The plot of OUR versus time for the 2 aerated reactors is presented in Fig 4.85. Before the introduction of the selector, the OUR in the first aerobic reactor was always higher than that in the second. After the introduction of the selector, the OUR's in the two aerobic reactors were very nearly the same but lower than before the selector introduction. This difference in behaviour was due to nitrification effects: before the selector was introduced, nitrification occurred principally in the first of the two aerated reactors; after the selector was introduced, a large fraction of the nitrification occurred in the selector. The OUR's in the two aerobic reactors were now controlled largely by the rate of hydrolysis of the particulate COD, a relatively slow reaction, so that the stored COD, and hence the OUR's also, remained substantially the same in both reactors.

(v) P release, uptake and removal

The concentration of phosphorus in the effluent and the 4 reactors is plotted versus time in Figs 4.86 to 4.90. The plots of P release, uptake and removal are presented in Figs 4.91 to 4.95.

The excess P removal was approximately 9 mgP/ℓ during the period without the selector and reduced to about 6 mgP/ℓ after the selector was incorporated. The lower P removal probably was due to the increased nitrification which resulted in a higher concentration of nitrate being recycled to the anaerobic zone. The decrease in P release in the first anaerobic reactor (Fig 4.91) supports this hypothesis.

Comparing the P removal of the 3 day sludge age Split-feed system with that in the 3 day sludge age Phoredox systems (Sections 3 and 4), the mean removal of the Split-feed system ranged from 6 to 9 mgP/ℓ and that of the Phoredox systems ranged from 9 to 15 mgP/ℓ. The generally higher removals in the Phoredox system can be ascribed to the total influent flow being directed to the anaerobic reactor; in the Split-feed system, 2/3 of the influent was directed to the anerobic reactor so that the P removal could be expected to be two-thirds lower, i.e. reduced from 9-15 mgP/ℓ to 6-12 mgP/ℓ. It would seem therefore that, from a P removal point of view, the split-feed mode of operation is not to be recommended in nutrient removal plants at short sludge ages.

(vi) Settleability

The settleability of the sludge is shown as a plot of Diluted Sludge Volume Index (DSVI) versus time in Fig 4.96.

During the running of the Phoredox system prior to splitting the feed, a slow increase in the DSVI of the sludge was observed. A microscope study revealed an abundance of the filamentous organism *S.natans*. The known causes of this organism are firstly, a low dissolved oxygen concentration in the aeration basin and secondly, a nutrient deficiency. The organism has clinging properties which allows it to attach itself to the inside of pipes and reactors and therefore it can thrive in areas providing favourable conditions such as dirty feed lines and dirty reactor surfaces. However, extreme care was taken to prevent these conditions - the feed lines were cleaned with hot water daily and any clinging sludge was removed by stretching the pipe around a tap handle; the feed bucket was scrubbed and rinsed with hot water daily; the reactor walls were brushed frequently during the day, and stirring paddles were cleaned every second day.

At the time the feed was split, the DSVI of the sludge was approximately 165 mℓ/g. Thereafter operating the system for 19 days, the DSVI increased to 540 mℓ/g (see Fig 4.96). The selector reactor was then introduced between the anaerobic and aerobic sections (see Fig 4.71). After the introduction of the selector, the settleability continued to deteriorate and within 9 days, the DSVI of the sludge had reached 688 mℓ/g and the system was aborted.

In order to determine whether the introduction of the selector did influence the maximum specific growth rates of the heterotrophs and the nitrifiers ($\hat{\mu}_H$ and $\hat{\mu}_N$), these parameters were measured the day before the selector was introduced into the system and 9 days later. The procedure used to determine the maximum specific growth rates was that proposed by Ekama,Dold and Marais (1986). The detailed results and calculations are presented in Appendix C.

Contrary to expectation, $\hat{\mu}_H$ decreased after introducing the selector which, if Ekama and Marais' findings were applicable to short sludge age systems, would indicate a greater propensity for bulking.

(vii) Running problems

Throughout its operation, the Split-feed system provided problems with maintenance. The clinging properties of *S.natans* resulted in large deposits of sludge adhering to the sides of reactors and the walls of the interconnecting pipes. This necessitated vigorous and regular brushing and cleaning. The presence of the filamentous organisms also resulted in a carry-over of sludge into the effluent bucket. This sludge was returned to the reactors daily but it created an uncertainty as to the exact mass that was wasted, i.e. a measure of uncertainty with regard to the actual sludge age.

Large polysaccharide deposits were observed on the stirrers, walls and airstones in the aerobic reactors. Although apparently not influencing the behaviour of the system, these deposits required regular cleaning.

Lumps of red worms were observed in the aerobic reactors but they were not present in sufficient quantities to cause blocking in the pipes.

5.4 Analysis of Split-Feed system

5.4.1 Statistical analysis

The experimental data obtained from the Split-feed system was analysed by the statistical procedure outlined in Appendix D. The plots showed strong normal characteristics for all process parameters. The set of mean values and the standard deviations for the various parameters are presented separately for the two configurations (with and without the selector) in Tables 4.13 and 4.14.

5.4.2 Acceptability of data

The statistically determined mean values for the Split-feed system without the selector (Table 4.13) were used in the mass balance equations derived in Appendix E. Assuming a COD:VSS ratio of 1,48 mgCOD/mgVSS and a N:VSS ratio of 0,1 mgN/mgVSS for the sludge, the data provided a COD recovery of 78 percent and a nitrogen recovery of 92 percent. As with all the short sludge age systems investigated, the COD recovery is low. The factors discussed in Section 2.4.2, as well as the generation of slime discussed in Section 4.3, could have been responsible for the poor COD mass balance.

A mass balance could not be performed on the system incorporating the selector because OUR measurements were not taken in that reactor.

5.5 Discussion

The objective of this experiment was to determine whether introducing a selector and splitting the feed between the anaerobic and the aerobic zones would inhibit the growth of the filamentous organism *S.natans* in the Phoredox system. In order to achieve this objective, a Phoredox system was operated with a 3 day sludge age (1,62 day aerobic sludge age) with 2/3 of the feed directed into the first anaerobic reactor and the remainder into the first aerobic reactor. After 12 days of operation, a selector was introduced between the last anaerobic reactor and the first aerobic reactor and the feed previously directed into the aerobic zone was fed into the selector.

The response of the system prior to the introduction of the selector makes it clear that splitting the feed does not inhibit the growth of *S.natans* but, rather, favours it. Within 12 days of operation, the DSVI of the sludge rose from about 165 mℓ/g to about 540 mℓ/g due to the rapid growth of *S.natans*. The behaviour of the system after the introduction of the selector indicates that the selector did not inhibit the growth of *S.natans*. The DSVI of the sludge continued to rise at the same rapid rate as observed prior to the incorporation of the selector.

With the poorer P removal relative to the Phoredox systems and the greatly increased bulking tendency observed, it would appear that the split feed operation of the Phoredox system at low sludge ages is not to be recommended.

6. 3-STAGE BARDENPHO SYSTEM

6.1 System selection

In Sections 2, 3 and 4 a detailed account was presented of the behaviour of Phoredox systems with 50 percent unaerated mass fractions operated at 3 and 4 day sludge ages. The principal findings were that, at the operating temperature of 20°C, the 4 day system nitrified partially and the 3 day system intermittently; the 4 day system gave a good settling sludge, clear effluent and a filtered effluent COD a little above that observed in long sludge age plants treating the same effluent whereas the 3 day sludge age systems gave bulking sludges, turbid effluents and filtered COD's about 50 percent higher than those from long sludge age systems. With regard to P removal, both the 4 and 3 day sludge age systems gave biological excess P removals significantly higher than those observed in long sludge age units, $\Delta P/\Delta COD$ = 0,025 to 0,03 as against 0,015 to 0,02. The adverse effect of nitrate recycled to the anaerobic reactor was also clearly evident in the short sludge age units.

The fact that nitrification could occur in these units at such short sludge ages and that nitrate has such an adverse effect on P removal, placed the Phoredox system in doubt as a reliable P removal system, particularly during the summer months. One could provide greater security against nitrification by reducing the sludge age below 3 days but the experimental indications are that the systems then have a higher potential for producing bulking sludges, turbid effluents and higher filtered effluent COD's.

As a consequence of the findings above, it was decided to accept nitrification and to study systems, such as the 3-stage Bardenpho and UCT systems, that allow control of the nitrate concentration in the recycles to the anaerobic reactor. However, to retain the short sludge age character, an upper limit to the sludge age of 6 days would be imposed on the system.

The first system selected was the 3-stage Bardenpho system shown diagramatically in Fig 4.97. The four reactor Phoredox system described in Sections 2 and 3 was retained but an a-recycle was introduced, from the second aerated reactor to the second unaerated (anoxic) reactor in order to reduce the nitrate concentration in the effluent via denitrification in the anoxic reactor.

The sludge age was selected at 6 days with a 50 percent unaerated mass fraction (25 percent anaerobic and 25 percent anoxic). The system would have a 3 day aerobic sludge age which should be adequate for complete nitrification (judged in terms of experience with the two previous systems) and yet not increase the total sludge age substantially.

For this system to operate at its maximum efficiency, the anoxic reactor should be operated at its full denitrification potential. The choice of the a-recycle ratio therefore was important. Initially it was chosen as 2:1 with respect to the feed flow rate but, when the nitrate concentration in the anoxic reactor was measured to be zero, the a-recycle ratio was increased to 4:1 with respect to the feed flow rate; the nitrate in the anoxic reactor increased to about 5 mgN/ℓ which indicated that the nitrate supply slightly exceeded the removal potential. As the full denitrification potential was being used, the recycle ratio of 4:1 was retained.

A VSS concentration of approximately 2400 mgVSS/ℓ was selected and, from Eq (4.1), a COD mass loading rate of 12500 mgCOD/d was calculated. The wastewater COD concentration was selected at 500 mgCOD/ℓ and hence a rate of 25 ℓ/d was required in order to meet the calculated loading rate.

All other process parameters were left unchanged from those in the 3 and 4 day sludge age Phoredox systems. The system specifications are presented in Table 4.15.

6.2 System operation

Details of the daily operation, control and experimental procedures followed in running the system have been set out in Chapter 3.

The system was operated for 86 days from 27/6/85 to 1/10/85. After allowing 14 days for the system to stabilise, daily measurements of process parameters were taken for 71 days (11/7/85 to 30/9/85).

During this period (after 24 days of taking readings), 7ℓ of sludge was lost due to a pipe connection breaking overnight. The sludge was replaced with sludge from a modified UCT system operating at a 21 day sludge age. The system was given 8 days to stabilise before testing recommenced.

6.2.1 Influent characteristics

The measured influent characteristics, COD (S_{ti}), readily biodegradable COD (S_{bsi}), unfiltered TKN (N_{ti}) and total phosphorus over the experimental period are shown in Figs 4.98 to 4.101.

Over this period, 8 different batches of wastewater were fed to the sludge. The mean influent characteristics are presented separately for each batch in Table 4.16. These mean values were not calculated but estimated by visual investigation of the plots of the daily values.

6.3 System Response

Figures 4.98 to 4.122 show the measured responses of the various parameters in the reactors and the effluent, i.e. COD, soluble TKN, OUR, VSS, P, nitrate and DSVI.

(i) COD

A plot of influent and effluent COD values is presented in Fig 4.98. The COD removal showed little fluctuation throughout the period of operation of the system. The influent COD, of approximately 500 mgCOD/ℓ, was reduced to a filtered effluent value of approximately 40 mgCOD/ℓ, i.e. a 92 percent removal, 8 percent remaining.

(ii) Nitrogen behavour

The TKN concentrations of the influent and filtered effluent are plotted in Fig 4.100. The nitrate concentrations in the reactors and the effluent are plotted in Figs 4.102 to 4.106. The system nitrified completely throughout its period of operation and consistently reduced the TKN to an effluent value of less than 5 mg(TKN-N)/ℓ.

From day zero to day 9, with an a-recycle ratio of 2:1, the nitrate quality in the effluent was low (about 6 mgN/ℓ) and in the anoxic reactor, zero. The TKN in the influent during this period was exceptionally low, only 33 mgN/ℓ. The remaining batches all had TKN values of 45 mgN/ℓ and higher which conformed more closely to those expected for this wastewater. The nitrate in the effluent concomitantly increased to about 14 mgN/ℓ. To ensure that the anoxic zone was used to its full denitrification potential, the a-recycle ratio was increased to 4:1 on day 9. This increase, combined with a higher TKN in the influent, caused the nitrate in the anoxic zone to increase from zero to about 8 mgN/ℓ so that the denitrification capacity of the anoxic zone was being used to its full potential.

(iii) Volatile Suspended Solids (VSS)

The VSS concentrations in the four reactors are plotted in Figs 4.107 to 4.110. The VSS's in all the reactors were stable at approximately 2200 mgVSS/ℓ over the period of operation.

(iv) Oxygen Utilization Rate (OUR)

The plot of OUR versus time, for the 2 aerated reactors, is presented in Fig 4.111.

The OUR's in the 2 aerated reactors were reasonably stable throughout the test period. The OUR in the first reactor was always higher than in the second, the difference remaining relatively constant at about 30 mgO/ℓ/h.

(v) P release, uptake and removal

The concentrations of phosphorus in the effluent and the 4 reactors are plotted versus time in Figs 4.112 to 4.116. The plots of P release, uptake and removal are shown in Figs 4.117 to 4.121.

The excess P removal (Fig 4.121) initially was erratic but, after day 16, it stabilised at approximately 8 mgP/ℓ. A removal of 8 mgP/ℓ (ΔP/influent COD = 0,016 mgP/mgCOD) is much less than that obtained with the 3 and 4 day sludge age Phoredox units (± 15 mgP/ℓ when no nitrification occurs, i.e. ΔP/influent COD = 0,03 mgP/mgCOD in influent). The principal cause for the reduced removal in the 3-stage Bardenpho system was the high nitrate concentration recycled to the anaerobic reactor (± 13 mgN/ℓ). In the 3 and 4 day sludge age Phoredox systems, nitrification, when it did occur, was partial and the nitrate concentration in the underflow recycle rarely exceeded 5 mgN/ℓ. The adverse influence of the nitrate concentration in the underflow recycle is clearly demonstrated in Figs 4.106, 4.117 and 4.121 showing the nitrate concentration in the effluent (and hence in the underflow), the P release in the anaerobic reactor and the P removal respectively. From day zero to day 9, the effluent nitrate concentration was about 6 mgN/ℓ, the P release in the anaerobic reactor about 40 mgP/ℓ and the P removal about 12 mgP/ℓ. After 10 days, the effluent nitrate was 13 mgN/ℓ, the P release about 8 mgP/ℓ and the P removal about 7 mgP/ℓ.

(vi) Settleability

The plot of Diluted Sludge Volume Index (DSVI) versus time is presented in Fig 4.112. The results from the system demonstrate how a low F/M (food/microorganism), bulking sludge can be cured by imposing a high organic loading rate: As described earlier after 24 days of taking readings, 7ℓ of the 8ℓ of sludge in the system was lost due to a pipe connection breaking overnight. The replacement sludge, from a modified UCT system operating at a 21 day sludge age, had a DSVI of over 250 mℓ/g. As illustrated in the plot, the DSVI in the 3-stage Bardenpho system decreased to less than 100 mℓ/g within 25 days and the settling was maintained at this level thereafter.

(vii) Running problems

The TKN/COD ratio of the sewage varied considerably from one batch to the next, as can be seen from Fig 4.100. When changing from a sewage with a low TKN/COD ratio to one with a high TKN/COD ratio, denitrification occurred in the settler for 4 to 5 days after the change. The nitrogen bubbles became entrapped in the sludge and the whole, or part of, the mass floated to the surface, from where it was carried over with the effluent; this made control of sludge age difficult. Three different measures were taken to remedy the sludge carry over and collectively these proved effective. Firstly, the stirring time in the settler was increased to release the nitrogen bubbles from the attached sludge. Secondly, the effluent outlet from the settler was lowered while maintaining the same liquid level, so as not to remove the floating sludge. Thirdly, the sludge from the bottom of the settler was recycled through a peristaltic pump back into the settler; this once again separated the nitrogen bubbles from the sludge and reduced sludge flotation.

Whilst cleaning the system, the large jelly-like deposits described in Section 4.3 were again observed on the stirrers, walls and airstones in the aerobic reactors. These deposits were periodically cleaned outside the reactors in order to prevent system blocking.

Throughout the operation of the system, lumps of red worms were observed round the airstones and in the cracks in the aerobic reactors. When the reactor walls were brushed, these red worms broke away from their places of adherence but remained in lumps which caused clogging of inter reactor piping. The sludge mass was sieved regularly to remove the worms. This proved to be an adequate measure of controlling the worms but it did not eliminate them completely. The reason for the growth of these worms could not be determined; growth appears to be a seasonal phenomenon because the red worms proliferated at the same time in other units (with sludge ages of 20 days) in the laboratory.

6.4 Analysis of 3-stage Bardenpho system

6.4.1 Statistical Analysis

The experimental data obtained from the 3-stage Bardenpho system was analysed by the statistical procedure set out in Appendix D. A steady state period was identified, days 26 to 51, the mean values and their standard deviations were determined and these are presented in Table 4.17.

6.4.2 Acceptability of data

The statistically determined mean values were used in the mass balance equations (derived in Appendix E) to calculate the percentage COD and nitrogen recoveries. Assuming a COD:VSS ratio of 1,48 mgCOD/mgVSS and a N/VSS ratio of 0,1 mgN/mgVSS for the sludge, the data provided a COD recovery of 75 percent and a nitrogen recovery of 83 percent. These recoveries are even lower than those observed with the four previous short sludge age systems. The three factors discussed in Section 2.4.2 as well as the slime generation discussed in Section 4.3 again could have been partially responsible for the low recoveries.

6.5 Discussion

The objective of this experiment was to determine whether, with a 3-stage Bardenpho System (see Fig 4.97), the nitrate concentration in the underflow to the anaerobic reactor could be reduced sufficiently to enable high P release and associated excess P removal. To accomplish this objective, the system was operated at a total sludge age of 6 days with a 50 percent unaerated zone (25 percent anoxic, 25 percent anaerobic), giving a 3 day aerobic sludge age. The a-recycle was initially set at 2:1 with respect to the feed flow rate and this resulted in the nitrate concentration being zero in the anoxic reactor; the a-recycle ratio was increased to 4:1 with respect to the feed flow rate, to introduce more nitrate into the anoxic zone and, since nitrate appeared in the recycle stream from this reactor, the reactor must have been operating at its full denitrification potential. The COD was set at 500 mgCOD/ℓ with a readily biodegradable COD concentration of approximately 90 mgCOD/ℓ.

The experimental results indicate the following:

(i) With the influent wastewater utilised, the system nitrified completely throughout its period of operation. Denitrification fluctuated somewhat with the nitrate in the effluent ranging from 4 to 19 mgN/ℓ; these concentrations were recycled to the anaerobic reactor via the underflow recycle.

(ii) The biological excess P removal was very variable but averaged approximately 8 mgP/ℓ. This removal was significantly less than that achieved in the 3 and 4 day sludge age Phoredox systems (see Sections

2, 3 and 4). The reduced removal most likely was caused by the high average nitrate concentration in the underflow recycle, approximately 13 mgN/ℓ.

(iii) The settleability of the sludge was consistently good (DSVI ~ 100 mℓ/g).

(iv) The COD removal of the system, based on the filtered effluent, was steady at a value of approximately 92 percent, i.e. 8 percent of the influent COD appeared in the filtered effluent. This COD effluent fraction is lower than those obtained in the 3 and 4 day sludge age Phoredox systems.

(v) The good settleability and clear effluent made the system easier to operate and maintain than the 3 day sludge age Phoredox system.

From the results of the 3-stage Bardenpho system, it is apparent that, with the wastewater used in this investigation (TKN/COD ~ 0,1), despite having a large anoxic mass fraction (25 percent) operating at its full denitrification potential, the nitrate concentration in the effluent averaged about 13 mgN/ℓ. This concentration of nitrate was recycled to the anaerobic reactor and therefore, a large fraction of the influent readily biodegradable COD in the anaerobic reactor must have been used up for denitrification. The reduced readily biodegradable COD concentration in the anaerobic reactor then would be expected to lead to a lower than normal P release and associated excess P removal; this, in fact, proved to be the case. This data therefore supports the contention of the WRC (1984) that the 3-stage Bardenpho configuration is not an acceptable system for biological excess P removal, particularly for the treatment of wastewaters with high TKN/COD ratios. Indeed, the system configuration is such that nitrate will always be recycled to the anaerobic zone. The only operational option available to the operator to improve the situation is to reduce the underflow recycle ratio. This option however would be available only if the settling tank was designed for this lower recycle ratio at some maximum DSVI.

It is apparent from the performance of the above system that, in order to obtain optimal biological excess P removal, the nitrate concentration recycled to the anaerobic reactor must be controlled so that it is low, preferably zero. There are two system configurations that allow greater control of the nitrate recycled to the anaerobic zone; (1) the UCT/Modified UCT system and (2), a modification of the Phoredox system in which an anoxic zone is introduced into the underflow recycle. This modification has been proposed by the Johannesburg municipality and, for that reason, will be termed the Johannesburg system. It was decided therefore to investigate both the UCT and Johannesburg systems as alternatives to the 3-stage Bardenpho system for biological excess P removal at short sludge ages.

7. UCT SYSTEM

7.1 System selection

The reasons for the choice of the UCT system were twofold. Firstly, having encountered problems with a high nitrate concentration in the underflow of the 3-stage Bardenpho system (see Section 6), it was decided to operate a system in which the effluent nitrate concentration (and hence underflow nitrate concentration) did not affect the excess P removal. In the UCT system, by setting the a-recycle at a value found by trial and error, the anoxic reactor can be operated at, or just below, its denitrification potential, i.e. the nitrate concentration in the anoxic reactor will be approximately zero. The recycle from the anoxic to the anaerobic reactor (r-recycle) therefore will return no nitrate to the anaerobic zone, thereby allowing the polyP organisms to obtain full benefit of the readily biodegradable COD in the influent wastewater. The second reason for the system selection was that, although considerable success had been obtained with excess P removal in the UCT system at long sludge ages, the system had not been tested at a sludge age of less than 10 days; for the sake of completeness, the behaviour under short sludge age conditions was of great interest.

The sludge age of 6 days for the 3-stage Bardenpho system had resulted in relatively stable nitrification and therefore it was retained for the UCT system.

As explained earlier, the choice of the a-recycle in the UCT system is important as its magnitude will determine whether nitrate will be present in the anoxic reactor or not. Initially, the a-recycle ratio was set at 2:1 with respect to the feed flow rate but, under these conditions, the stream leaving the anoxic reactor contained approximately 4 mgN/ℓ. This indicated that the anoxic reactor was overloaded with nitrate. Accordingly, after 34 days, the a-recycle ratio was reduced to 1:1 which resulted in zero nitrate in the anoxic reactor.

The r-recycle ratio was selected at 1. Experience with long sludge age plants had led to the conclusion that higher ratios result in smaller P removals. Lower ratios lead to excessively large anaerobic reactor volumes with respect to the anaerobic sludge mass fractions (WRC, 1984).

With one exception, all other process parameters and reactor volumes were left unchanged from those in the 3-stage Bardenpho system. The exception was the anaerobic mass fraction; by retaining the same volumes as in the Bardenpho system with an r-recycle ratio of 1:1, the mass fraction was in effect reduced from 25 percent to 14 percent. The system specifications are presented in Table 4.18 and a schematic diagram of the UCT configuration is presented in Fig 4.123.

7.2 System Operation

The system was operated for 70 days from 1/10/85 to 10/12/85. After allowing 10 days for the system to stabilise, daily measurements of process parameters were taken for 60 days (11/10/85 to 10/12/85). The a-recycle ratio was changed from 2 to 1 on 13/11/85 (34 days after starting measurements). In the middle of the study period, a batch of sewage was received that contained an appreciable concentration of dissolved hydrogen sulphide (H_2S). This caused bulking to develop through the growth of the filamentous organism *Thiothrix*. To prevent overflow of the secondary settler, the underflow recycle ratio was increased from 1:1 to 2:1 and simultaneously the a-recycle ratio was reduced from 1:1 to zero to maintain the same mass of nitrate in the recycle to the anoxic zone.

Details of the daily operation, control and experimental procedures followed in running the system have been set out in Chapter 3.

7.2.1 Influent characteristics

The measured influent characteristics, COD (S_{ti}), readily biodegradable COD (S_{bsi}), unfiltered TKN and total phosphorus over the experimental period are shown in Figs 4.124 to 4.127.

Over this period, 4 different batches of wastewater were fed to the sludge. The mean influent characteristics are presented separately for each batch in Table 4.19. These mean values are not calculated but estimated by visual investigation of the plots of the daily values.

7.3 System Response

Figures 4.124 to 4.148 show the measured responses of the various parameters in the reactors and the effluent, i.e. COD, soluble TKN, OUR, VSS, P, nitrate and DSVI.

(i) COD

A plot of the influent and effluent COD values is shown in Fig 4.124. The COD removal showed little fluctuation throughout the period of operation of the system. The influent COD, of approximately 500 mgCOD/ℓ, was reduced to an effluent value of approximately 35 mgCOD/ℓ, i.e. 93 percent removal, 7 percent remaining.

(ii) Nitrogen behaviour

The TKN concentrations of the influent and filtered effluent are plotted in Fig 4.126. The nitrate concentrations in the reactors and the effluent are plotted in Figs 4.128 to 4.132. The system nitrified completely throughout the period of study and the effluent TKN was consistently around 3 mgN/ℓ. The nitrate in the anoxic reactor (Fig 4.129) shows that while the recycle was maintained at 2:1, nitrate was present in the anoxic zone averaging about 4 mgN/ℓ. When the a-recycle ratio was reduced to 1:1 on day 34, the nitrate in the anoxic reactor fell to about 1 mgN/ℓ.

(iii) Volatile Suspended Solids (VSS)

The VSS concentrations in the 4 reactors versus time are shown in Figs 4.133 to 4.136. The VSS's in all the reactors were stable over the period of operation.

(iv) Oxygen Utilisation Rate (OUR)

The plot of OUR versus time for the 2 aerated reactors is presented in Fig 4.137. The values in the 2 reactors were stable throughout the period of operation of the system with the OUR in the first aerobic reactor always higher than that in the second aerobic reactor.

(v) P release, uptake and removal

The concentrations of phosphorus in the effluent and the four reactors are plotted versus time in Figs 4.138 to 4.142. The plots of P release, uptake and removal are shown in Figs 4.143 to 4.147.

Over the first 34 days while the a-recycle ratio was 2:1, the P release in the anaerobic reactor (number 1) ranged between zero and 5 mgP/ℓ. In the anoxic (second) reactor, there was a further slight release. The removal averaged about 7 mg/ℓ giving a ΔP/(influent COD) = 0,014. This poor removal probably was due to nitrate being recycled to the anaerobic zone (approximately 4 mgN/ℓ). When the a-recycle was reduced to 1:1 on day 34, the nitrate in the r-recycle fell to about 1 mgN/ℓ and less. Immediately the P release in the anaerobic reactor commenced to increase from near zero and continued to do so for the rest of the test period attaining about 25 mgP/ℓ release by day 60. At the same time, the P removal showed a steady increase and by day 60 had attained a removal of 12 mgP/ℓ. From the removal pattern observed, there is every indication that the removal would have increased further should the experiment have been continued longer.

(vi) Settleability

The plot of Diluted Sludge Volume Index (DSVI) versus time is presented in Fig 4.148. The DSVI was consistently low initially (approximately 110 mℓ/g) but increased sharply during a period in the middle of the study due to a proliferation of the filamentous organism *Thiothrix*. This growth was due to high sulphide concentrations in a sewage batch. When this was established, the batch was discarded and another batch collected, whereupon the settleability improved markedly and was still improving when the system was shut down.

(vii) Running Problems

The principal problem experienced with running the system occurred during the period when the settleability deteriorated due to the growth of *Thiothrix*. Sludge built up in the settler, the sludge mass turned anoxic and denitrified. Nitrogen bubbles became entrapped in the sludge which floated to the surface and was carried over with the effluent. The three measures described in detail in Section 6.3(vii) again were implemented and these proved effective in preventing sludge loss in the effluent. Briefly the measures entailed:

concentration in the anoxic reactor was measured to be approximately 4 mgN/ℓ, it was concluded that the anoxic reactor was overloaded with nitrate and the a-recycle ratio was reduced to 1. Thereafter, the nitrate concentration in the anoxic reactor was about 1 mgN/ℓ. The underflow (s) and r-recycle ratios were set at 1:1 with respect to the feed flow rate. The system was fed with 25 ℓ/d of raw wastewater having a total COD concentration of approximately 500 mgCOD/ℓ and a readily biodegradable COD concentration of approximately 95 mgCOD/ℓ.

The experimental results indicate the following:

(i) With the influent wastewater utilised, the system nitrified completely throughout its period of operation. For an a-recycle ratio 2:1, about 4 mgN/ℓ of nitrate was present in the r-recycle to the anaerobic zone and the P release was near zero.

(ii) The biological excess P removal was stable at approximately 7 mgP/ℓ while nitrate was recycled to the anaerobic reactor, i.e. a = 2. From the time that the a-recycle ratio was reduced to 1, the nitrate in the r-recycle to the anaerobic reactor became near zero and the P release and excess P removal commenced to increase steadily, and were continuing to do so when the experiment was terminated, by which time the P release had reached about 25 mgP/ℓ and the P removal about 12 mgP/ℓ.

(iii) The settleability of the sludge was good (DSVI ~ 110 mℓ/g) excepting a period during the experiment when the settleability deteriorated to DSVI values of approximately 200 mℓ/g (see Fig 4.148) due to the presence of the filamentous organism *Thiothrix*. The presence of this filament is related to high concentrations of sulphide in the wastewater. On changing the sewage batch, the settleability rapidly improved.

(iv) The COD removal of the system, based on the filtered effluent, was consistent at a value of 93 percent, i.e. 7 percent of the influent COD appeared in the filtered effluent.

(v) The system provided no serious running problems.

From the results of the UCT system, it is evident that the initial low excess P removal was due to the a-recycle ratio being incorrectly chosen - the a-recycle ratio was too high and therefore the anoxic reactor was overloaded with nitrate, i.e. despite working at its full denitrification potential, the anoxic reactor still contained approximately 4 mgN/ℓ. The recycle stream to the anaerobic reactor (r-recycle) therefore contained about 4 mgNO_3-N/ℓ which, on entering the anaerobic reactor, would have utilised approximately 8,6 x 4 = 34,4 mg of readily biodegradable COD per litre recycled. Therefore, approximately 1/3 of the readily biodegradable COD in the influent was utilised for denitrification, leaving only 2/3 for sequestration by the polyP organisms. When the a-recycle ratio was reduced to 1:1, there was little or no nitrate in the anoxic reactor, and the P release and excess P removal immediately started to increase. These parameters were still increasing when the experiment was terminated and therefore steady state values were not obtained. Despite this premature shut-down, the results from the experiment indicate that, by careful selection of the system recycle rates, the UCT configuration may be used effectively as a P removal system to treat wastewaters with high TKN/COD ratios at short sludge ages.

8. JOHANNESBURG SYSTEM AT A 3 DAY SLUDGE AGE

8.1 System Selection

The data obtained from all the experimental investigations indicated that, in order to achieve the optimal excess P removal, it is necessary to minimise the nitrate in the recycle to the anaerobic reactor. In Section 6.5, two configurations were proposed to achieve this control of nitrate in the recycle; the UCT system and the Johannesburg system. The UCT system was investigated in Section 7 and, although the experiment was terminated prematurely, it did indicate that the system has the capacity to produce high levels of excess P removal even when treating waters with high TKN/COD ratios. This section will describe the investigation into the potential of the Johannesburg system for minimising the nitrate entering the anaerobic reactor.

A Johannesburg system was set up as shown in Fig 4.149. Note in particular that the denitrification reactor is located in the underflow recycle. With a 1:1 underflow recycle ratio, this implies that the denitrification reactor is required to remove only 50 percent of the total nitrate generated in order to ensure a nitrate free discharge to the anaerobic reactor. The fraction of nitrate requiring denitrification can be reduced by decreasing the recycle ratio; for example, if the recycle/influent flow ratio is 1:2, then only 1/3 of the total nitrate generated need be removed. A low recycle ratio however will be possible only if the sludge settles well. Should the nitrate in the underflow be denitrified in the anoxic reactor, all the readily biodegradable COD in the influent would become available to the polyP organisms for sequestration in the anaerobic reactor and the system would provide the optimal conditions for P removal.

The system was operated at a 3 days sludge age with a 50 percent unaerated mass fraction (25 percent anoxic, 25 percent aerobic). With a 1:1 recycle ratio, the density of the sludge in the underflow is twice that in the system and accordingly, the volume of the anoxic reactor (1ℓ) was only half that of the anaerobic reactor (2ℓ). This reduced the actual process volume to 7ℓ but maintained the effective volume at 8ℓ. All other process parameters were left unchanged from the Phoredox systems. The system specifications are presented in Table 4.21.

Although, for consistency, this experiment is reported at this point in the sequence of the investigation, in fact it was conducted out of the sequence reported and followed immediately after the split-feed experiment reported in Section 5. The split-feed system showed excessive bulking behaviour and the study was terminated just before the settling tank failed. The sludge was retained for the Johannesburg system investigation.

8.2 System Operation

The system was operated for 33 days from 5/5/86 to 6/6/86. After allowing one day for the system to stabilise, daily readings were taken for 32 days.

8.2.1 Influent characteristics

The measured influent characteristics, COD (S_{ti}), readily biodegradable COD (S_{bsi}), unfiltered TKN (N_{ti}) and total phosphorus over the experimental period are shown in Figs 4.150 to 4.153.

Over this period, 3 different batches of wastewater were fed to the sludge. The mean influent characteristics are presented separately for each batch in Table 4.22. These mean values were not calculated but estimated visually from the plots of the daily values.

8.3 System Response

Figures 4.150 to 4.177 show the measured responses of the various parameters in the reactors and the effluent, i.e. COD, soluble TKN, OUR, VS, P, nitrate and DSVI.

(i) COD

A plot of the influent and filtered effluent COD values is presented in Fig 4.150. The COD removal, based on the filtered effluent, showed little fluctuation throughout the period of operation of the system. The unfiltered influent COD of approximately 500 mgCOD/ℓ was reduced to a filtered effluent value of approximately 60 mgCOD/ℓ, i.e. 88 percent removal or, alternatively, 12 percent of the influent COD appeared in the filtered effluent.

(ii) Nitrogen behaviour

The TKN concentrations of the influent and filtered effluent are plotted in Fig 4.152. The nitrate concentrations in the reactors and the effluent are plotted in Figs 4.154 to 4.159.

Figure 4.152 indicates that the TKN reduction of the system (TKN_{in} - TKN_{out}) fluctuated between approximately 20 and 40 mgN/ℓ. Sharp drops in the reduction occurred on day 8 and also on the two occasions that the wastewater feed batch was changed (days 16 and 28).

The fluctuating TKN reductions of the system were reflected in the nitrate concentrations in the reactors and the effluent (see Figs 4.154 to 4.159). This behaviour indicates that, as in the other 3 day sludge age studies, the system sludge age was very close to the minimum for nitrification at 20°C. Under such conditions, minor changes in the feed composition or operational procedures can cause the nitrifiers to be either retained or washed out of the system; hence the fluctuating nitrate values.

(iii) Volatile Suspended Solids (VSS)

The VSS concentrations in four of the reactors are plotted against time in Figs 4.160 to 4.163. The VSS in the selector was not measured.

The VSS's in the first two reactors (unaerated reactors) were stable over the period of operation. As expected, the solids concentration in the first reactor was approximately double that in the second. The VSS's in the last 2 reactors displayed a slow rise and fall between days 1 and 12. Thereafter the solids concentrations remained stable.

(iv) Oxygen Utilization Rate (OUR)

The plot of OUR versus time for the three aerated reactors is presented in Fig 4.164.

In each reactor, the OUR showed slight fluctuations. Furthermore the fluctuations in the 3 reactors appeared to be in step. The OUR in the selector was approximately three times the rate observed in the following two reactors. The rates in the last two reactors were very similar, with the OUR in the last reactor always being slightly lower than that in the preceding reactor.

The fluctuations in OUR in the system possibly stemmed from the variable nitrification.

(v) P release, uptake and removal

The concentrations of phosphorus in the effluent and the five reactors are plotted versus time in Figs 4.165 to 4.170.. The plots of P release, uptake and removal are shown in Figs 4.171 to 4.176.

The excess P removal was fairly stable at approximately 8 mgP/ℓ for the first wastewater batch and at approximately 9 mgP/ℓ for the next two batches. Figure 4.154 indicates that all the nitrate in the underflow was denitrified in the first unaerated reactor and consequently, it should have had no effect on the P release in the anaerobic zone.

(vi) Settleability

The plot of Diluted Sludge Volume Index (DSVI) versus time is presented in Fig 4.177. The system was started with a very poor settling sludge (DSVI of approximately 680 mℓ/g) that contained an abundance of the filamentous organism *S.natans*. Over the first seven days of operation, the DSVI declined sharply to approximately 300 mℓ/g. Thereafter the DSVI dropped at a steady rate and, when the 3 day sludge age experiment was terminated after 32 days, the DSVI was 230 mℓ/g.

A microscope study on day 9 revealed that the sludge still contained an abundance of *S.natans*. Many of the filaments had floc-formers growing along their length which may indicate that the filaments were dying off - when proliferating, the filaments tend to be free of attached flocs.

(vii) Running problems

The initial poor settleability of the sludge caused denitrification to occur in the settler. The nitrogen bubbles became entrapped in the sludge and the sludge rose to the surface from where it was carried over into the effluent bucket. The three measures described in detail in Section 6.3(vii) again were implemented and these proved effective in reducing sludge carry over with the effluent.

A small number of red worms was always present in the aerobic reactors. Their numbers however were insufficient to cause any pipe blockages.

The large jelly-like deposits noted in Section 4.2 were observed on the stirrers, walls and airstones in the aerobic reactors. These necessitated vigorous and regular cleaning.

8.4 Analysis of Johannesburg system at 3 days sludge age

8.4.1 Statistical Analysis

The experimental data obtained from the system was analysed by the statistical procedure set out in Appendix D. The set of mean values and the standard deviations for the various parameters are presented in Table 4.23.

8.4.2 Acceptability of data

The mean values from Table 4.23 were used in the mass balance equations derived in Appendix E. Assuming a COD:VSS ratio of 1,48 mgCOD/mgVSS and a N:VSS ratio of 0,1 mgN/mgVSS for the sludge, the data provided a COD recovery of 80 percent and a nitrogen recovery of 94 percent. The low COD recovery could be due to the three factors discussed in Section 2.4.2 or to the generation of slime (see Section 4.3).

8.5 Discussion

The objective of this experiment was to operate a system where optimal P removal could be attained by minimising the nitrate concentration entering the anaerobic reactor. Since the nitrate concentration in the anoxic reactor was approximately zero throughout the period of operation, in this respect the experimental objective was achieved.

The system consistently removed between 8 and 9 mgP/ℓ. In order to compare this excess P removal with those achieved in the two 3 day sludge age systems, the removals together with other relevant information are listed in Table 4.24.

Clearly, when no nitrate was generated, the Phoredox system appeared to have a high potential for removing phosphorus, probably because of the high anaerobic mass fraction; once nitrate was present in appreciable concentrations as in Phoredox (2), the effective anaerobic mass and the available readily biodegradable COD in the influent were reduced and the P removal concomitantly decreased. From the data for Phoredox (2) however, it is not possible to link explicitly the nitrate concentration in the recycle to the reduction in P removal because of the massive and almost random fluctuations in the nitrate.

The Johannesburg 3 day sludge age system had to contend with appreciable nitrate concentrations in the recycle (8,6 mgN/ℓ on average).This nitrate however was always removed in the anoxic reactor. The excess P removal achieved (8-9 mgP/ℓ influent) was significantly less than that in Phoredox (1) which also had zero nitrate discharge to the anaerobic reactor. The anaerobic mass fraction of the Johannesburg system was 25 percent as against 50 percent of the Phoredox (2) and this reduced mass fraction may have been the main reason for the reduced P removal in the Johannesburg system.

9. JOHANNESBURG SYSTEM AT FIVE DAY SLUDGE AGE

9.1 System selection

In Section 8, the 3 day sludge age Johannesburg system was evaluated for conditions in which no (or relatively little) nitrification occurred. Under these conditions, the system dealt effectively with the nitrate in the underflow recycle and gave a reasonable P removal (0,018 mgP/mgCOD in the influent). However, as with the other 3 day sludge age systems investigated, the effluent was turbid and the system produced a bulking sludge. As the Johannesburg system appeared to deal very effectively with the nitrate in the recycle, it raised the question as to whether this system could serve as an alternate to the UCT and 3-stage Bardenpho systems at a 6 day sludge age if complete nitrification did take place. Should the Johannesburg system operate successfully, then certainly it would be preferable to the other 2 systems in that no other recycles would be needed, i.e. the Johannesburg system would be simpler to operate than both the UCT or 3-stage Bardenpho systems. Accordingly, a Johannesburg system was set up that should nitrify.

This study was the last one to be undertaken in the investigation. Research work into the kinetics of the activated sludge process had, by this time, been developed to a sophisticated degree by Dold and Marais (1985). Accordingly, the kinetic model was used to proportion the reactor volumes to give a theoretical response that would be satisfactory in terms of nitrate removal, nitrification and COD removal. Using this approach a Johannesburg system, as shown schematically in Fig 4.178-, was developed. The sludge age was 5 days, anoxic mass fraction 0,36, anaerobic mass fraction 0,24 and aerobic mass fraction 0,40. The aerobic sludge age therefore was 2 days. The specifications of the system are listed in Table 4.25

In retrospect, it is unfortunate that so much weight was put on developing the system using the kinetic model as a basis. All previous studies at the longer sludge ages were at 6 days sludge age. From a comparison aspect, it would have been preferable to have used the longer sludge age of 6 days and to have retained the same anoxic, anaerobic and aerobic mass fractions as for the other systems.

9.2 System Operation

The system was operated with an underflow (s) recycle ratio of 0,5:1 for 22 days. After allowing 5 days for the system to stabilise, daily measurements of process parameters were taken for 17 days. The nitrate in the anoxic reactor proved to be zero which indicated that this reactor was operating below its denitrification potential. Accordingly the underflow recycle ratio was increased to 1:1 and, in order to maintain all the mass fractions the same as before, the volume of the anoxic reactor was increased from 1,0 to 1,5ℓ. Thereafter, daily readings of process parameters were taken for 43 days.

9.2.1 Influent characteristics

The measured influent characteristics, COD (S_{ti}), readily biodegradable COD (S_{bsi}), unfiltered TKN (N_{ti}) and total phosphorus over the experimental period are shown in Figs 4.179 to 4.182.

Over the period, 5 different batches of wastewater were fed to the sludge. The mean influent characteristics are presented separately for each batch in Table 4.26. Measurements of the readily biodegradable COD concentration were not undertaken for the first 3 sewage batches due to a breakdown of the oxygen measuring equipment. From the TKN and COD values, the TKN:COD ratio for the influent ranged from 0,08 to 0,12 mgTKN/mgCOD.

9.3 System Response

Figures 4.179 to 4.206 show the measured responses of the various parameters in the reactors and the effluent, i.e. COD, soluble TKN, OUR, VSS, P, nitrate and DSVI.

(i) COD

A plot of the influent and filtered effluent COD values is presented in Fig 4.179. The COD removal (COD_{inf}-filtered COD_{eff}) showed little fluctuation throughout the period of operation. The influent COD, of approximately 500 mgCOD/ℓ was reduced to a filtered effluent value of approximately 50 mgCOD/ℓ, i.e. 90 percent removal, or, 10 percent of the influent COD appeared in the filtered effluent. The unfiltered effluent COD was not measured but the effluent was very clear.

(ii) Nitrogen behaviour

The TKN concentrations of the influent and filtered effluent are plotted in Fig 4.181. The nitrate concentrations in the reactors and the effluent are plotted in Figs 4.183 to 4.188.

The TKN in the effluent ranged from 1 to 15 mgN/ℓ with a mean value of about 8,5 mgN/ℓ. This indicated that the nitrification was incomplete, that is that the 2 day aerobic sludge age must have been only slightly longer than the minimum sludge age for nitrification.

Over the first 17 days of taking readings, when the s-recycle ratio was set at 0,5:1, the nitrate concentration in the anoxic (first) reactor was close to zero indicating that all the recycled nitrate was being denitrified. This behaviour of the anoxic reactor indicated that it was operating below its denitrification potential. Accordingly, the underflow recycle ratio (s) was increased to 1:1 and the anoxic reactor volume was suitably adjusted to maintain the anaerobic, anoxic and aerobic mass fractions as before. After the change was made, the nitrate in the anoxic reactor increased steadily over about 4 days to 5 mgN/ℓ. The positive nitrate concentration indicated that the anoxic reactor was now overloaded with nitrate, that is, its denitrification potential was exceeded and nitrate was recycled to the anaerobic reactor.

(iii) P release, uptake and removal

The concentrations of phosphorus in the effluent and the five reactors are plotted versus time in Figs 4.189 to 4.194. The plots of P release, uptake and removal are shown in Figs 4.195 to 4.200.

With an s-recycle ratio of 0,5:1, the nitrate recycled to the anaerobic reactor was zero and the excess P removal of the system was stable at approximately 13 mgP/ℓ. When the s-recycle ratio was increased to 1:1, there was an immediate increase in the nitrate concentration leaving the anoxic reactor (i.e. entering the anaerobic reactor) from zero to about 2,5 mgN/ℓ. Concomitantly, there was an immediate decline in the excess P removal from 13 to about 7 mgP/ℓ. The nitrate concentration entering the anaerobic zone fluctuated widely between zero and 5 mgN/ℓ and, likewise, the P removal fluctuated between 2 and 12 mgP/ℓ. The behavioural patterns of these parameters appears to be strongly linked, thereby supporting the hypothesis that, as nitrate entering the anaerobic zone increases, the system P removal decreases.

(iv) Volatile Suspended Solids (VSS)

The VSS concentrations in the reactors are plotted against time in Figs 4.201 to 4.204. The VSS in the selector was not measured.

The VSS's in reactors 2, 3 and 4 were stable over the entire period of operation and were unaffected by altering the underflow recycle ratio (s) because the volumes and associated mass fractions of these reactors were not altered. The volume of reactor 1 was altered although the sludge mass fraction remained the same and accordingly, the mean VSS changed as expected theoretically.

(v) Oxygen Utilisation Rate (OUR)

The plot of OUR versus time for the 3 aerated reactors is presented in Fig 4.205.

The OUR in the selector was approximately twice the rate observed in the following two reactors. The rates in the last two reactors were very similar with the OUR in the last reactor always being slightly lower. The change in the underflow recycle ratio on day 17 had virtually no effect on the OUR's in the various reactors.

(vi) Settleability

The plot of Diluted Sludge Volume Index (DSVI) versus time is presented in Fig 4.206. The system was started with a sludge containing an abundance of the filamentous organism *S.natans* and having a DSVI of approximately 230 mℓ/g. The settleability was unchanged for the first 28 days of taking readings. Then, within 10 days, the DSVI of the sludge dropped to approximately 130 mℓ/g and remained at this level thereafter.

A microscope study on the sludge performed during the period when rapid improvement in settleability was taking place indicated that no *S.natans* was present. *Thiothrix* was the dominant filamentous organism while Type 0914 (containing large sulphur granules) was also common. The sudden change in settleability did not coincide with a new sewage batch or with any change in operational procedure. A microscope study on the sludge just prior to shutting down the unit, when the DSVI ~ 130 mℓ/g, indicated that both filaments were still present but at reduced concentrations. Throughout this experiment, *S.natans* was present only in minor concentrations. The bulking tendency therefore appears to be principally due to *Thiothrix*; the growth of this organism we have noted previously is usually associated with dissolved hydrogen sulphide in the influent.

(vii) Maximum specific growth rates

Prior to closing down the unit, an aerobic batch test was carried out on the sludge to determine the maximum specific growth rates of the heterotrophs and the nitrifiers. The detailed results and calculations associated with this test are presented in Appendix C. The following maximum specific growth rate values were determined:

$\hat{\mu}_H$ = growth rate of heterotrophs = 4,3 /d
$\hat{\mu}_N$ = growth rate of nitrifiers = 0,44 /d

(viii) Running problems

The initial poor settleability of the sludge resulted in an accumulation of sludge in the settling tank. Since the sludge was under anoxic conditions, denitrification took place and sludge was carried over into the effluent. The amount of sludge carried over was minimal however and no measures to contain the sludge were necessary.

A small number of red worms was always present in the aerobic reactors. Every two weeks the sludge was sieved through a wire mesh to remove lumps of these worms and prevent them from blocking up pipes.

The large jelly-like deposits noted in Section 4.3(vii) again were observed on the stirrers, walls and airstones in the aerobic reactors. These necessitated vigorous and regular cleaning.

9.4 Analysis of Johannesburg system at 5 day sludge age

9.4.1 Statistical analysis

The experimental data from the investigation was analysed by the statistical procedure set out in Appendix D. The data for the 2 different operating parameters (s-recycle ratios of 0,5 and 1) were analysed separately and the two sets of mean values and standard deviations for the various parameters are presented in Tables 4.27 and 4.28.

9.4.2 Acceptability of data

The statistically determined mean values from Tables 4.27 and 4.28 were used in the mass balance equations (see Appendix E) to calculate the percentage COD and nitrogen recoveries. With both sets of data, a COD:VSS ratio of 1,48 mgCOD/mgVSS and a N:VSS ratio of 0,1 mgN/mgVSS were assumed for the sludge. The Johannesburg system with an underflow recycle ratio of 0,5 produced a COD recovery of 79 percent and a nitrogen recovery of lo4 percent; the system with an underflow recycle ratio of 1 provided a COD recovery of 80 percent and a nitrogen recovery of 103 percent. As with all the systems operated in this investigation, the nitrogen recoveries are acceptable but the COD recoveries are very poor. Again the reasons for the low COD recoveries could be the 3 factors discussed in Section 2.4.2 and the slime generation discussed in Section 4.3.

9.5 Discussion

The Johannesburg configuration was proposed to minimise the nitrate recycled to the anaerobic reactor, and thereby produce the optimal excess P removal. This investigation indicates that, if the underflow recycle ratio can be reduced sufficiently so that no nitrate passes from the anoxic to the anaerobic reactor, the system can achieve excellent excess P removal. While the system was operated with an underflow recycle ratio of 0,5:1, the nitrate concentration in the anoxic reactor was zero and the excess P removal averaged about 13 mgP/ℓ. When the underflow recycle ratio was raised to 1, the nitrate concentration in the anoxic reactor varied between 1 and 5 mgN/ℓ and the excess P removal dropped to about 7 mgP/ℓ.

The 5 day sludge age version of the Johannesburg system did not nitrify completely (the effluent TKN ranged from 2 to 12 mgN/ℓ). If the maximum specific growth rate of the nitrifiers was equal to the value observed in the batch test, $\hat{\mu}_N$ = 0,44/d incomplete nitrification was to be expected. Roughly, the aerobic sludge age required for nitrification would then be given by $1/\hat{\mu}_N = 1/0{,}44 \sim 2{,}3$ days and the aerobic sludge age for the system was 2 days. This comparison is not strictly valid as the death of the nitrifiers takes place also in the unaerated zones. One can readily see that if $\hat{\mu}_N$ had declined to about 0,3/day due to temperature or other effects, nitrification probably would have ceased completely. On the other hand, should nitrification be complete, the data obtained in this experiment indicated that the anaerobic reactor can be protected from nitrate entering by the underflow recycle for TKN/COD values up to about 0,10 mgTKN/mgCOD provided the settleability of the sludge is sufficiently good that underflow recycle ratios of about 0,5 to 0,7 can be used.

Table 4.1: Specifications for Phoredox system

Type		Phoredox	
Sludge age (R_s)		4	days
Daily average influent flow rate (Q)		30	ℓ/d
Influent COD (S_{ti})		500	mgCOD/ℓ
Volume of sludge wasted per day (q)		2	ℓ/d
Underflow recycle ratio (s)		1	
Number of unaerated reactors		2	
Number of aerated reactors		2	
Reactor volumes	1	2	ℓ
	2	2	ℓ
	3	2	ℓ
	4	2	ℓ
	total	8	ℓ
Reactor sludge volume and mass ratios		volume	mass
	1	0,25	0,25
	2	0,25	0,25
	3	0,25	0,25
	4	0,25	0,25
Anaerobic mass fraction		0,5	

Table 4.2: Influent wastewater characteristics for Phoredox system operating at 4 day sludge age.

SEWAGE BATCH NO.	SEWAGE CHARACTERISTICS			
	COD (mgCOD/ℓ)	S_{bsi} (mgCOD/ℓ)	TKN (mgN/ℓ)	Phosphorus (mgP/ℓ)
1	490	65	39	21
2	500	85	48	20
3	540	120	44	23
4	510	110	38	23
5	530	100	34	23
6	500	130	37	23
7	500	110	29	23

Table 4.2: Influent wastewater characteristics for Phoredox system operating at 4 day sludge age.

SEWAGE BATCH NO.	SEWAGE CHARACTERISTICS			
	COD (mgCOD/ℓ)	S_{bsi} (mgCOD/ℓ)	TKN (mgN/ℓ)	Phosphorus (mgP/ℓ)
1	490	65	39	21
2	500	85	48	20
3	540	120	44	23
4	510	110	38	23
5	530	100	34	23
6	500	130	37	23
7	500	110	29	23

Table 4.3: Mean data for 4 day sludge age Phoredox system.

System type			Phoredox (4d)
Steady state period			Days 17 to 51
Experimental process volume		(ℓ)	8
Influent flow rate per day		(ℓ/d)	30
Sludge wasted per day		(ℓ/d)	4
System sludge age		(d)	2
s-recycle ratio			1
a-recycle ratio			-
r-recycle ratio			-
Anaerobic mass fraction			0,5
Influent COD concentration		(mgCOD/ℓ)	515,0 ± 11,5
Effluent COD concentration		(mgCOD/ℓ)	61,0 ± 4,9
Influent readily biodegradable COD		(mgCOD/ℓ)	115 ± 9
Influent TKN concentration		(mgN/ℓ)	40,5 ± 2,6
Effluent TKN concentration		(mgN/ℓ)	22,5 ± 1,5
Nitrate concentration in reactor	1	(mgN/ℓ)	-
	2	(mgN/ℓ)	-
	3	(mgN/ℓ)	-
	4	(mgN/ℓ)	-
	Effluent	(mgN/ℓ)	1,1 ± 0,2
Phosphate concentration in	Influent	(mgP/ℓ)	23,5 ± 0,5
	reactor 1	(mgP/ℓ)	37,2 ± 1,0
	2	(mgP/ℓ)	44,2 ± 1,3
	3	(mgP/ℓ)	20,5 ± 1,0
	4	(mgP/ℓ)	7,8 ± 0,5
	Effluent	(mgP/ℓ)	6,3 ± 0,6
P Uptake	reactor 1	(mgP/ℓ)	- 43,1
	2	(mgP/ℓ)	- 14,0
	3	(mgP/ℓ)	+ 47,4
	4	(mgP/ℓ)	+ 25,4
System P release		(mgP/ℓ)	57,1
System P uptake		(mgP/ℓ)	72,8
System P removal		(mgP/ℓ)	15,7
Oxygen utilisation rate in	reactor 3	(mgO/ℓ/h)	66 ± 3
	4	(mgO/ℓ/h)	45,5 ± 3,0
Volatile suspended solids in	reactor 1	(mgVSS/ℓ)	2080 ± 70
	2	(mgVSS/ℓ)	1960 ± 70
	3	(mgVSS/ℓ)	2220 ± 95
	4	(mgVSS/ℓ)	2160 ± 90

Table 4.4: Specifications for Phoredox system

Type		Phoredox	
Sludge age (R_s)		3	days
Daily average influent flow rate (Q)		30	ℓ/d
Influent COD (S_{ti})		500	mgCOD/ℓ
Volume of sludge wasted per day (q)		2,67	ℓ/d
Underflow recycle ratio (s)		1	
Number of unaerated reactors		2	
Number of aerated reactors		2	
Reactor volumes	1	2	ℓ
	2	2	ℓ
	3	2	ℓ
	4	2	ℓ
	total	8	ℓ
Reactor sludge volume and mass ratios		volume	mass
	1	0,25	0,25
	2	0,25	0,25
	3	0,25	0,25
	4	0,25	0,25
Anaerobic mass fraction		0,5	

Table 4.5: Influent sewage characteristics for Phoredox system operating at 3 day sludge age.

SEWAGE BATCH NO.	SEWAGE CHARACTERISTICS			
	S_{ti} (mgCOD/ℓ)	S_{bsi} (mgCOD/ℓ)	TKN (mgTKN-N/ℓ)	Phosphorus (mgP/ℓ)
1	500	110	42	23
2	490	115	39	23
3	490	105	40	25
4	480	90	47	26
5	500	80	40	27
6	500	85	53	27

Table 4.6: Mean data for 3 day sludge age Phoredox system.

System type			Phoredox (3d)
Steady state period			Days 15 to 64
Experimental process volume		(ℓ)	8
Influent flow rate per day		(ℓ/d)	30
Sludge wasted per day		(ℓ/d)	2,67
System sludge age		(d)	3
s-recycle ratio			1
a-recycle ratio			-
r-recycle ratio			-
Anaerobic mass fraction			0,5
Influent COD concentration		(mgCOD/ℓ)	490,0 ± 2,8
Effluent COD concentration		(mgCOD/ℓ)	67,0 ± 0,8
Influent readily biodegradable COD		(mgCOD/ℓ)	89 ± 3
Influent TKN concentration		(mgN/ℓ)	43,7 ± 0,6
Effluent TKN concentration		(mgN/ℓ)	26,2 ± 0,6
Nitrate concentration in reactor	1	(mgN/ℓ)	-
	2	(mgN/ℓ)	-
	3	(mgN/ℓ)	-
	4	(mgN/ℓ)	-
	Effluent	(mgN/ℓ)	1,9 ± 0,1
Phosphate concentration in	Influent	(mgP/ℓ)	25,7 ± 0,3
	reactor 1	(mgP/ℓ)	31,0 ± 0,9
	2	(mgP/ℓ)	38,9 ± 1,4
	3	(mgP/ℓ)	24,1 ± 0,8
	4	(mgP/ℓ)	11,2 ± 0,8
	Effluent	(mgP/ℓ)	10,7 ± 0,7
P Uptake	reactor 1	(mgP/ℓ)	- 25,1
	2	(mgP/ℓ)	- 15,8
	3	(mgP/ℓ)	+ 29,6
	4	(mgP/ℓ)	+ 25,8
System P release		(mgP/ℓ)	40,9
System P uptake		(mgP/ℓ)	55,4
System P removal		(mgP/ℓ)	14,5
Oxygen utilisation rate in	reactor 3	(mgO/ℓ/h)	60 ± 1
	4	(mgO/ℓ/h)	42 ± 1
Volatile suspended solids in	reactor 1	(mgVSS/ℓ)	1280 ± 18
	2	(mgVSS/ℓ)	1210 ± 20
	3	(mgVSS/ℓ)	1400 ± 17
	4	(mgVSS/ℓ)	1300 ± 28

Table 4.7: Specifications for 3 day sludge age Phoredox system (1986).

Type		Phoredox	
Sludge age (R_s)		3	days
Daily average influent flow rate (Q)		25	ℓ/d
Influent COD (S_{ti})		500	mgCOD/ℓ
Volume of sludge wasted per day (q)		2,67	ℓ/d
Underflow recycle ratio (s)		1	
Number of unaerated reactors		2	
Number of aerated reactors		2	
Reactor volumes	1	2	ℓ
	2	2	ℓ
	3	2	ℓ
	4	2	ℓ
	total	8	ℓ
Reactor sludge volume and mass ratios		volume	mass
	1	0,25	0,25
	2	0,25	0,25
	3	0,25	0,25
	4	0,25	0,25
Anaerobic mass fraction		0,5	

Table 4.8: Influent sewage characteristics for Phoredox system operating at 3 day sludge age.

SEWAGE BATCH NO.	SEWAGE CHARACTERISTICS			
	S_{ti} (mgCOD/ℓ)	S_{bsi} (mgCOD/ℓ)	TKN (mgTKN-N/ℓ)	Phosphorus (mgP/ℓ)
1	490	-	57	23
2	480	-	39	22
3	500	-	41	24
4	490	75	43	24
5	490	120	43	24
6	450	120	44	23
7	490	120	51	23

Table 4.9: Mean data for repeat investigation of 3 day sludge age Phoredox system.

System type Steady state period		Phoredox (3d) (repeat) Days 33 to 44
Experimental process volume	(ℓ)	8
Influent flow rate per day	(ℓ/d)	25
Sludge wasted per day	(ℓ/d)	2,67
System sludge age	(d)	3
s-recycle ratio		1
a-recycle ratio		-
r-recycle ratio		-
Anaerobic mass fraction		0,5
Influent COD concentration	(mgCOD/ℓ)	485,0 ± 5,5
Effluent COD concentration	(mgCOD/ℓ)	62,0 ± 3,3
Influent readily biodegradable COD	(mgCOD/ℓ)	120 ± 3
Influent TKN concentration	(mgN/ℓ)	44,1 ± 0,7
Effluent TKN concentration	(mgN/ℓ)	18,5 ± 1,3
Nitrate concentration in reactor 1	(mgN/ℓ)	0,3 ± 0,1
2	(mgN/ℓ)	0,5 ± 0,1
3	(mgN/ℓ)	6,7 ± 0,4
4	(mgN/ℓ)	8,4 ± 1,2
Effluent	(mgN/ℓ)	9,2 ± 0,8
Phosphate concentration in Influent	(mgP/ℓ)	23,7 ± 0,4
reactor 1	(mgP/ℓ)	29,7 ± 1,1
2	(mgP/ℓ)	31,9 ± 1,1
3	(mgP/ℓ)	20,4 ± 0,6
4	(mgP/ℓ)	13,8 ± 1,0
Effluent	(mgP/ℓ)	17,9 ± 1,2
P Uptake reactor 1	(mgP/ℓ)	- 21,9
2	(mgP/ℓ)	- 4,4
3	(mgP/ℓ)	+ 23,0
4	(mgP/ℓ)	+ 13,2
System P release	(mgP/ℓ)	26,3
System P uptake	(mgP/ℓ)	36,2
System P removal	(mgP/ℓ)	9,9
Oxygen utilisation rate in reactor 3	(mgO/ℓ/h)	52,0 ± 4,0
4	(mgO/ℓ/h)	40,0 ± 2,0
Volatile suspended solids in reactor 1	(mgVSS/ℓ)	1275 ± 53
2	(mgVSS/ℓ)	1240 ± 47
3	(mgVSS/ℓ)	1200 ± 59
4	(mgVSS/ℓ)	1200 ± 62

Table 4.10: Specifications for Split-feed system

Type		Split-feed	
Sludge age (R_s)		3	days
Daily average influent flow rate (Q)		25	ℓ/d
Influent COD (S_{ti})		500	mgCOD/ℓ
Volume of sludge wasted per day (q)		2,44	ℓ/d
Underflow recycle ratio (s)		1	
Number of unaerated reactors		2	
Number of aerated reactors		2 (3)	
Reactor volumes	1	2	ℓ
	2	2	ℓ
	selector	(0,35)	ℓ
	3	2	ℓ
	4	2	ℓ
	total	8 (8,35)	ℓ
Reactor sludge volume and mass ratios		volume	mass
	1	0,25 (0,24)	0,27 (0,26)
	2	0,25 (0,24)	0,27 (0,26)
	selector	- (0,04)	- (0,04)
	3	0,25 (0,24)	(0,23 (0,22)
	4	0,25 (0,24)	(0,23 (0,22)
Anaerobic mass fraction		0,52	

Table 4.11: Influent wastewater characteristics for Split-feed system

SEWAGE BATCH NO.	SEWAGE CHARACTERISTICS			
	S_{ti} (mgCOD/ℓ)	S_{bsi} (mgCOD/ℓ)	N_{ti} (mgN/ℓ)	Phosphorus (mgP/ℓ)
1	500	115	40	24
2	450	115	34	23
3	490	-	45	23

Table 4.12: Maximum specific growth rates

	$\hat{\mu}_H$ (/d)	$\hat{\mu}_N$ (/d)
Without selector	2,98	0,32
With selector	1,89	0,54

Table 4.13: Mean data for Split-feed system without selector reactor.

System type Steady state period		Split-feed without selector Days 1 to 11
Experimental process volume	(ℓ)	8
Influent flow rate per day	(ℓ/d)	25
Sludge wasted per day	(ℓ/d)	2,44
System sludge age	(d)	3,57
s-recycle ratio		1
a-recycle ratio		-
r-recycle ratio		-
Anaerobic mass fraction		0,545
Influent COD concentration	(mgCOD/ℓ)	502,0 ± 5,1
Effluent COD concentration	(mgCOD/ℓ)	61,0 ± 5,1
Influent readily biodegradable COD	(mgCOD/ℓ)	117 ± 3
Influent TKN concentration	(mgN/ℓ)	39,8 ± 0,9
Effluent TKN concentration	(mgN/ℓ)	12,1 ± 0,7
Nitrate concentration in reactor 1	(mgN/ℓ)	0,07 ± 0,01
2	(mgN/ℓ)	0,22 ± 0,04
3	(mgN/ℓ)	4,00 ± 0,5
4	(mgN/ℓ)	6,4 ± 0,8
Effluent	(mgN/ℓ)	2,2 ± 0,3
Phosphate concentration in Influent	(mgP/ℓ)	24,2 ± 0,3
reactor 1	(mgP/ℓ)	30,3 ± 1,1
2	(mgP/ℓ)	31,5 ± 0,9
3	(mgP/ℓ)	20,8 ± 0,8
4	(mgP/ℓ)	15,3 ± 0,7
Effluent	(mgP/ℓ)	20,1 ± 0,7
P Uptake reactor 1	(mgP/ℓ)	-19,1
2	(mgP/ℓ)	- 2,0
3	(mgP/ℓ)	+ 19,0
4	(mgP/ℓ)	+ 11,0
System P release	(mgP/ℓ)	21,1
System P uptake	(mgP/ℓ)	30,0
System P removal	(mgP/ℓ)	+ 8,9
Oxygen utilisation rate in reactor 3	(mgO/ℓ/h)	53,5 ± 3,0
4	(mgO/ℓ/h)	39,5 ± 2,0
Volatile suspended solids in reactor 1	(mgVSS/ℓ)	1320 ± 63
2	(mgVSS/ℓ)	1280 ± 63
3	(mgVSS/ℓ)	1225 ± 69
4	(mgVSS/ℓ)	1170 ± 67

Table 4.14: Mean data for Split-feed system with selector reactor.

System type			Split feed with selector
Steady state period			Days 12 to 20
Experimental process volume		(ℓ)	835
Influent flow rate per day		(ℓ/d)	25
Sludge wasted per day		(ℓ/d)	2,44
System sludge age		(d)	3,72
s-recycle ratio			1
a-recycle ratio			-
r-recycle ratio			-
Anaerobic mass fraction			0,505
Influent COD concentration		(mgCOD/ℓ)	436,0 ± 13,3
Effluent COD concentration		(mgCOD/ℓ)	57,0 ± 8,0
Influent readily biodegradable COD		(mgCOD/ℓ)	-
Influent TKN concentration		(mgN/ℓ)	33,6 ± 1,3
Effluent TKN concentration		(mgN/ℓ)	6,0 ± 1,1
Nitrate concentration in reactor	1	(mgN/ℓ)	0,25 ± 0,02
	2	(mgN/ℓ)	0,5 ± 0,1
	Selector	(mgN/ℓ)	-
	3	(mgN/ℓ)	7,2 ± 0,8
	4	(mgN/ℓ)	8,5 ± 1,1
	Effluent	(mgN/ℓ)	6,6 ± 1,2
Phosphate concentration in	Influent	(mgP/ℓ)	22,6 ± 0,4
	reactor 1	(mgP/ℓ)	26,6 ± 1,7
	2	(mgP/ℓ)	27,9 ± 1,4
	Selector	(mgP/ℓ)	-
	3	(mgP/ℓ)	19,4 ± 1,2
	4	(mgP/ℓ)	16,0 ± 0,7
	Effluent	(mgP/ℓ)	17,7 ± o,7
P Uptake	reactor 1	(mgP/ℓ)	- 13,3
	2	(mgP/ℓ)	- 2,2
	Selector	(mgP/ℓ)	-
	3	(mgP/ℓ)	+ 15,3
	4	(mgP/ℓ)	+ 6,8
System P release		(mgP/ℓ)	15,5
System P uptake		(mgP/ℓ)	22,1
System P removal		(mgP/ℓ)	+ 6,6
Oxygen utilisation rate in	reactor 3	(mgO/ℓ/h)	33,0 ± 1,0
	4	(mgO/ℓ/h)	24,5 ± 2,0
Volatile suspended solids in reactor	1	(mgVSS/ℓ)	1320 ± 63
	2	(mgVSS/ℓ)	1280 ± 63
	3	(mgVSS/ℓ)	1225 ± 69
	4	(mgVSS/ℓ)	1170 ± 67

Table 4.15: Specifications for 3-stage Bardenpho system

Type		3-stage Bardenpho	
Sludge age (R_s)		6,0	days
Daily average influent flow rate (Q)		25	ℓ/d
Influent COD (S_{ti})		500	mgCOD/ℓ
Volume of sludge wasted per day (q)		1,33	ℓ/d
Underflow recycle ratio (s)		1	ℓ/d
a-recycle ratio (a)		4 (2)	
Number of unaerated reactors		2	
Number of aerated reactors		2	
Reactor volumes	1	2	ℓ
	2	2	ℓ
	3	2	ℓ
	4	2	ℓ
	total	8	ℓ
Reactor sludge volume and mass ratios		volume	mass
	1	0,25	0,25
	2	0,25	0,25
	3	0,25	0,25
	4	0,25	0,25
Anaerobic mass fraction		0,25	

Table 4.16: Influent sewage characteristics for 3-stage Bardenpho system operating at 6 day sludge age.

SEWAGE BATCH NO.	SEWAGE-CHARACTERISTICS			
	COD (mgCOD/ℓ)	S_{bsi} (mgCOD/ℓ)	TKN (mgTKN-N/ℓ)	Phosphorus (mgPO$_4$-P)
1	500	70	33	21
2	490	105	50	23
3	500	100	53	25
4	500	75	53	25
5	490	80	45	27
6	510	100	45	23
7	500	100	45	24
8	500	90	58	25

Table 4.17: Mean data for 3-stage Bardenpho System.

System type			3-stage Bardenpho
Steady state period			Days 26 to 51
Experimental process volume		(ℓ)	8
Influent flow rate per day		(ℓ/d)	25
Sludge wasted per day		(ℓ/d)	1,33
System sludge age		(d)	6,0
s-recycle ratio			1
a-recycle ratio			4
r-recycle ratio			-
Anaerobic mass fraction			0,25
Influent COD concentration		(mgCOD/ℓ)	493,0 ± 4,9
Effluent COD concentration		(mgCOD/ℓ)	40,0 ± 2,2
Influent readily biodegradable COD		(mgCOD/ℓ)	85 ± 5
Influent TKN concentration		(mgN/ℓ)	50,7 ± 2,0
Effluent TKN concentration		(mgN/ℓ)	3,3 ± 0,5
Nitrate concentration in reactor	1	(mgN/ℓ)	0,1 ± 0,1
	2	(mgN/ℓ)	8,8 ± 0,6
	3	(mgN/ℓ)	12,0 ± 0,6
	4	(mgN/ℓ)	13,2 ± 0,4
	Effluent	(mgN/ℓ)	13,4 ± 0,9
Phosphate concentration in	Influent	(mgP/ℓ)	25,7 ± 0,6
	reactor 1	(mgP/ℓ)	24,1 ± 0,7
	2	(mgP/ℓ)	19,8 ± 0,7
	3	(mgP/ℓ)	19,2 ± 0,4
	4	(mgP/ℓ)	18,0 ± 0,6
	Effluent	(mgP/ℓ)	18,0 ± 0,6
P Uptake	reactor 1	(mgP/ℓ)	- 4,5
	2	(mgP/ℓ)	+ 1,4
	3	(mgP/ℓ)	+ 3,6
	4	(mgP/ℓ)	+ 7,2
System P release		(mgP/ℓ)	4,5
System P uptake		(mgP/ℓ)	12,2
System P removal		(mgP/ℓ)	+ 7,7
Oxygen utilisation rate in	reactor 3	(mgO/ℓ/h)	74 ± 2
	4	(mgO/ℓ/h)	47 ± 3
Volatile suspended solids in	reactor 1	(mgVSS/ℓ)	2390 ± 77
	2	(mgVSS/ℓ)	2315 ± 65
	3	(mgVSS/ℓ)	2285 ± 83
	4	(mgVSS/ℓ)	2310 ± 52

Table 4.18: Specifications for UCT system

Type		UCT	
Sludge age (R_s)		6	days
Daily average influent flow rate (Q)		25	ℓ/d
Influent COD (S_{ti})		500	mgCOD/ℓ
Volume of sludge wasted per day (q)		1,167	ℓ/d
Underflow recycle ratio (s)		1	
a-recycle ratio (a)		2 (1)	
r-recycle ratio (r)		1	
Number of unaerated reactors		2	
Number of aerated reactors		2	
Reactor volumes	1	2	ℓ
	2	2	ℓ
	3	2	ℓ
	4	2	ℓ
	total	8	ℓ
Reactor sludge volume and mass ratios		volume	mass
	1	0,25	0,14
	2	0,25	0,29
	3	0,25	0,29
	4	0,25	0,29
Anaerobic mass fraction		0,14	

Table 4.19: Influent sewage characteristics for UCT system.

SEWAGE BATCH NO.	SEWAGE CHARACTERISTICS			
	COD (mgCOD/ℓ)	S_{bsi} (mgCOD/ℓ)	TKN (mgN/ℓ)	Phosphorus (mgPℓ)
1	500	105	60	27
2	505	85	44	27
3	510	90	48	25
4	520	90	42	26

Table 4.20: Mean data for UCT system.

System type			UCT
Steady state period			Days 43 to 60
Experimental process volume		(ℓ)	8
Influent flow rate per day		(ℓ/d)	25
Sludge wasted per day		(ℓ/d)	1,167
System sludge age		(d)	6,0
s-recycle ratio			1
a-recycle ratio			1
r-recycle ratio			1
Anaerobic mass fraction			0,142
Influent COD concentration		(mgCOD/ℓ)	510,0 ± 3,7
Effluent COD concentration		(mgCOD/ℓ)	40,0 ± 1,6
Influent readily biodegradable COD		(mgCOD/ℓ)	88 ± 5
Influent TKN concentration		(mgN/ℓ)	41,9 ± 0,8
Effluent TKN concentration		(mgN/ℓ)	3,5 ± 0,3
Nitrate concentration in reactor	1	(mgN/ℓ)	0,5 ± 0,1
	2	(mgN/ℓ)	1,5 ± 0,2
	3	(mgN/ℓ)	9,4 ± 0,4
	4	(mgN/ℓ)	10,6 ± 0,5
	Effluent	(mgN/ℓ)	10,5 ± 0,4
Phosphate concentration (by day 60) in			
	Influent	(mgP/ℓ)	27,1 ± 0,9
reactor	1	(mgP/ℓ)	40,0
	2	(mgP/ℓ)	27,0
	3	(mgP/ℓ)	18,7
	4	(mgP/ℓ)	18,1
	Effluent	(mgP/ℓ)	18,0
P Uptake reactor	1	(mgP/ℓ)	- 25,9
	2	(mgP/ℓ)	- 1,8
	3	(mgP/ℓ)	+ 24,9
	4	(mgP/ℓ)	+ 16,8
System P release		(mgP/ℓ)	27,7
System P uptake		(mgP/ℓ)	41,7
System P removal		(mgP/ℓ)	+ 14
Oxygen utilisation rate in reactor	3	(mgO/ℓ/h)	78,5 ± 4,0
	4	(mgO/ℓ/h)	43,0 ± 4,5
Volatile suspended solids in reactor	1	(mgVSS/ℓ)	1300 ± 37
	2	(mgVSS/ℓ)	2350 ± 78
	3	(mgVSS/ℓ)	2380 ± 74
	4	(mgVSS/ℓ)	2370 ± 78

Table 4.21: Specifications for 3 day sludge age Johannesburg system.

Type		Johannesburg	
Sludge age (R_s)		3	days
Daily average influent flow rate (Q)		25	ℓ/d
Influent COD (S_{ti})		500	mgCOD/ℓ
Volume of sludge wasted per day (q)		2,78	ℓ/d
Underflow recycle ratio (s)		1	
Number of unaerated reactors		2	
Number of aerated reactors		3	
Reactor volumes	1	1	ℓ
	2	2	ℓ
	selector	0,35	ℓ
	3	2	ℓ
	4	2	ℓ
	total	7,35	ℓ
Reactor sludge volume and mass ratios		volume	mass
	1	0,14	0,24
	2	0,27	0,24
	selector	0,05	0,04
	3	0,27	0,24
	4	0,27	0,24
Anaerobic mass fraction		0,24	

Table 4.22: Influent wastewater characteristics for Johannesburg system operating at 3 day sludge age.

SEWAGE BATCH NO.	SEWAGE CHARACTERISTICS			
	S_{ti} (mgCOD/ℓ)	S_{bsi} (mgCOD/ℓ)	N_{ti} (mgN/ℓ)	Phosphorus (mgP/ℓ)
1	490	-	37	22
2	510	-	50	22
3	500	-	41	22

Table 4.23: Mean data for Johannesburg system at 3 day sludge age.

System type Steady state period			Johannesburg Days 0 to 32
Experimental process volume		(ℓ)	7,35
Influent flow rate per day		(ℓ/d)	25
Sludge wasted per day		(ℓ/d)	2,78
System sludge age		(d)	3
s-recycle ratio			1
a-recycle ratio			-
r-recycle ratio			-
Anaerobic mass fraction			0,24
Influent COD concentration		(mgCOD/ℓ)	497,0 ± 6,7
Effluent COD concentration		(mgCOD/ℓ)	51,0 ± 3,3
Influent readily biodegradable COD		(mgCOD/ℓ)	-
Influent TKN concentration		(mgN/ℓ)	50,1 ± 1,1
Effluent TKN concentration		(mgN/ℓ)	14,2 ± 1,8
Nitrate concentration in reactor	1	(mgN/ℓ)	1,3 ± 0,1
	2	(mgN/ℓ)	0,5 ± 0,1
	Selector	(mgN/ℓ)	2,4 ± 0,1
	3	(mgN/ℓ)	6,3 ± 0,9
	4	(mgN/ℓ)	8,9 ± 0,8
	Effluent	(mgN/ℓ)	8,6 ± 0,6
Phosphate concentration in	Influent	(mgP/ℓ)	22,2 ± 0,3
	reactor 1	(mgP/ℓ)	17,0 ± 0,4
	2	(mgP/ℓ)	27,8 ± 0,7
	Selector	(mgP/ℓ)	24,6 ± 0,6
	3	(mgP/ℓ)	18,6 ± 0,3
	4	(mgP/ℓ)	13,8 ± 0,6
	Effluent	(mgP/ℓ)	13,7 ± 0,5
P Uptake	reactor 1	(mgP/ℓ)	- 3,2
	2	(mgP/ℓ)	-16,4
	Selector	(mgP/ℓ)	+ 6,4
	3	(mgP/ℓ)	+ 12,0
	4	(mgP/ℓ)	+ 9,6
System P release		(mgP/ℓ)	19,6
System P uptake		(mgP/ℓ)	28,0
System P removal		(mgP/ℓ)	+ 8,4
Oxygen utilisation rate in	selector	(mgO/ℓ/h)	98 ± 6
	reactor 3	(mgO/ℓ/h)	36 ± 1
	4	(mgO/ℓ/h)	31,5 ± 2
Volatile suspended solids in reactor	1	(mgVSS/ℓ)	2280 ± 104
	2	(mgVSS/ℓ)	1315 ± 44
	3	(mgVSS/ℓ)	1400 ± 50
	4	(mgVSS/ℓ)	1390 ± 75

Table 4.24: Comparison of excess P removal behaviour for the Phoredox and Johannesburg systems at 3 day sludge age.

System	Anoxic mass fraction	Anaerobic mass fraction	P removal	Remarks
Phoredox (1)	zero	0,5	14,5	No nitrification
Phoredox (2)	zero	0,5	9	± 9 mgN/ℓ to anaerobic reactor
Johannesburg	0,25	0,25	9	zero nitrate to anaerobic reactor

Table 4.25: Specifications for Johannesburg system at 5 day sludge age.

Type			Johannesburg		
Sludge age (R_s)			5		days
Daily average influent flow rate (Q)			18		ℓ/d
Influent COD (S_{ti})			500		mgCOD/ℓ
Volume of sludge wasted per day (q)			1,67		ℓ/d
Underflow recycle ratio (s)			0,5	(1)	
Number of unaerated reactors			2		
Number of aerated reactors			3		
Reactor volumes	1		1	(1,5)	ℓ
	2		2	(2)	ℓ
	selector		0,35	(0,35)	ℓ
	3		1,5	(1,5)	ℓ
	4		1,5	(1,5)	ℓ
	total		6,35	(6,85)	ℓ
Reactor sludge volume and mass ratios		volume			mass
	1	0,16 (0,22)			0,36 (0,36)
	2	0,31 (0,29)			0,24 (0,24)
	selector	0,05 (0,05)			0,04 (0,04)
	3	0,24 (0,22)			0,18 (0,18)
	4	0,24 (0,22)			0,18 (0,18)
Anaerobic mass fraction			0,24		

Table 4.26: Influent wastewater characteristics for Johannesburg system operating at 5 day sludge age.

SEWAGE BATCH NO.	SEWAGE CHARACTERISTICS			
	S_{ti} (mgCOD/ℓ)	S_{bsi} (mgCOD/ℓ)	N_{ti} (mgN/ℓ)	Phosphorus (mgP/ℓ)
1	480	-	41	24
2	510	-	42	23
3	490	-	44	21
4	470	135	50	23
5	500	130	61	23

Table 4.27: Mean data for Johannesburg system at 5 day sludge age (s = 0,5).

System type			Johannesburg (5d)
Steady state period			Days 5 to 17
Experimental process volume		(ℓ)	6,35
Influent flow rate per day		(ℓ/d)	18
Sludge wasted per day		(ℓ/d)	1,67
System sludge age		(d)	5
s-recycle ratio			0,5
a-recycle ratio			-
r-recycle ratio			-
Anaerobic mass fraction			0,24
Influent COD concentration		(mgCOD/ℓ)	505,0 ± 13,3
Effluent COD concentration		(mgCOD/ℓ)	61,0 ± 2,6
Influent readily biodegradable COD		(mgCOD/ℓ)	-
Influent TKN concentration		(mgN/ℓ)	42,0 ± 1,2
Effluent TKN concentration		(mgN/ℓ)	8,5 ± 0,9
Nitrate concentration in reactor	1	(mgN/ℓ)	0,14 ± 0,01
	2	(mgN/ℓ)	0,48 ± 0,03
	Selector	(mgN/ℓ)	3,5 ± 0,6
	3	(mgN/ℓ)	9,2 ± 1,0
	4	(mgN/ℓ)	14,2 ± 1,6
	Effluent	(mgN/ℓ)	13,6 ± 1,1
Phosphate concentration in	Influent	(mgP/ℓ)	22,7 ± 0,4
	reactor 1	(mgP/ℓ)	28,5 ± 2,1
	2	(mgP/ℓ)	41,4 ± 1,3
	Selector	(mgP/ℓ)	31,6 ± 1,0
	3	(mgP/ℓ)	18,6 ± 1,7
	4	(mgP/ℓ)	10,2 ± 0,5
	Effluent	(mgP/ℓ)	9,7 ± 0,5
P Uptake	reactor 1	(mgP/ℓ)	- 9,2
	2	(mgP/ℓ)	- 25,2
	Selector	(mgP/ℓ)	+ 14,7
	3	(mgP/ℓ)	+ 19,5
	4	(mgP/ℓ)	± 12,6
System P release		(mgP/ℓ)	34,4
System P uptake		(mgP/ℓ)	46,9
System P removal		(mgP/ℓ)	12,5
Oxygen utilisation rate in	Selector	(mgO/ℓ/h)	86,0 ± 6,0
	reactor 3	(mgO/ℓ/h)	46,0 ± 3,0
	4	(mgO/ℓ/h)	35,0 ± 3,0
Volatile suspended solids in reactor	1	(mgVSS/ℓ)	4195 ± 16
	2	(mgVSS/ℓ)	1650 ± 25
	3	(mgVSS/ℓ)	1650 ± 44
	4	(mgVSS/ℓ)	1600 ± 25

Table 4.28: Mean data for Johannesburg system at 5 day sludge age (s = 1).

System type Steady state period			Johannesburg (5d) Days 17 to 57
Experimental process volume		(ℓ)	6,85
Influent flow rate per day		(ℓ/d)	18
Sludge wasted per day		(ℓ/d)	1,67
System sludge age		(d)	5
s-recycle ratio			1
a-recycle ratio			-
r-recycle ratio			-
Anaerobic mass fraction			0,24
Influent COD concentration		(mgCOD/ℓ)	479,0 ± 9,2
Effluent COD concentration		(mgCOD/ℓ)	44,0 ± 2,8
Influent readily biodegradable COD		(mgCOD/ℓ)	129 ± 13
Influent TKN concentration		(mgN/ℓ)	46,8 ± 1,3
Effluent TKN concentration		(mgN/ℓ)	7,0 ± 0,9
Nitrate concentration in reactor	1	(mgN/ℓ)	2,2 ± 0,3
	2	(mgN/ℓ)	0,13 ± 0,01
	Selector	(mgN/ℓ)	2,3 ± 0,2
	3	(mgN/ℓ)	7,9 ± 0,3
	4	(mgN/ℓ)	13,0 ± 0,4
	Effluent	(mgN/ℓ)	13,6 ± 0,3
Phosphate concentration in	Influent	(mgP/ℓ)	22,2 ± 0,6
reactor	1	(mgP/ℓ)	19,8 ± 1,3
	2	(mgP/ℓ)	31,7 ± 1,9
	Selector	(mgP/ℓ)	24,9 ± 1,0
	3	(mgP/ℓ)	20,3 ± 1,1
	4	(mgP/ℓ)	14,8 ± 1,3
	Effluent	(mgP/ℓ)	13,4 ± 0,5
P Uptake reactor	1	(mgP/ℓ)	- 5,0
	2	(mgP/ℓ)	- 21,4
	Selector	(mgP/ℓ)	+ 13,6
	3	(mgP/ℓ)	+ 9,2
	4	(mgP/ℓ)	+ 11,0
System P release		(mgP/ℓ)	26,4
System P uptake		(mgP/ℓ)	33,8
System P removal		(mgP/ℓ)	7,4
Oxygen utilisation rate in	Selector	(mgO/ℓ/h)	89,0 ± 4,0
reactor	3	(mgO/ℓ/h)	46,0 ± 3,0
	4	(mgO/ℓ/h)	41,0 ± 2,0
Volatile suspended solids in reactor	1	(mgVSS/ℓ)	2660 ± 104
	2	(mgVSS/ℓ)	1560 ± 71
	3	(mgVSS/ℓ)	1530 ± 60
	4	(mgVSS/ℓ)	1510 ± 57

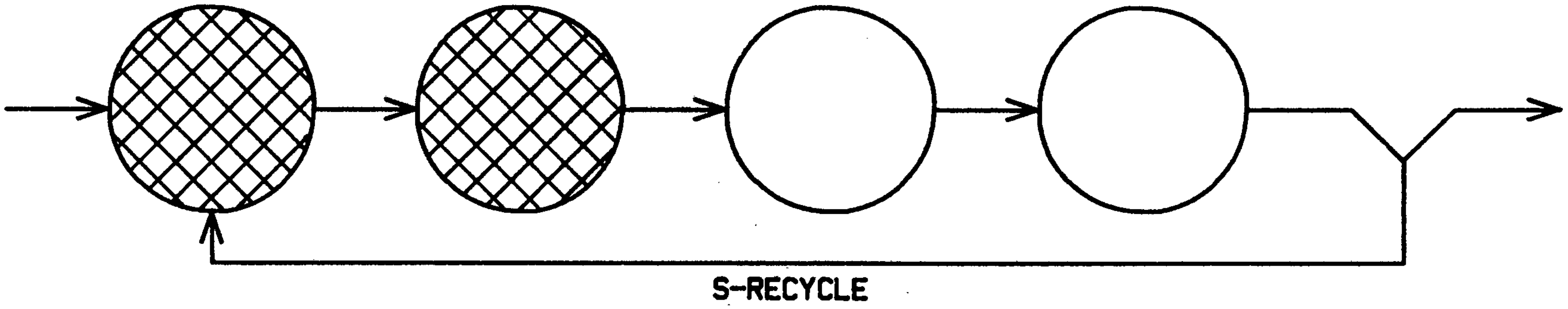
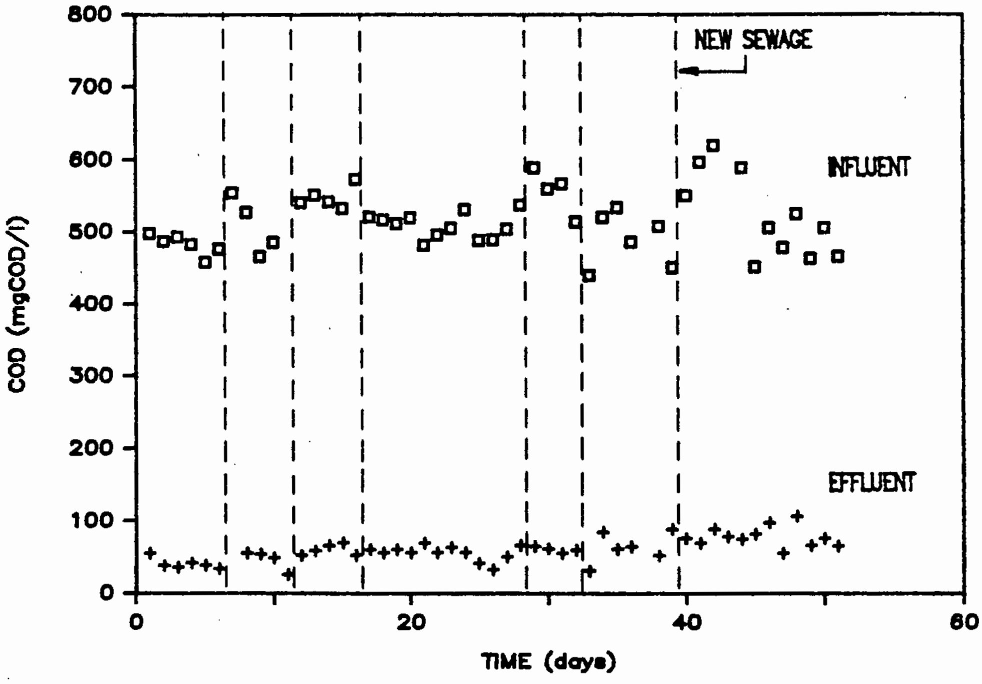
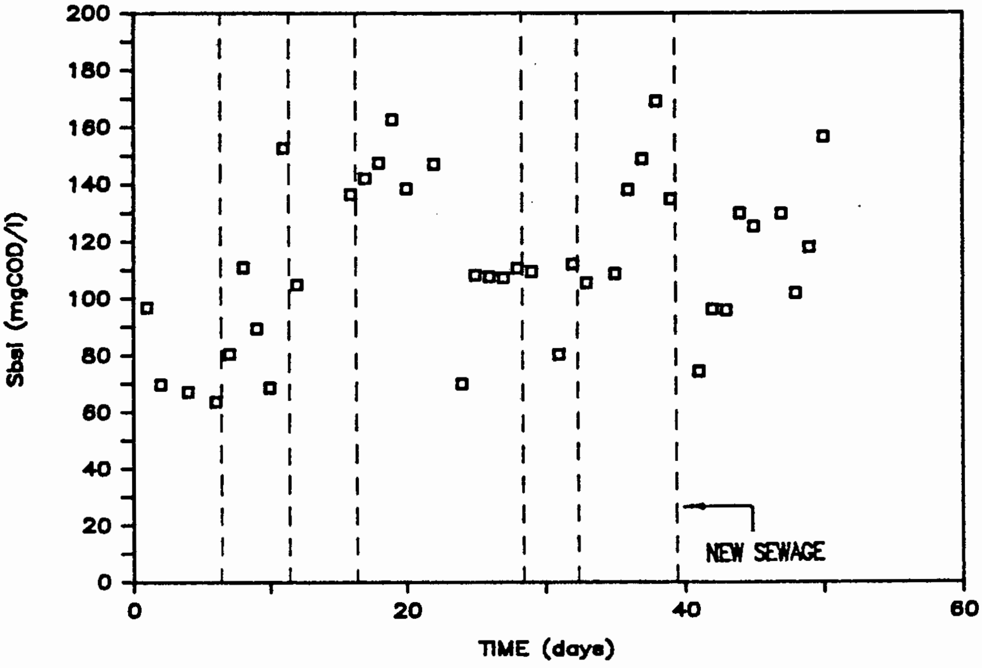


Fig 4.1: Schematic diagram of the Phoredox configuration.



<u>Fig 4.2</u>: Daily performance of the unfiltered influent and filtered effluent COD concentrations for the 4 day sludge age Phoredox system.



<u>Fig 4.3</u>: Daily performance of the influent readily biodegradable COD concentration for the 4 day sludge age Phoredox system.

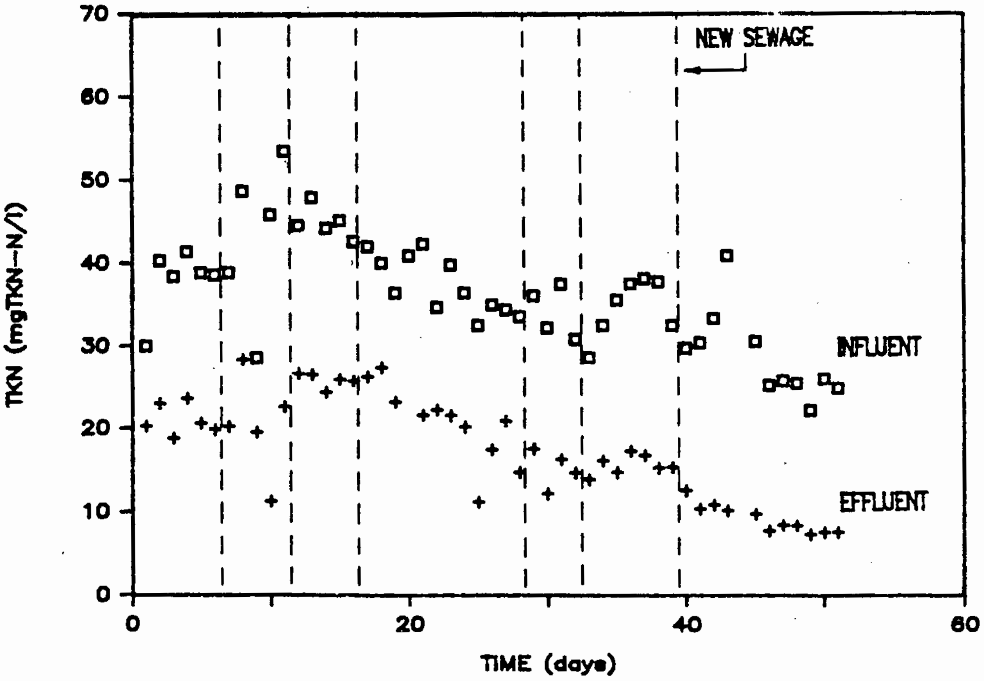


Fig 4.4: Daily performance of the unfiltered influent and filtered effluent TKN concentrations for the 4 day sludge age Phoredox system.

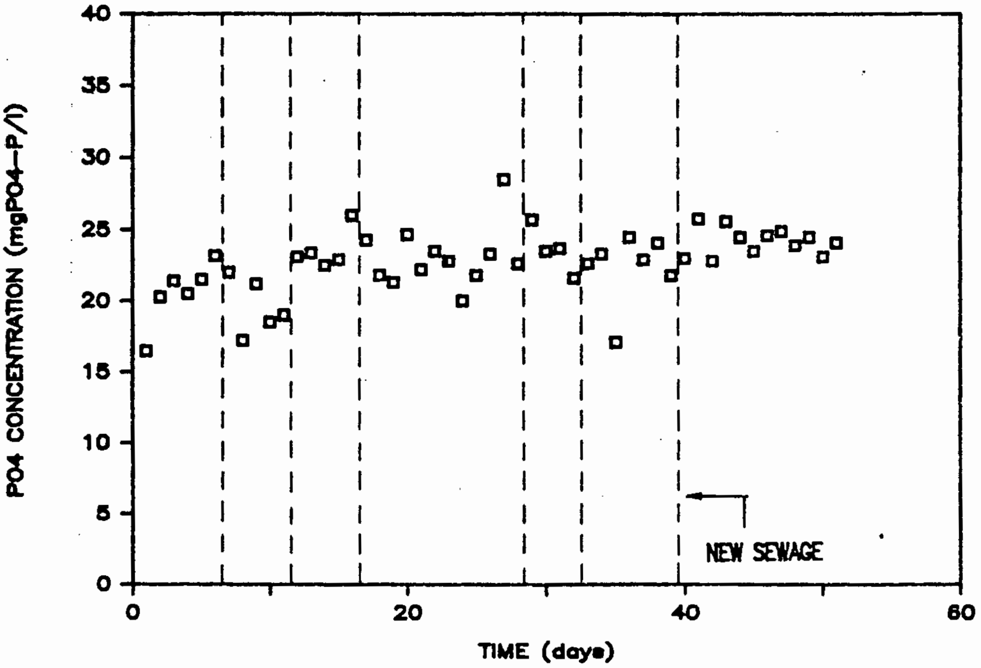


Fig 4.5: Daily performance of the phosphorus concentration in the influent for 4 day sludge age Phoredox system.

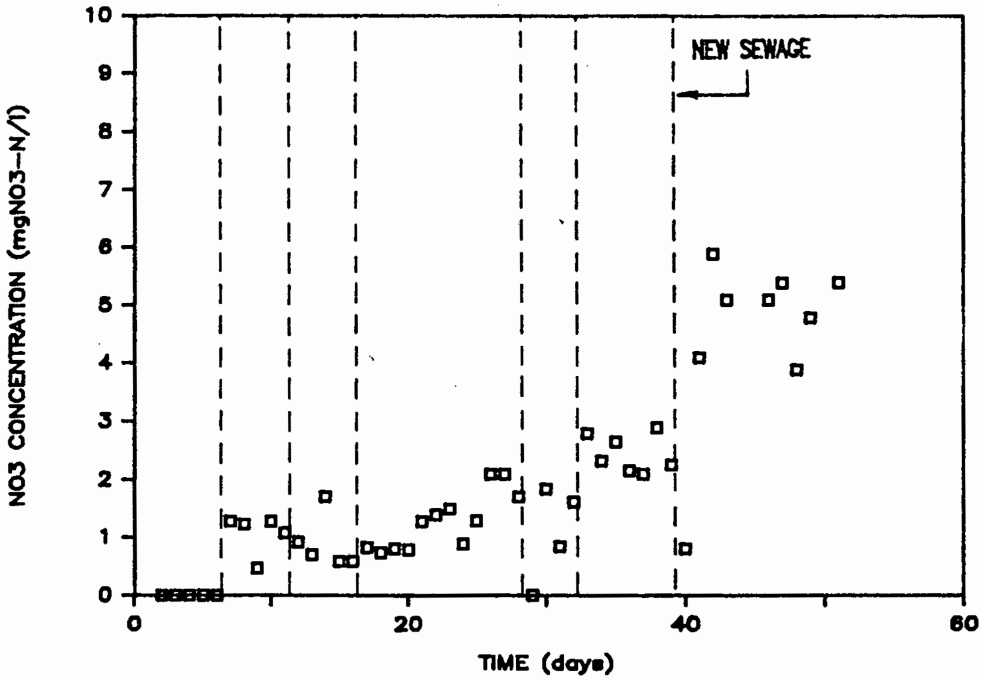


Fig 4.6: Daily performance of the nitrate concentration in the effluent for the 4 day sludge age Phoredox system.

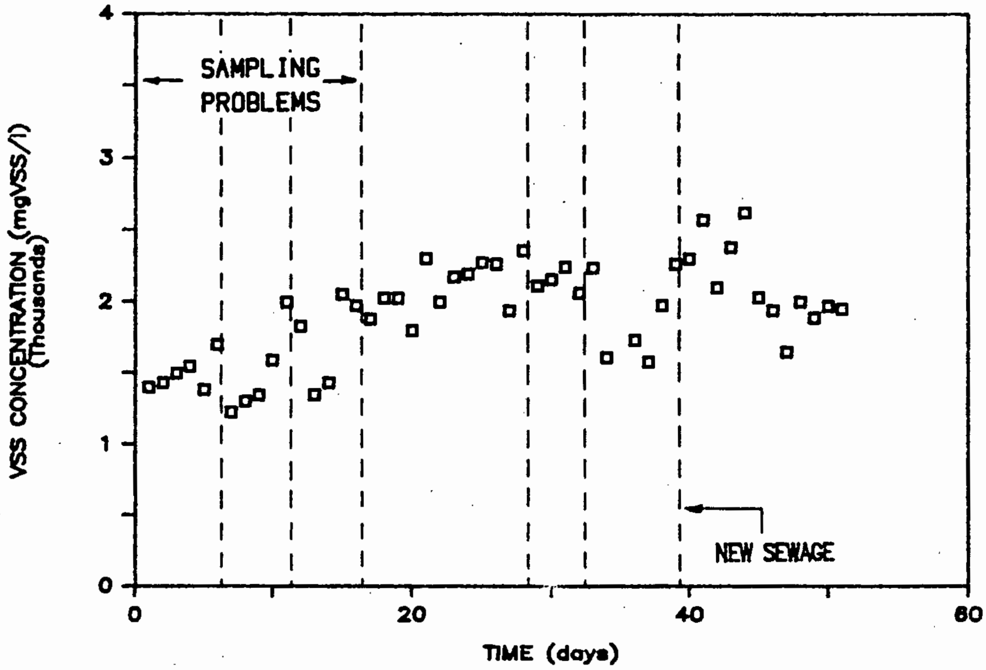


Fig 4.7: Daily performance of the volatile suspended solids in the first reactor of the 4 day sludge age Phoredox system.

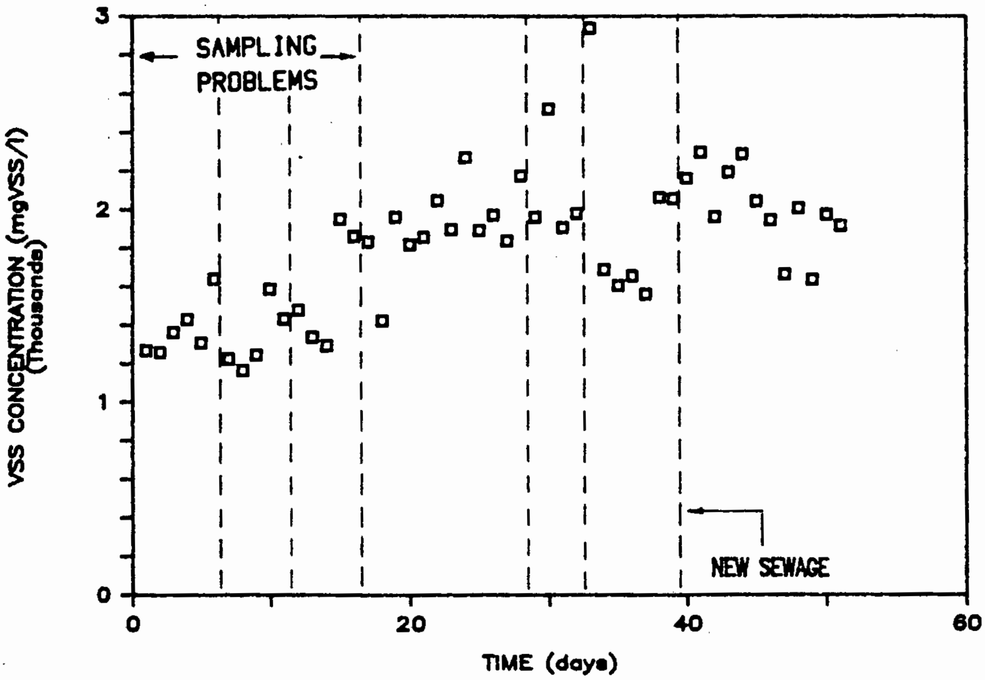


Fig 4.8: Daily performance of the volatile suspended solids in the second reactor of the 4 day sludge age Phoredox system.

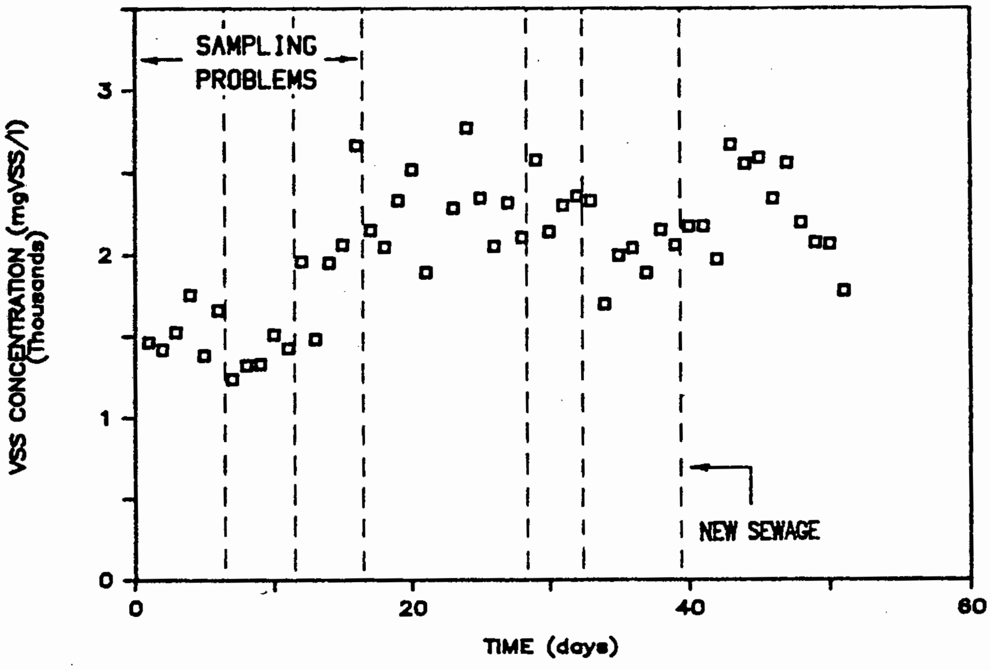


Fig 4.9: Daily performance of the volatile suspended solids in the third reactor of the 4 day sludge age Phoredox system.

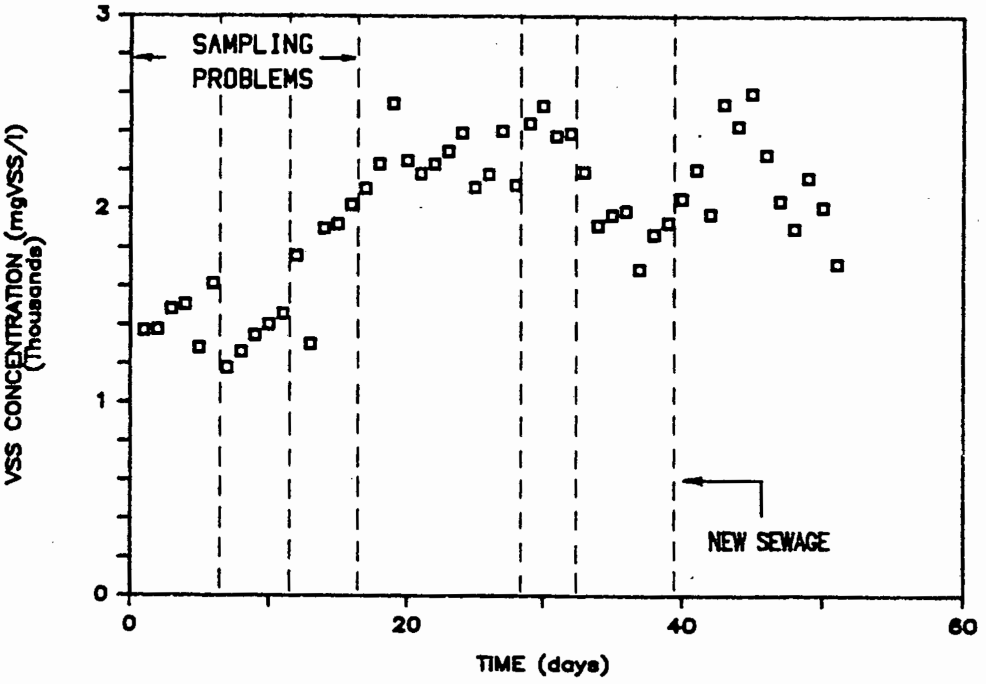


Fig 4.10: Daily performance of the volatile suspended solids in the fourth reactor of the 4 day sludge age Phoredox system.

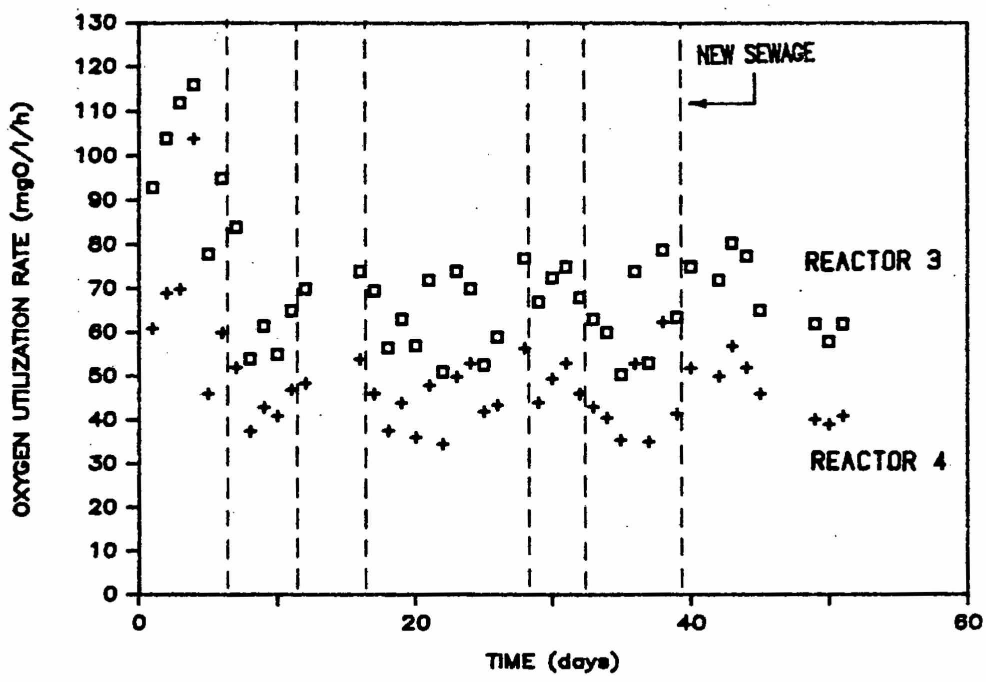


Fig 4.11: Daily performance of the oxygen utilisation rates in the aerobic reactors of the 4 day sludge age Phoredox system.

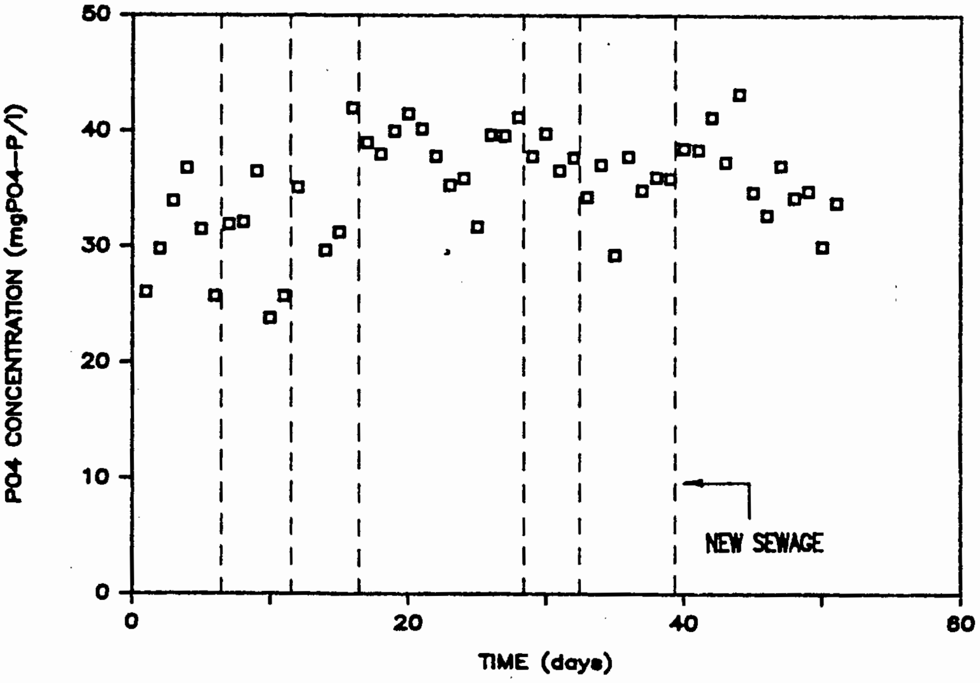


Fig 4.12: Daily performance of the phosphorus concentration in the first reactor of the 4 day sludge age Phoredox system.

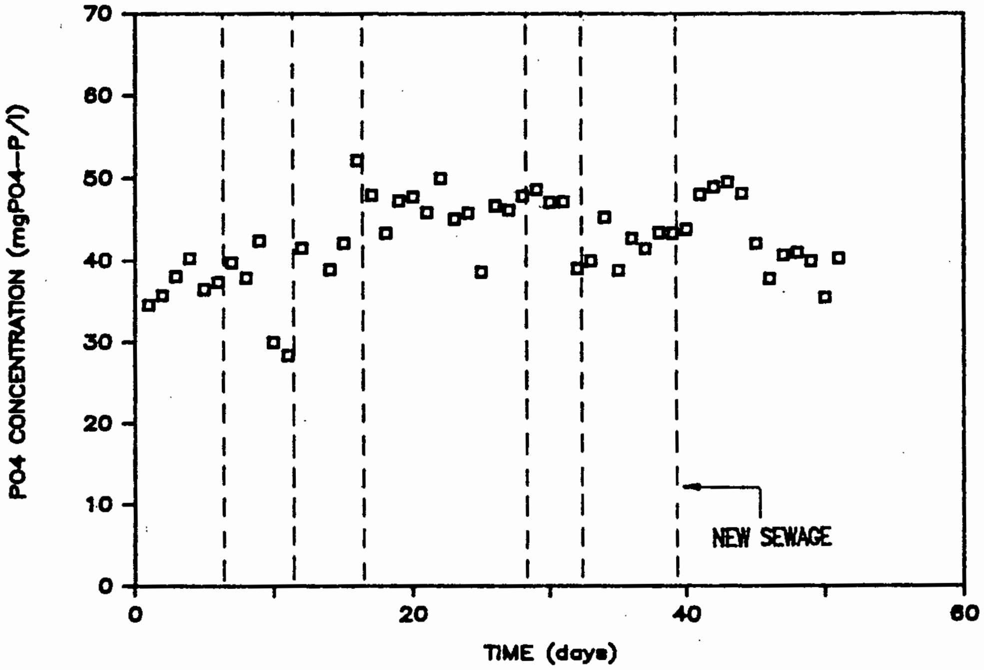


Fig 4.13: Daily performance of the phosphorus concentration in the second reactor of the 4 day sludge age Phoredox system.

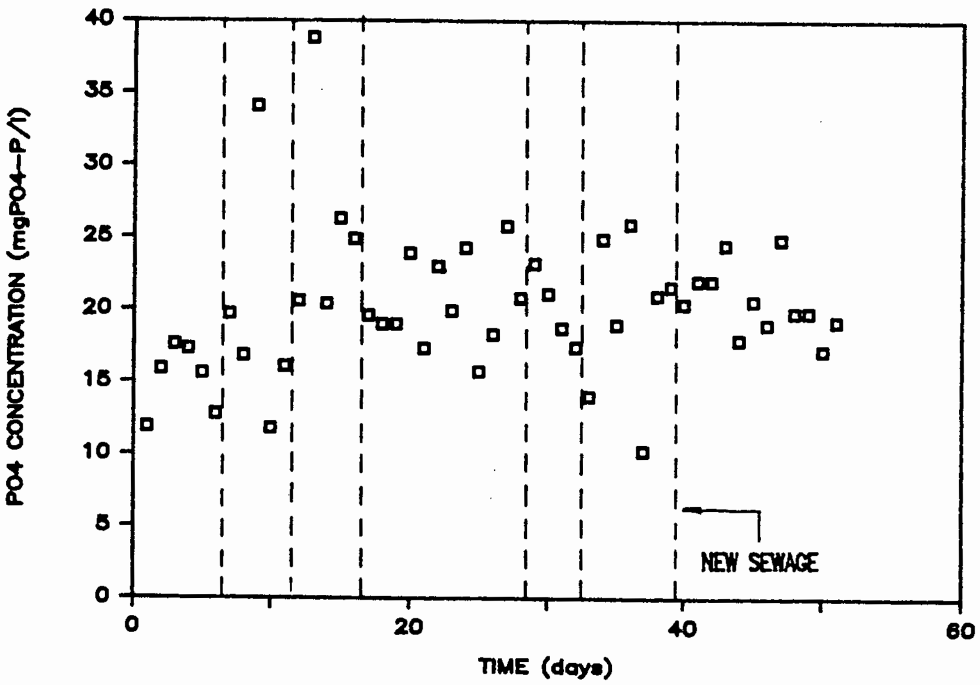


Fig 4.14: Daily performance of the phosphorus concentration in the third reactor of the 4 day sludge age Phoredox system.

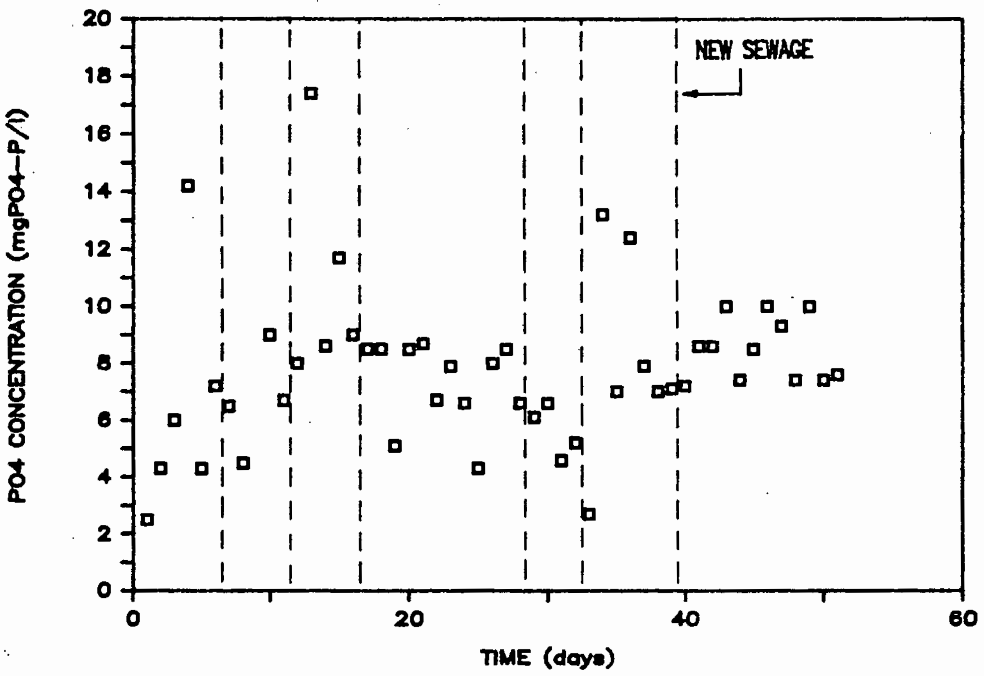


Fig 4.15: Daily performance of the phosphorus concentration in the fourth reactor of the 4 day sludge age Phoredox system.

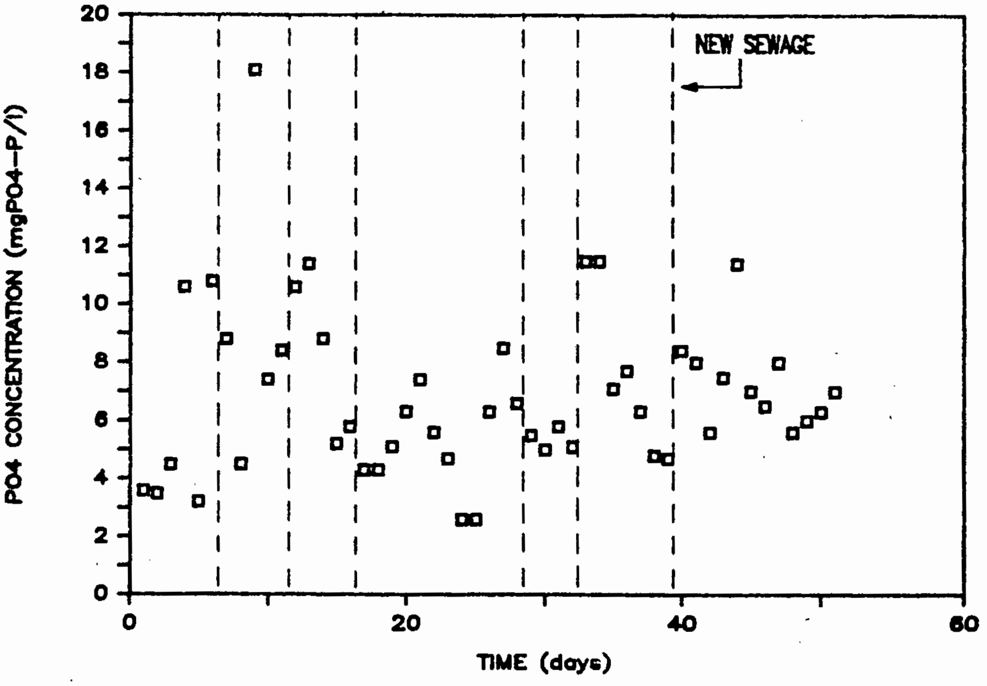


Fig 4.16: Daily performance of the phosphorus concentration in the filtered effluent from the 4 day sludge age Phoredox system.

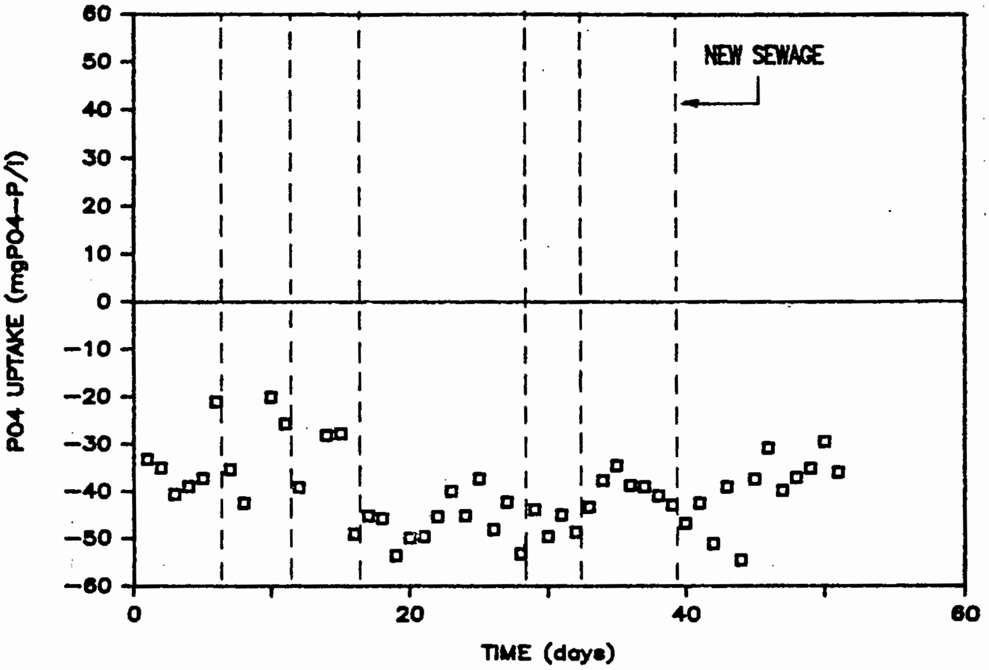


Fig 4.17: Daily performance of the phosphorus uptake in the first reactor of the 4 day sludge age Phoredox system.

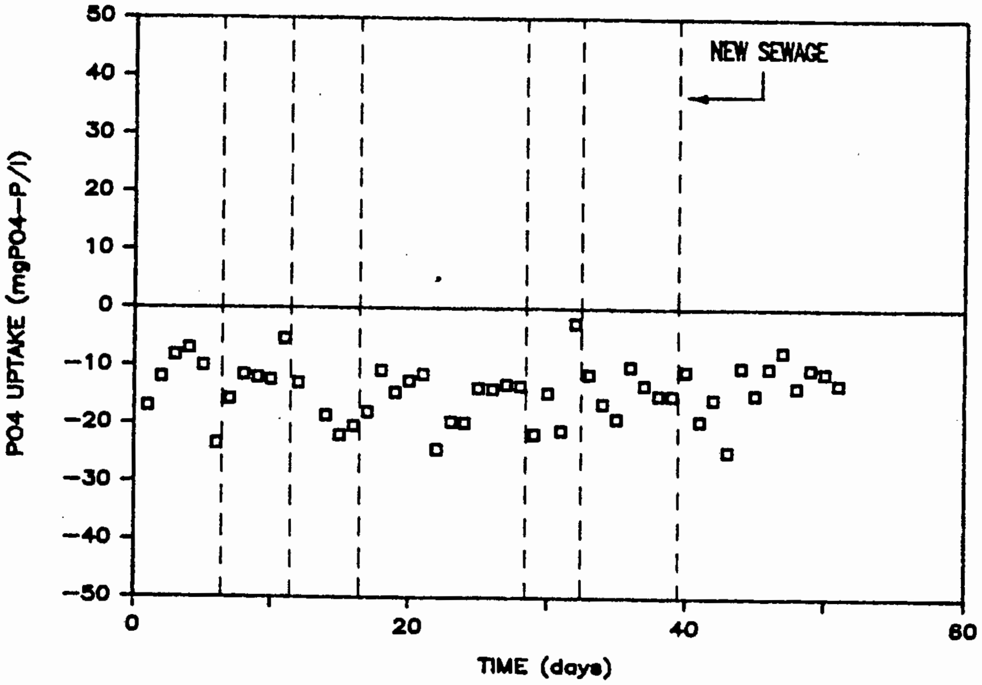


Fig 4.18: Daily performance of the phosphorus uptake in the second reactor of the 4 day sludge age Phoredox system.

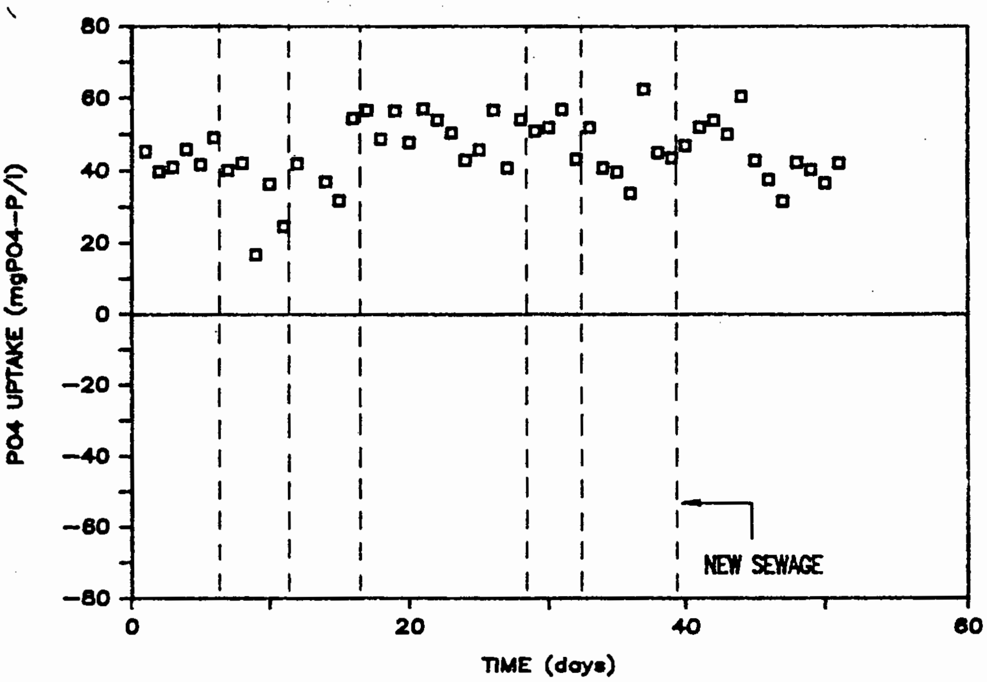


Fig 4.19: Daily performance of the phosphorus uptake in the third reactor of the 4 day sludge age Phoredox system.

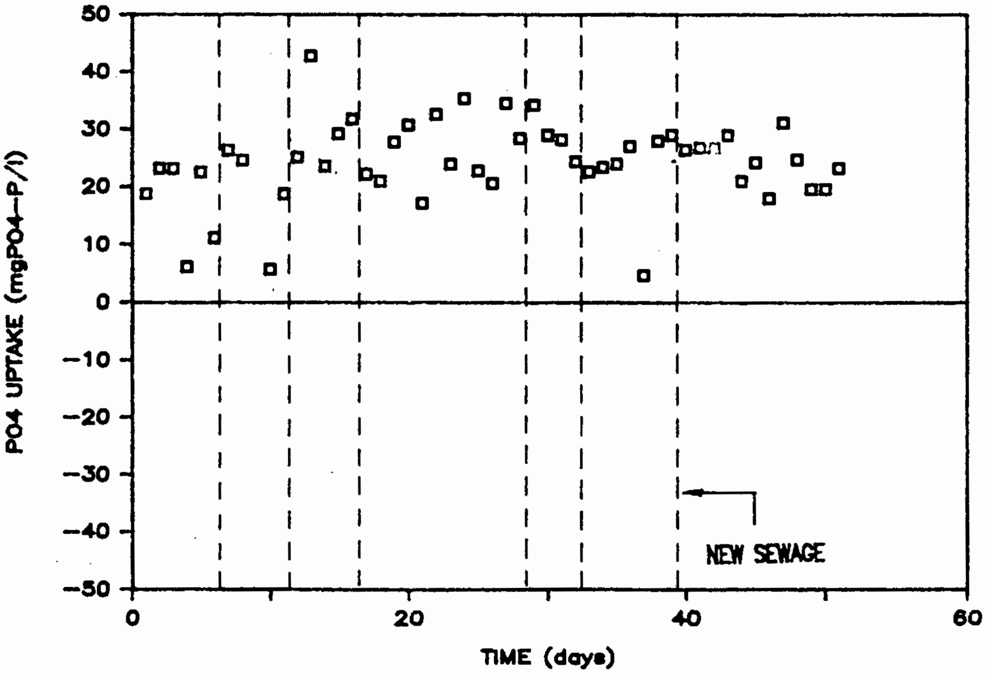


Fig 4.20: Daily performance of the phosphorus uptake in the fourth reactor of the 4 day sludge age Phoredox system.

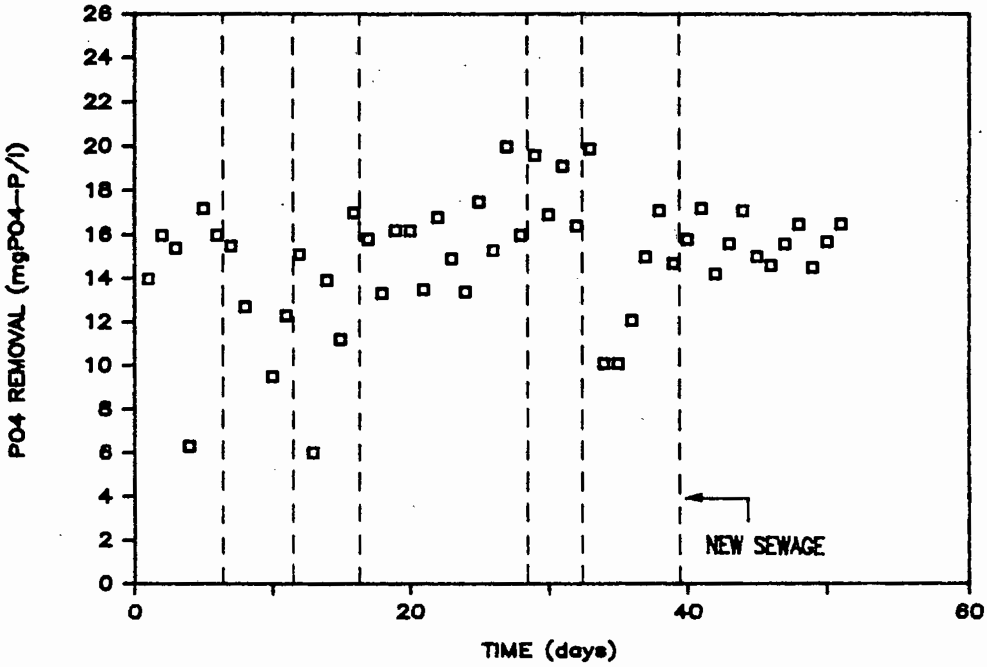


Fig 4.21: Daily performance of the phosphorus removal in the 4 day sludge age Phoredox system.

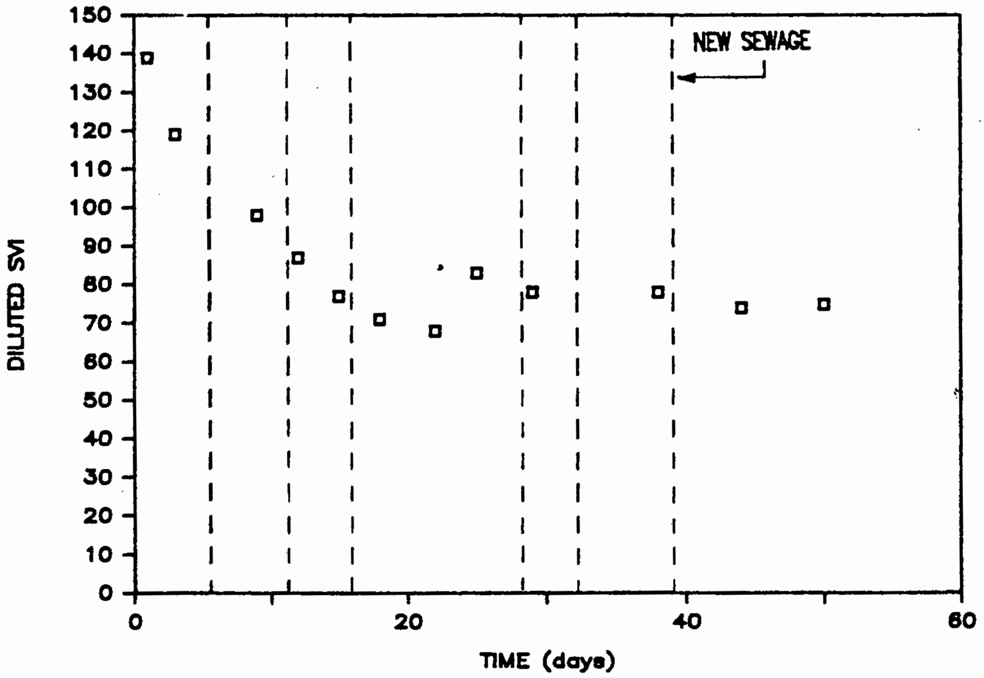


Fig 4.22: Daily performance of the Diluted Sludge Volume Index for the 4 day sludge age Phoredox system.

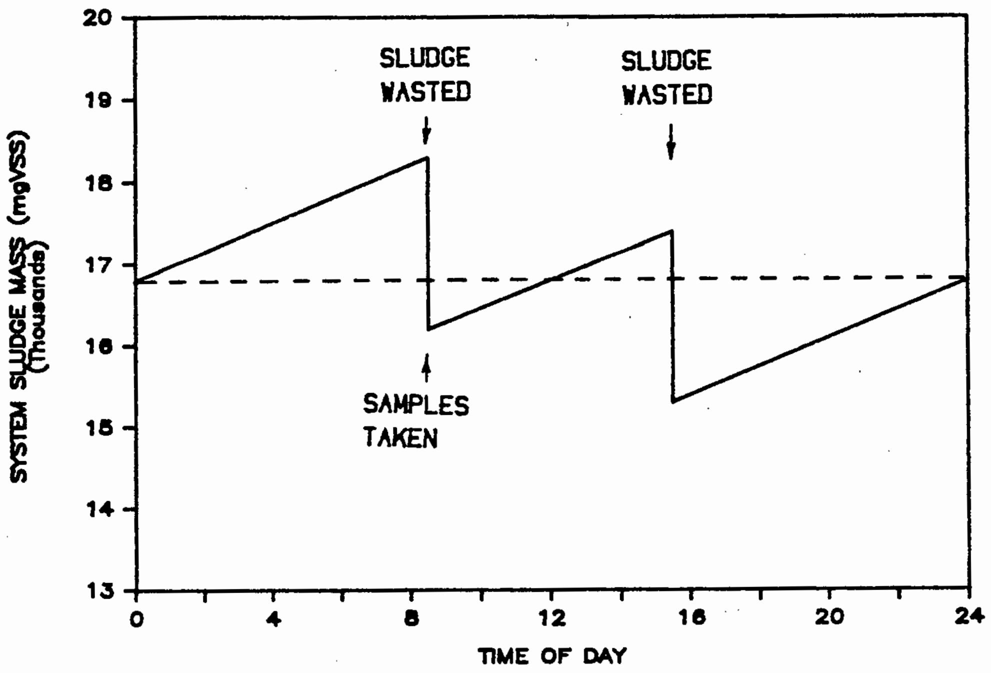


Fig 4.23: Daily variation in system sludge mass due to sludge age control wasting procedure.

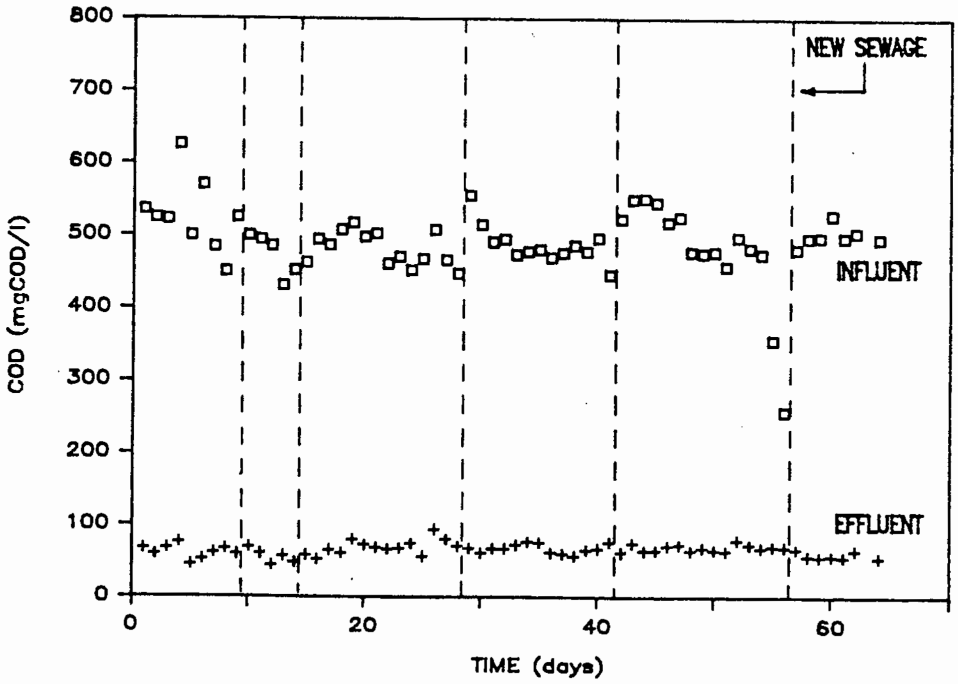


Fig 4.24: Daily performance of the unfiltered influent and filtered effluent COD concentrations for the 3 day sludge age Phoredox system.

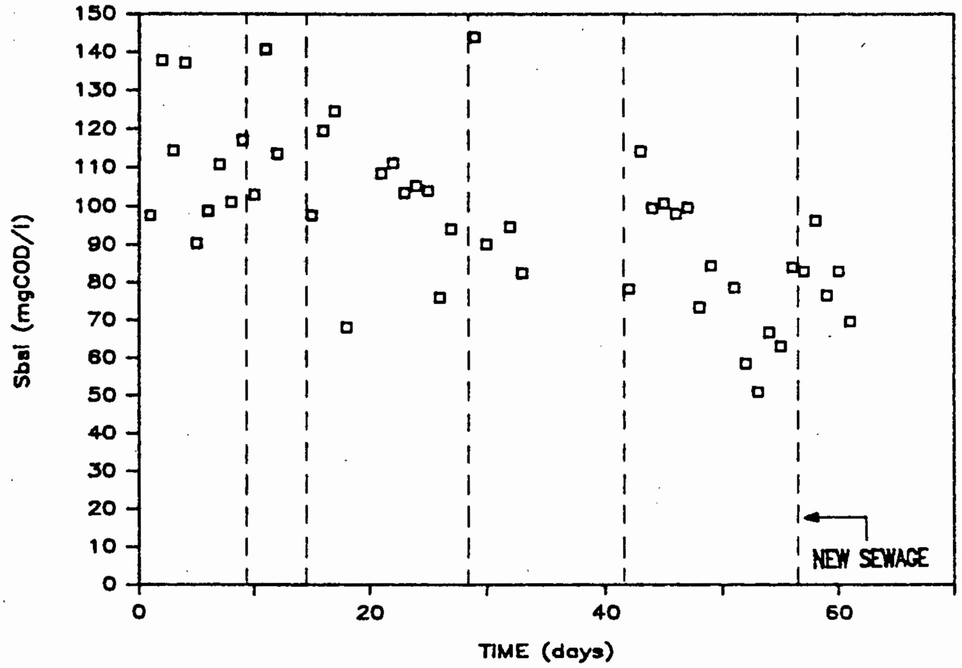


Fig 4.25: Daily performance of the influent readily biodegradable COD concentration for the 3 day sludge age Phoredox system.

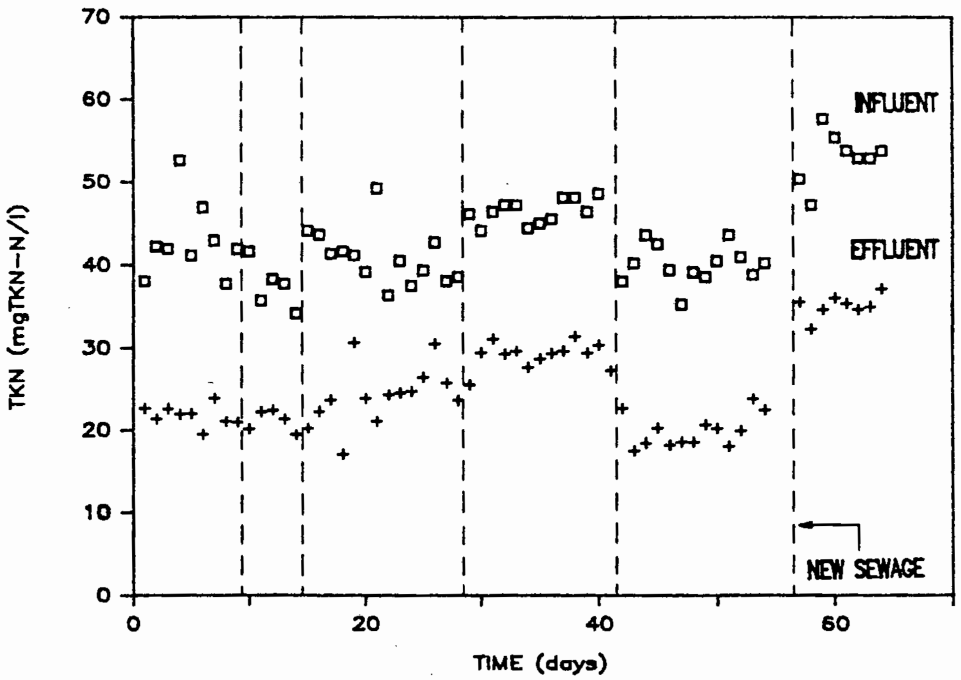


Fig 4.26: Daily performance of the unfiltered influent and filtered effluent TKN concentrations for the 3 day sludge age Phoredox system.

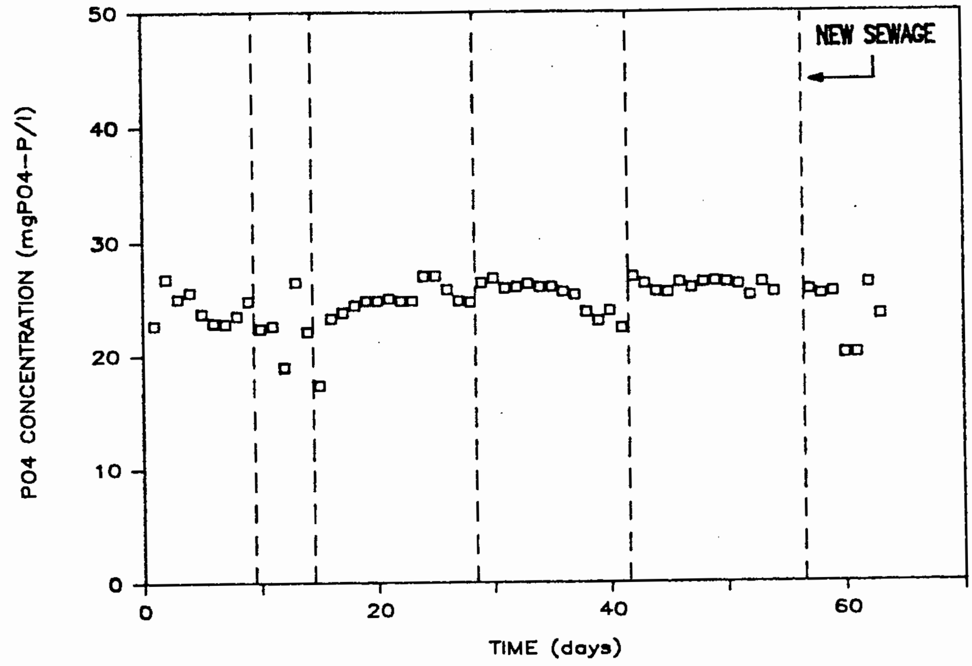


Fig 4.27: Daily performance of the phosphorus concentration in the influent to the 3 day sludge age Phoredox system.

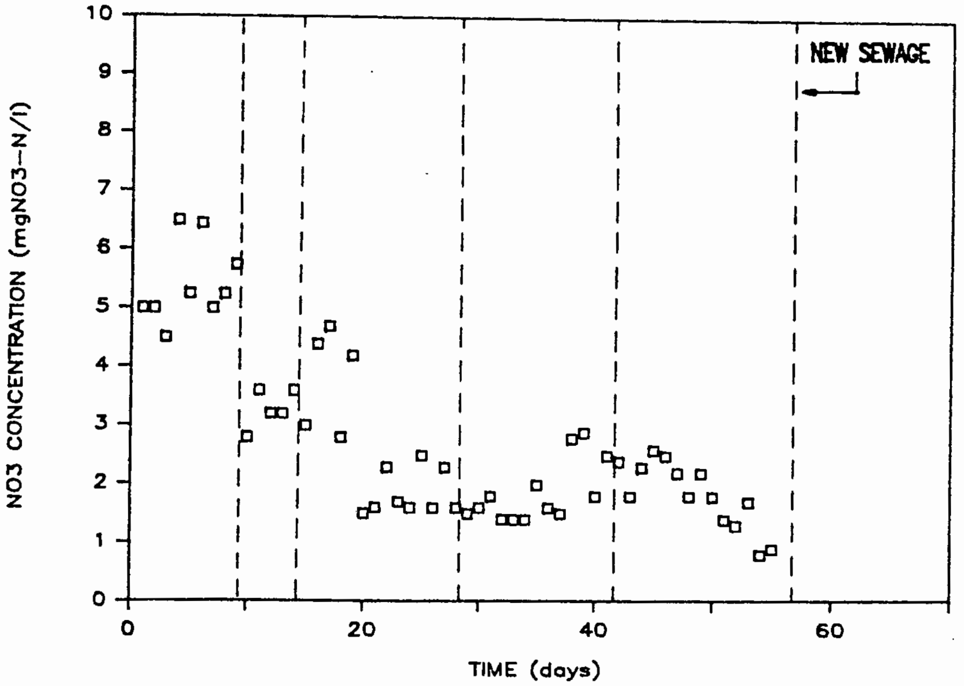


Fig 4.28: Daily performance of the nitrate concentration in the effluent from the 3 day sludge age Phoredox system.

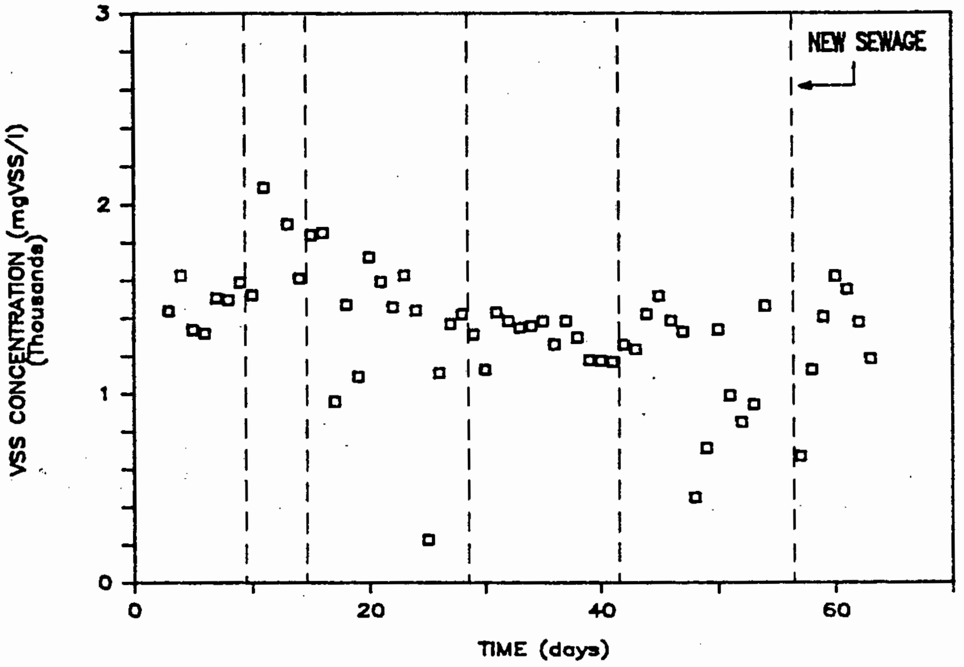


Fig 4.29: Daily performance of the volatile suspended solids in the first reactor of the 3 day sludge age Phoredox system.

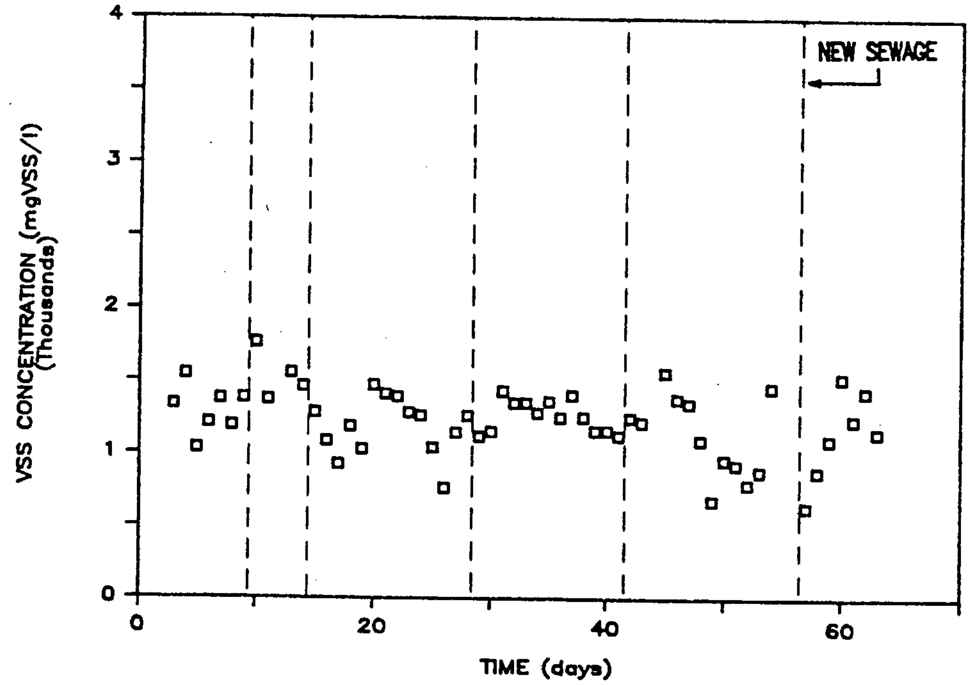


Fig 4.30: Daily performance of the volatile suspended solids in the second reactor of the 3 day sludge age Phoredox system.

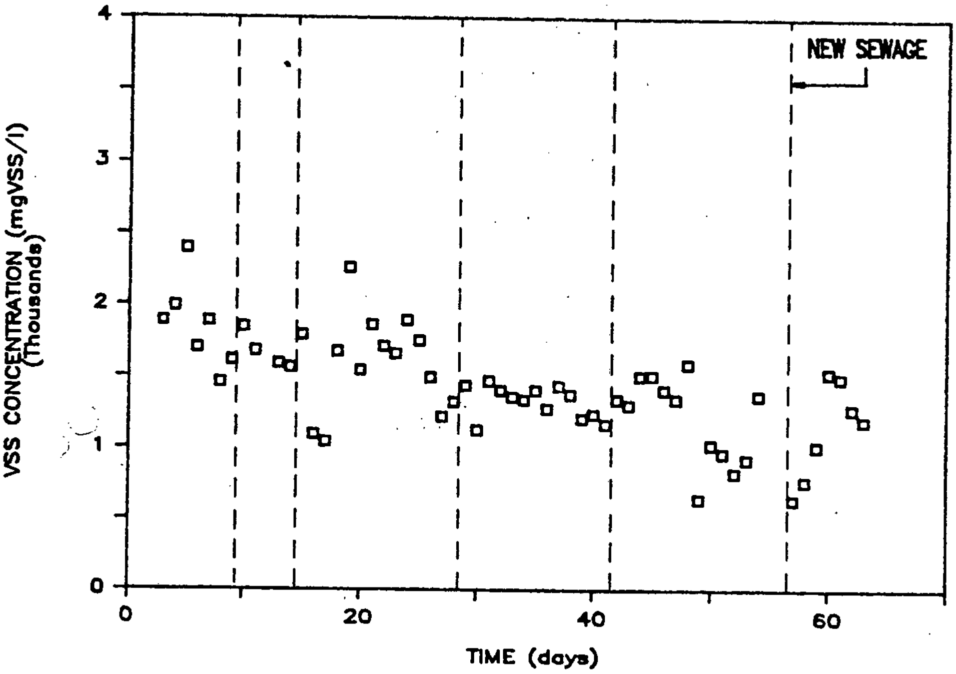


Fig 4.31: Daily performance of the volatile suspended solids in the third reactor of the 3 day sludge age Phoredox system.

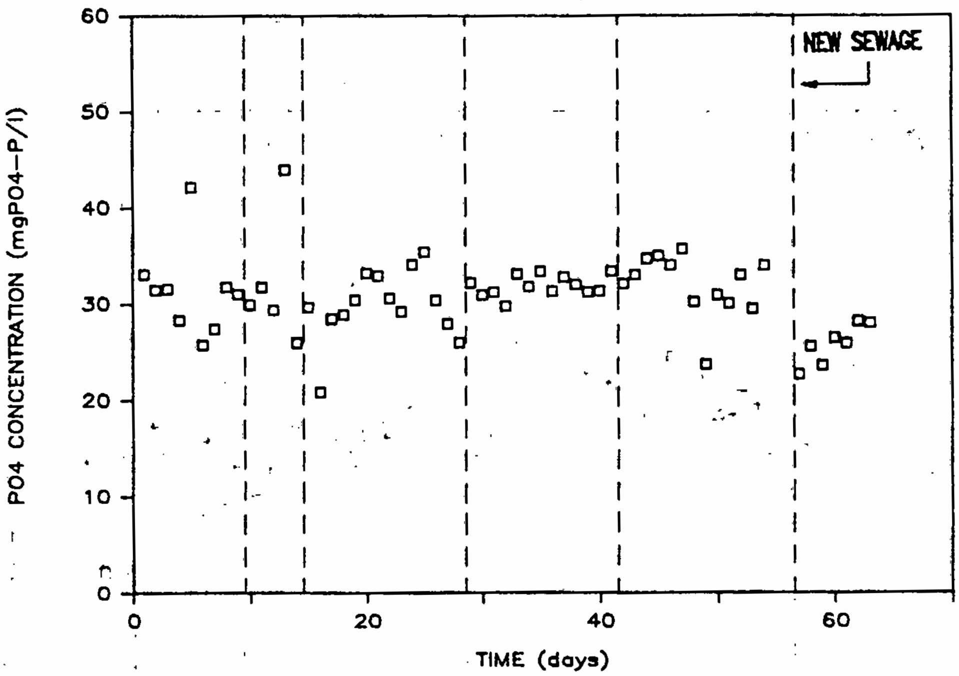


Fig 4.34: Daily performance of the phosphorus concentration in the first reactor of the 3 day sludge age Phoredox system.

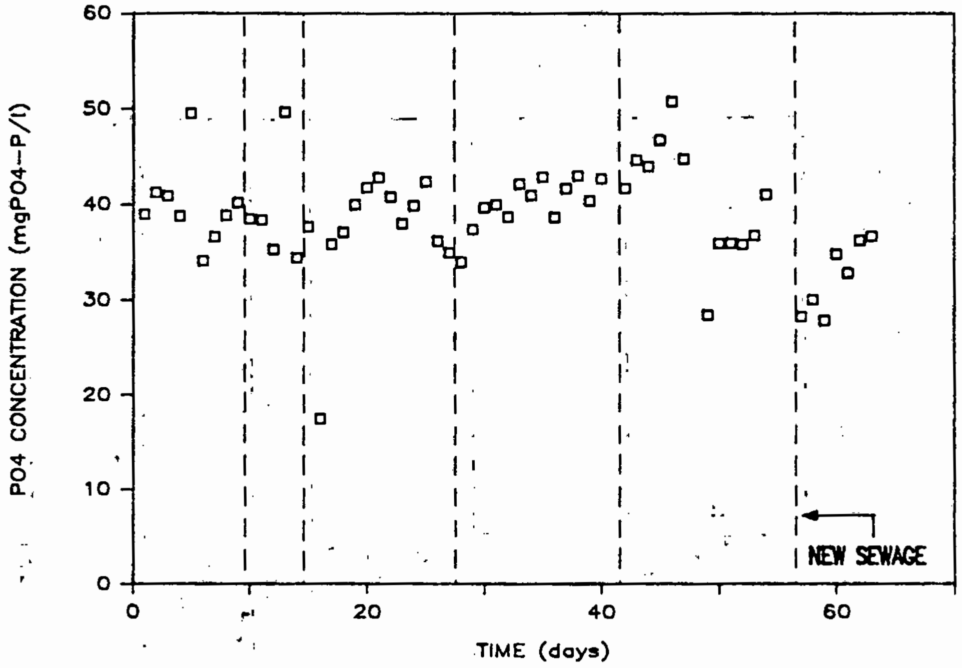


Fig 4.35: Daily performance of the phosphorus concentration in the second reactor of the 3 day sludge age Phoredox system.

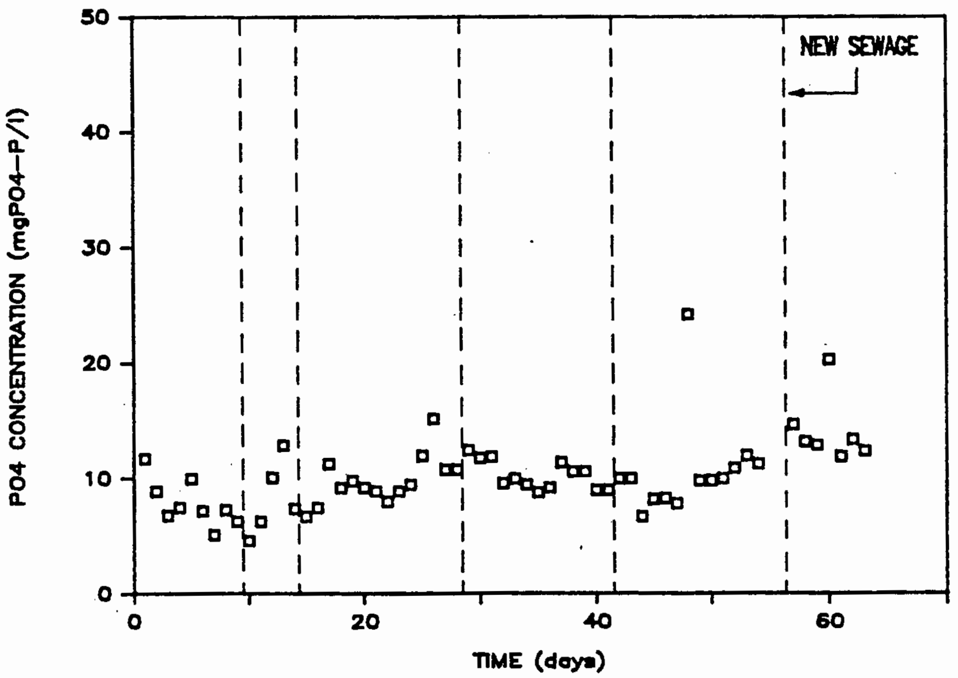


Fig 4.38: Daily performance of the phosphorus concentration in the filtered effluent from the 3 day sludge age Phoredox system.

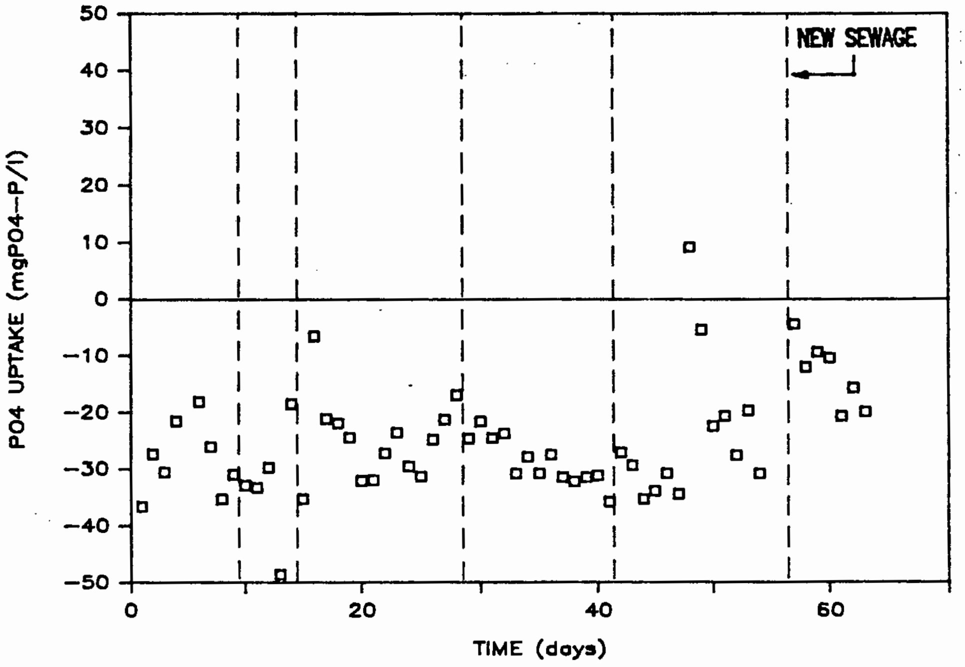


Fig 4.39: Daily performance of the phosphorus uptake in the first reactor of the 3 day sludge age Phoredox system.

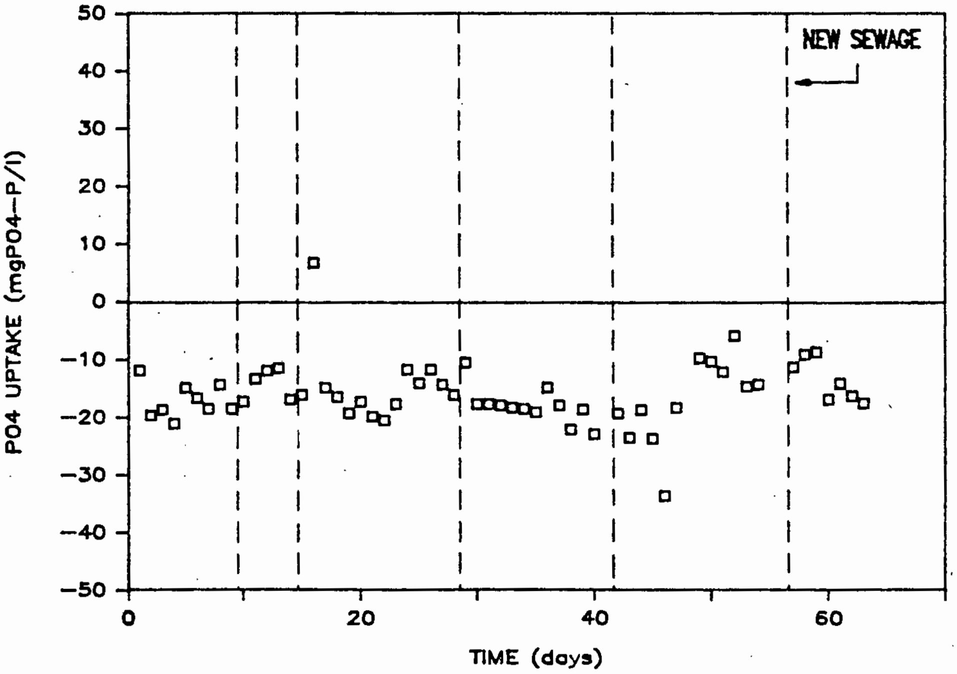


Fig 4.40: Daily performance of the phosphorus uptake in the second reactor of the 3 day sludge age Phoredox system.

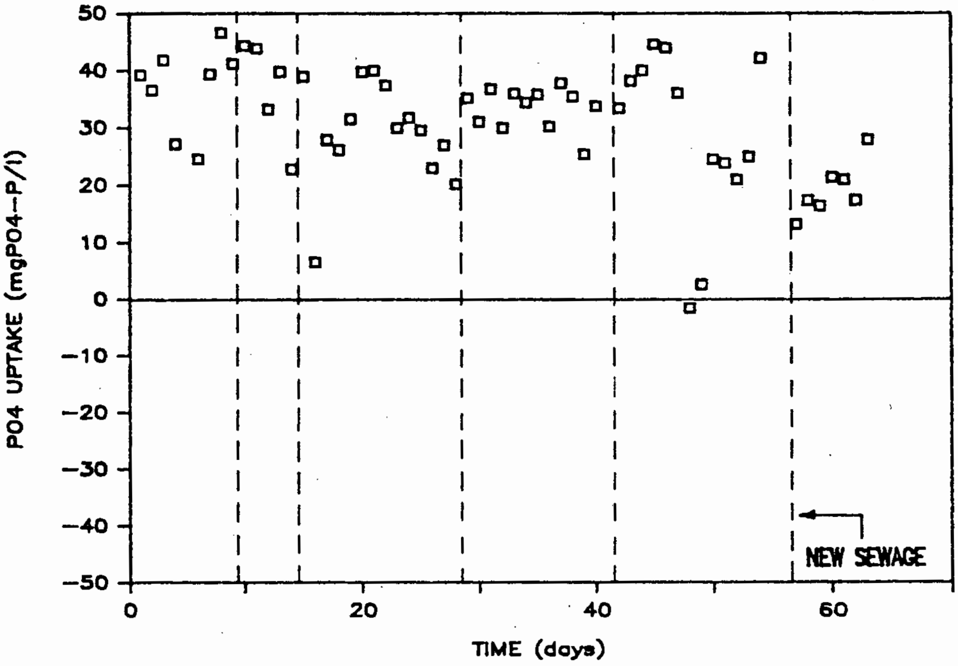


Fig 4.41: Daily performance of the phosphorus uptake in the third reactor of the 3 day sludge age Phoredox system.

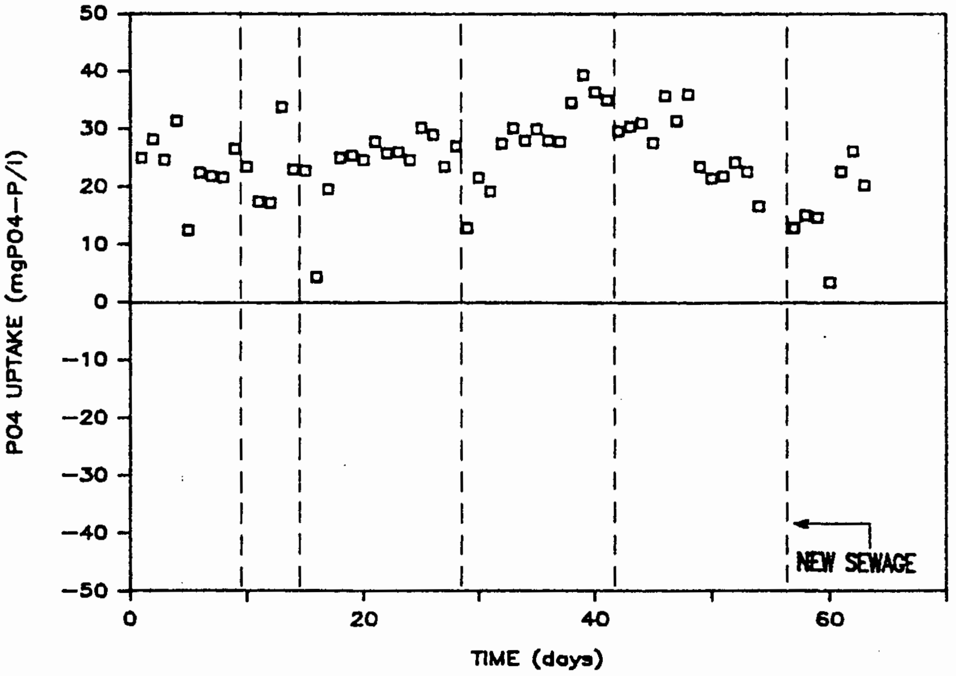


Fig 4.42: Daily performance of the phosphorus uptake in the fourth reactor of the 8 day sludge age Phoredox system.

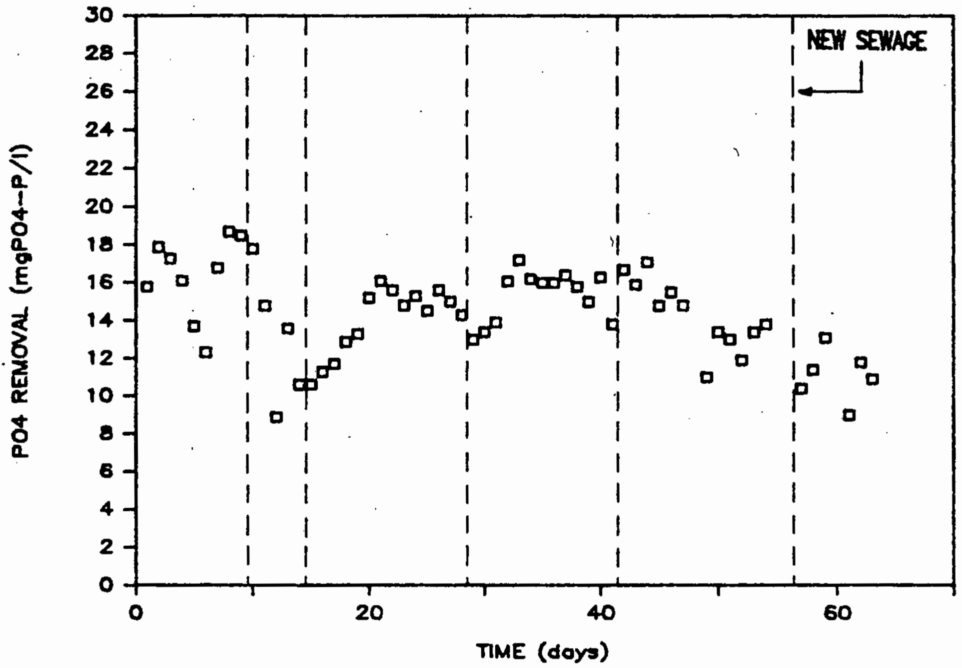


Fig 4.43: Daily performance of the phosphorus removal in the 3 day sludge age Phoredox system.

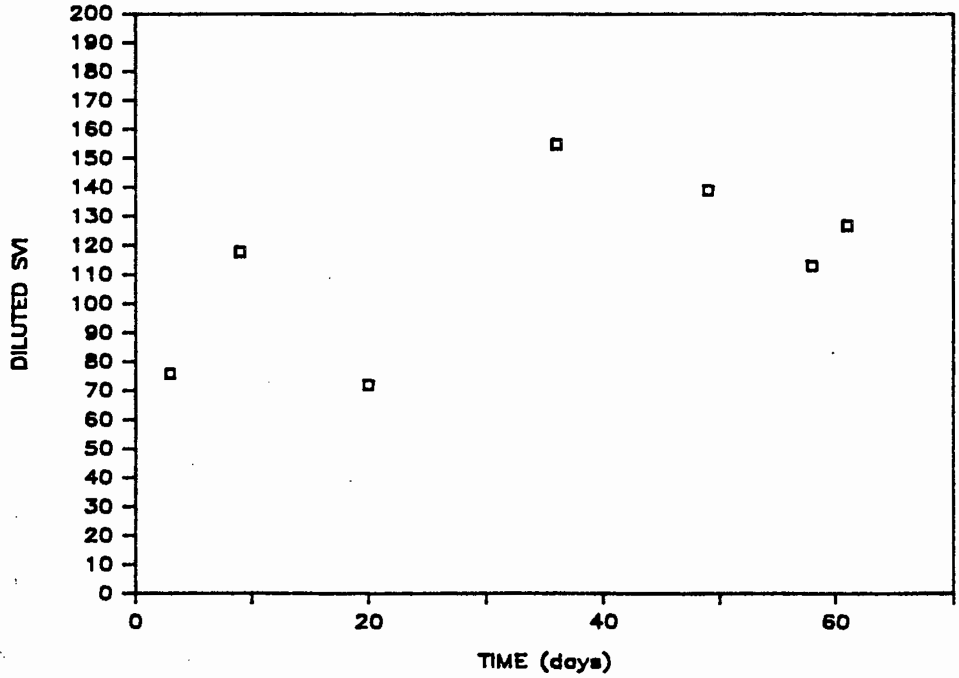
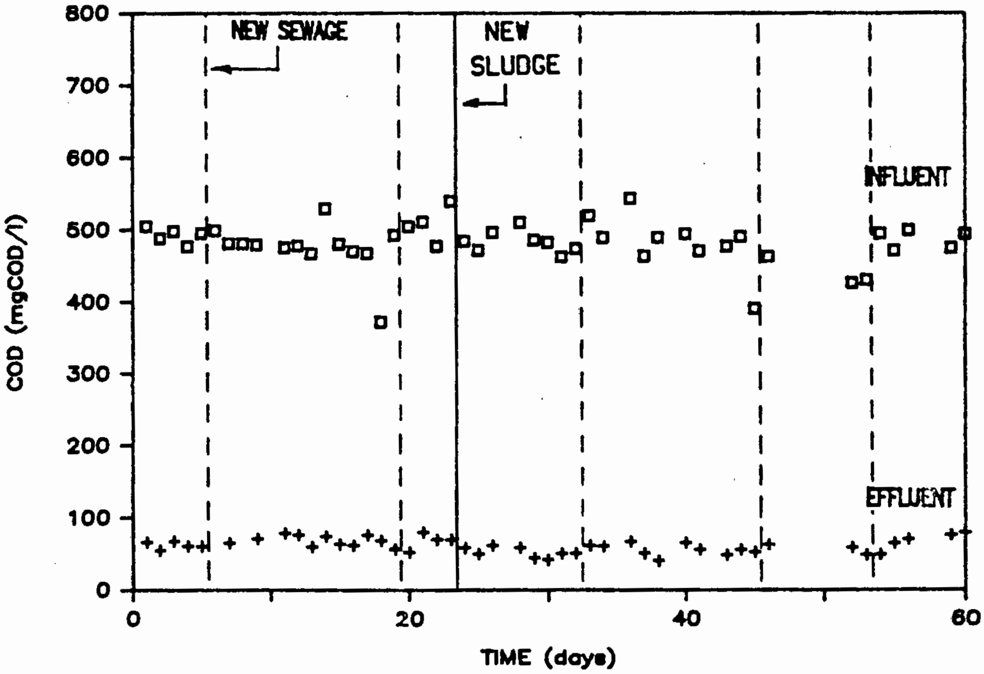
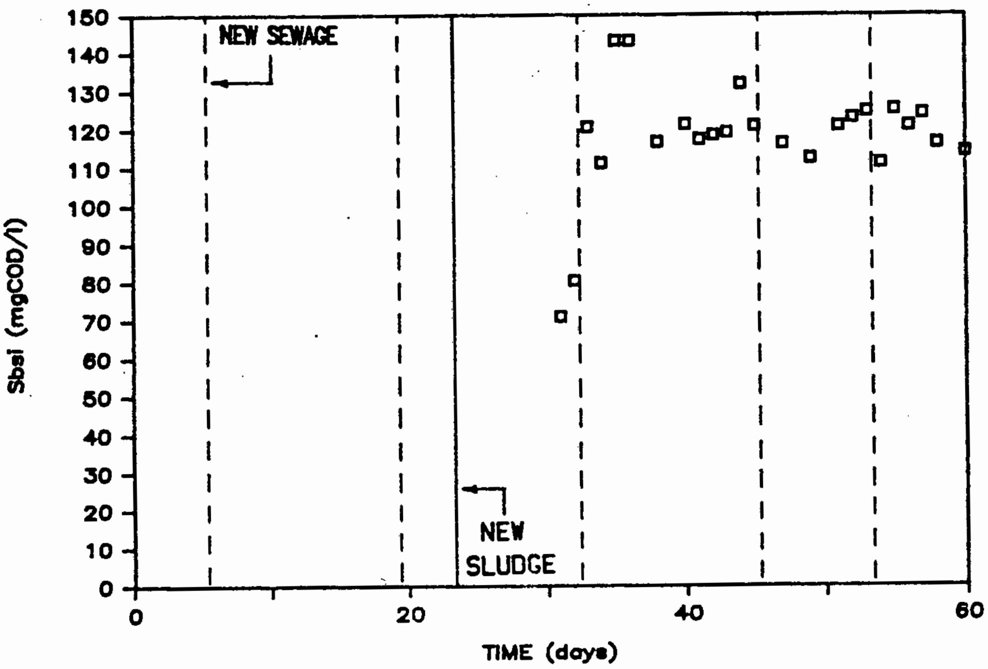


Fig 4.44: Daily performance of the Diluted Sludge Volume Index for the 3 day sludge age Phoredox system.



<u>Fig 4.45</u>: **Daily performance of the unfiltered influent and filtered effluent COD concentrations for the 3 day sludge age Phoredox system (repeat investigation).**



<u>Fig 4.46</u>: **Daily performance of the influent readily biodegradable COD concentration for the 3 day sludge age Phoredox system (repeat investigation).**

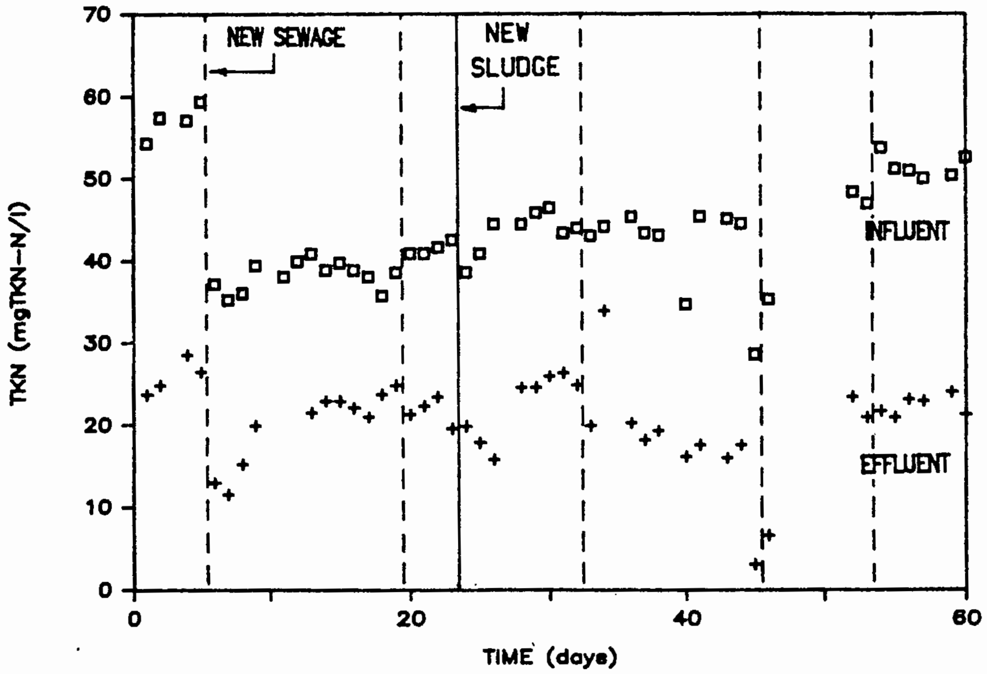


Fig 4.47: Daily performance of the unfiltered influent and filtered effluent TKN concentrations for the 3 day sludge age Phoredox system (repeat investigation).

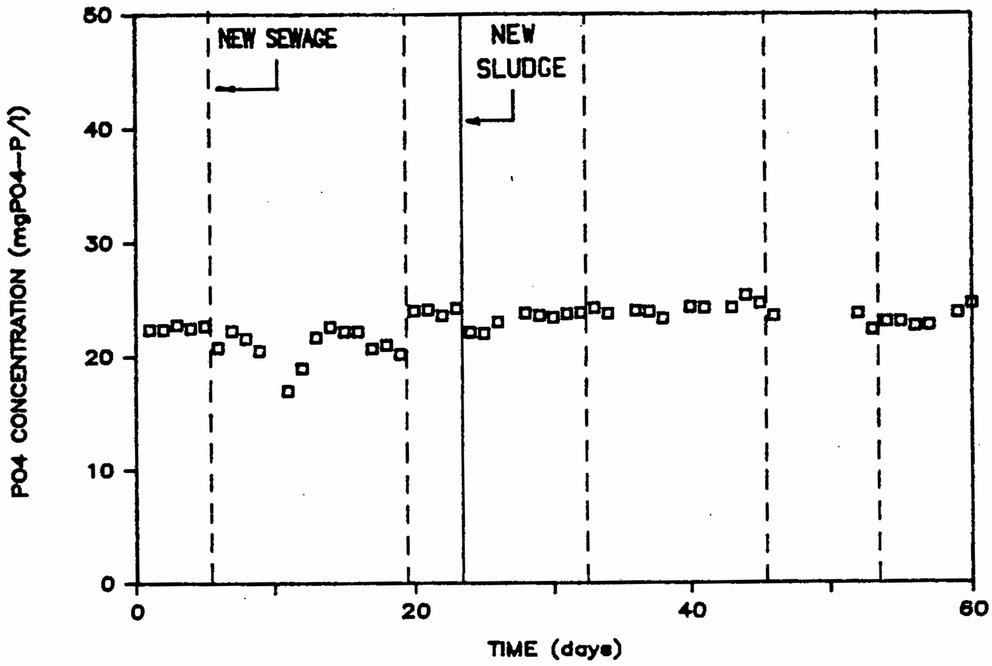


Fig 4.48: Daily performance of the phosphorus concentration in the influent to the 3 day sludge age Phoredox system (repeat investigation).

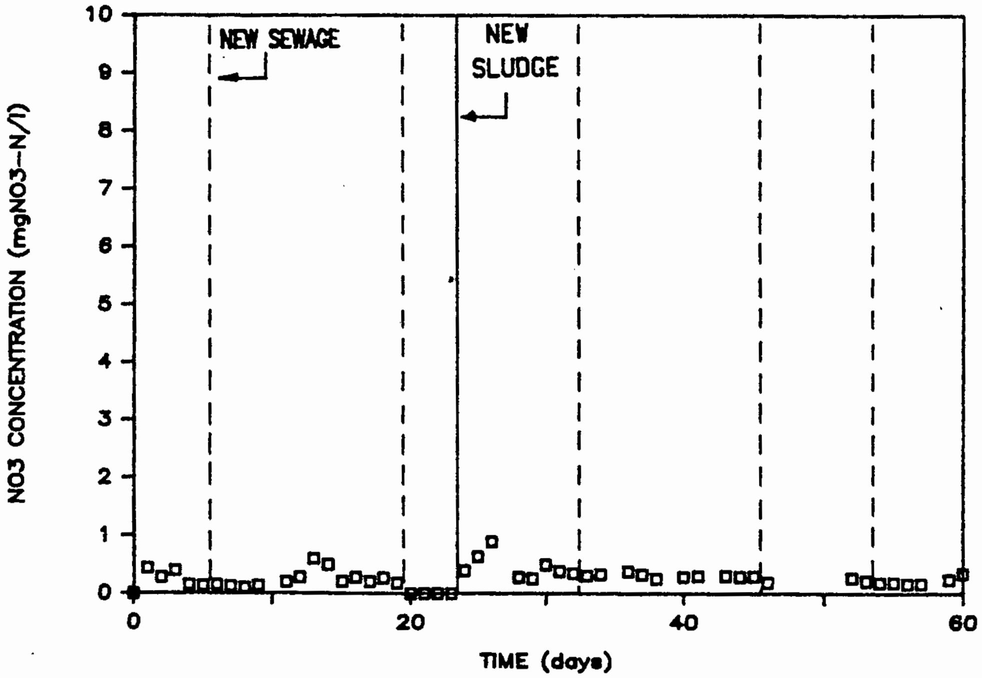


Fig 4.49: Daily performance of the nitrate concentration in the first reactor of the 3 day sludge age Phoredox system (repeat investigation).

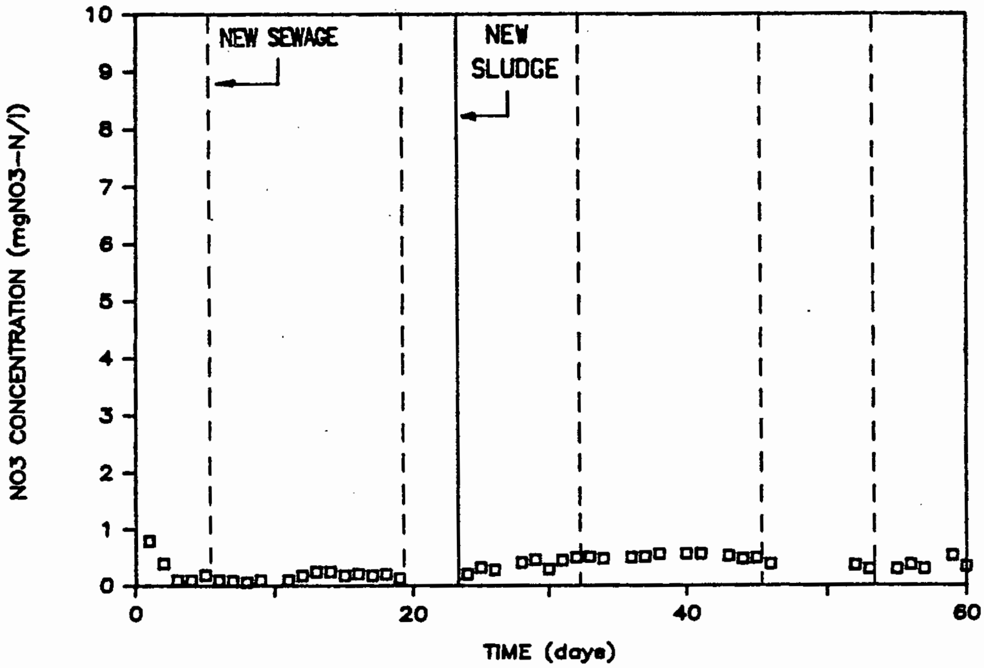


Fig 4.50: Daily performance of the nitrate concentration in the second reactor of the 3 day sludge age Phoredox system (repeat investigation).

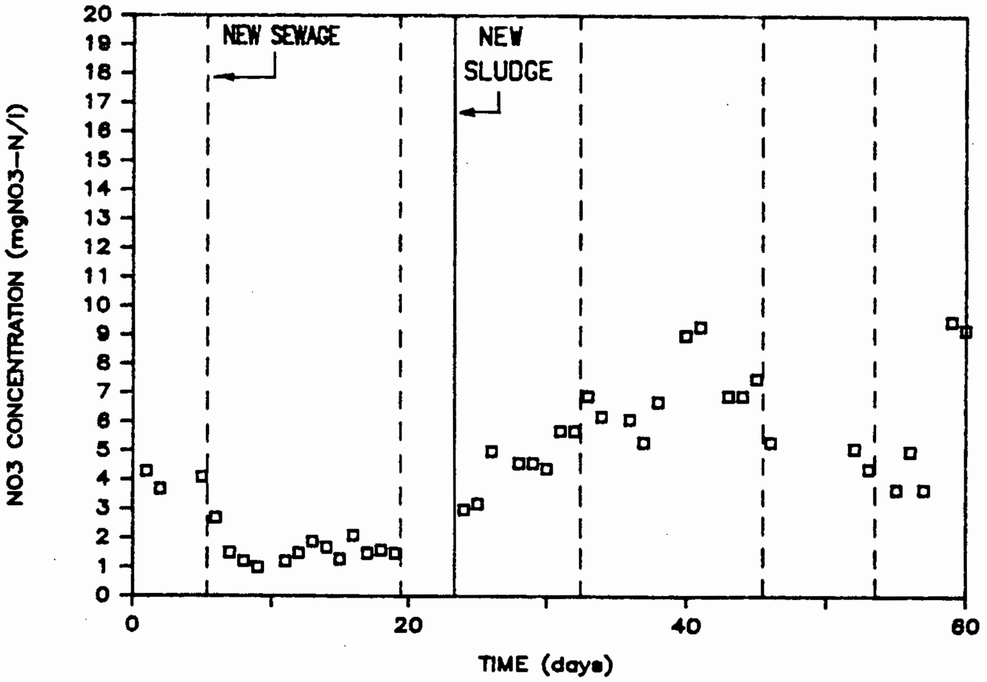


Fig 4.51: Daily performance of the nitrate concentration in the third reactor of the 3 day sludge age Phoredox system (repeat investigation).

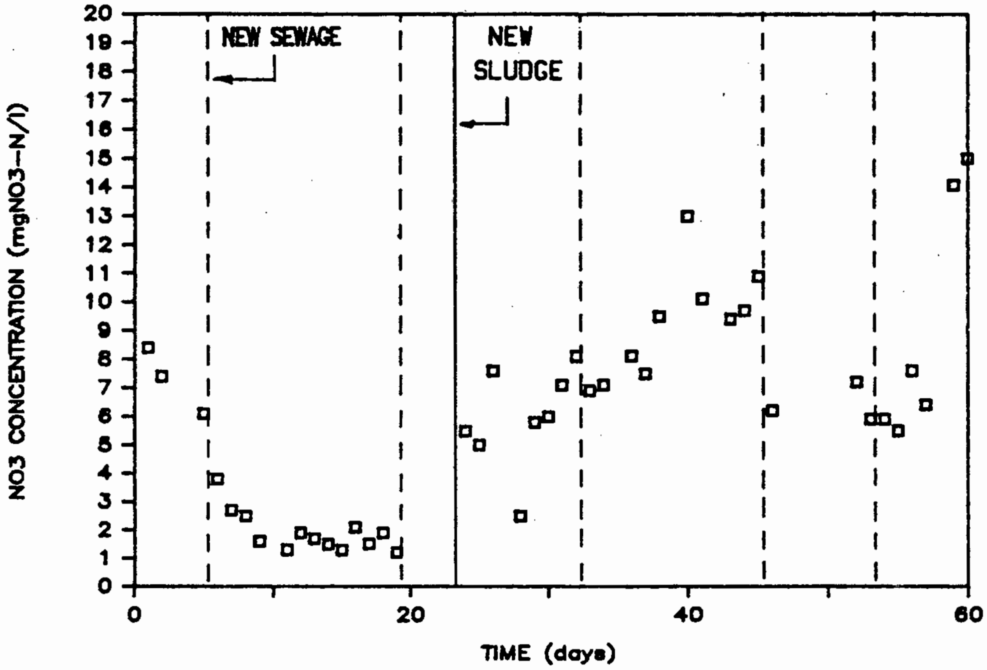


Fig 4.52: Daily performance of the nitrate concentration in the fourth reactor of the 3 day sludge age Phoredox system (repeat investigation).

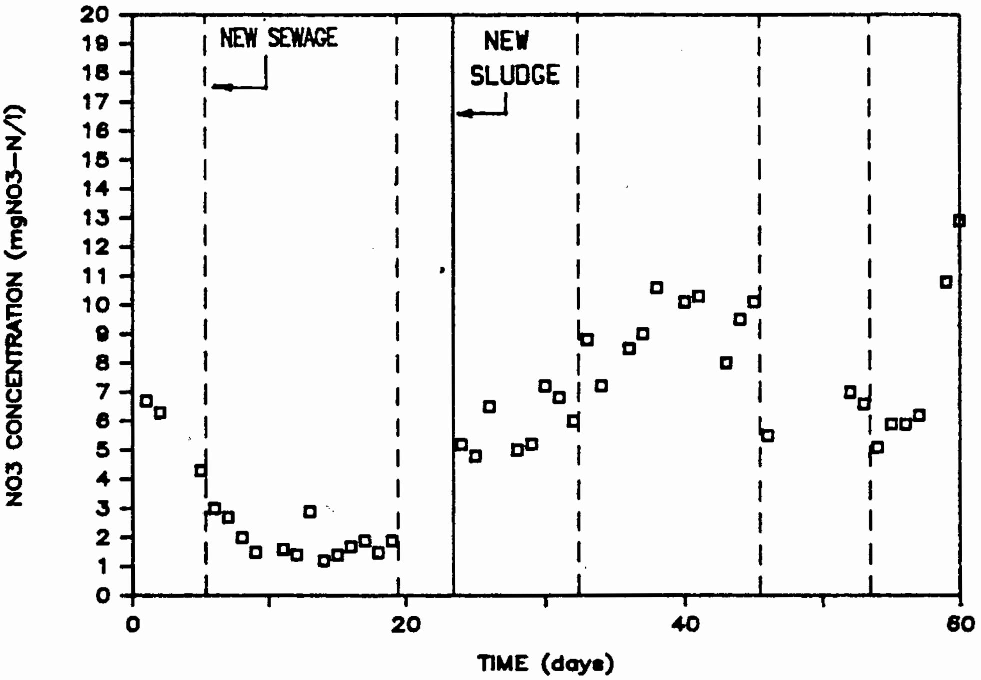


Fig 4.53: Daily performance of the nitrate concentration in the effluent from the 3 day sludge age Phoredox system (repeat investigation).

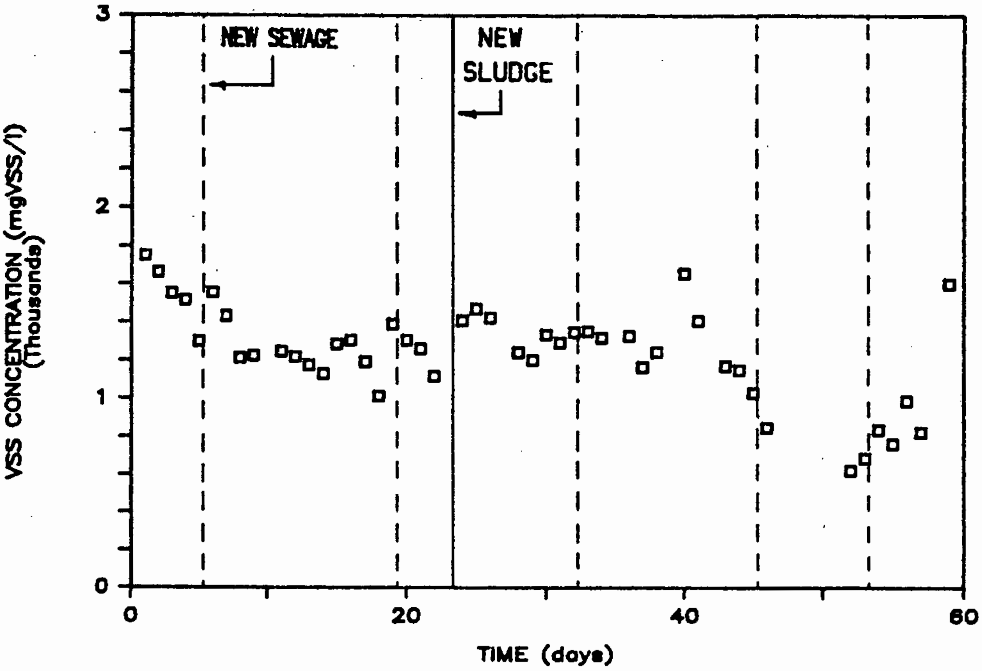


Fig 4.54: Daily performance of the volatile suspended solids in the first reactor of the 3 day sludge age Phoredox system (repeat investigation).

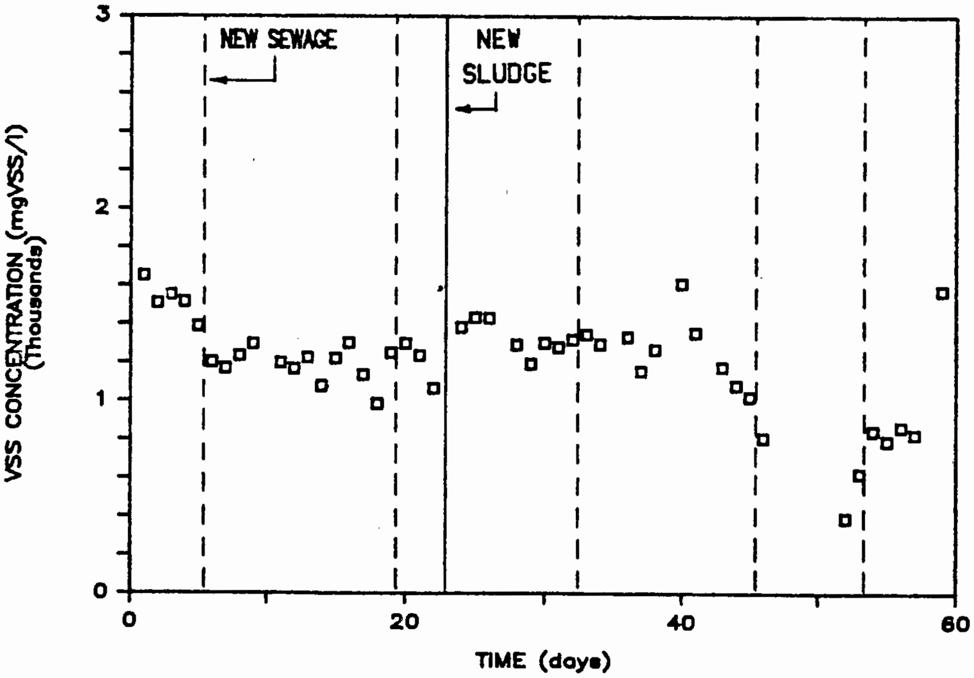


Fig 4.55: Daily performance of the volatile suspended solids in the second reactor of the 3 day sludge age Phoredox system (repeat investigation).

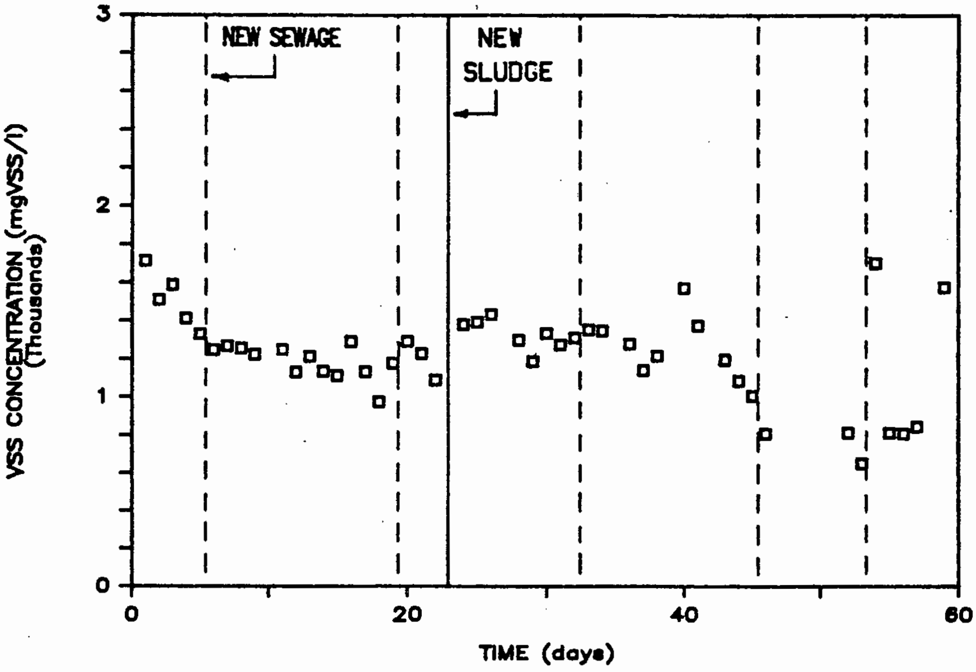


Fig 4.56: Daily performance of the volatile suspended solids in the third reactor of the 3 day sludge age Phoredox system (repeat investigation).

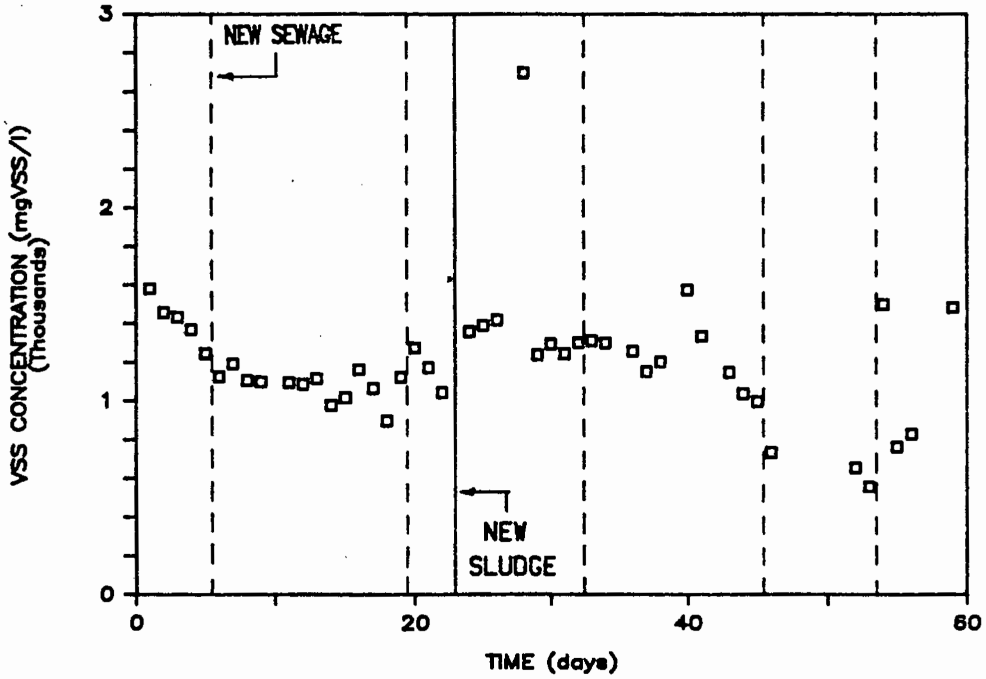


Fig 4.57: Daily performance of the volatile suspended solids in the fourth reactor of the 3 day sludge age Phoredox system (repeat investigation).

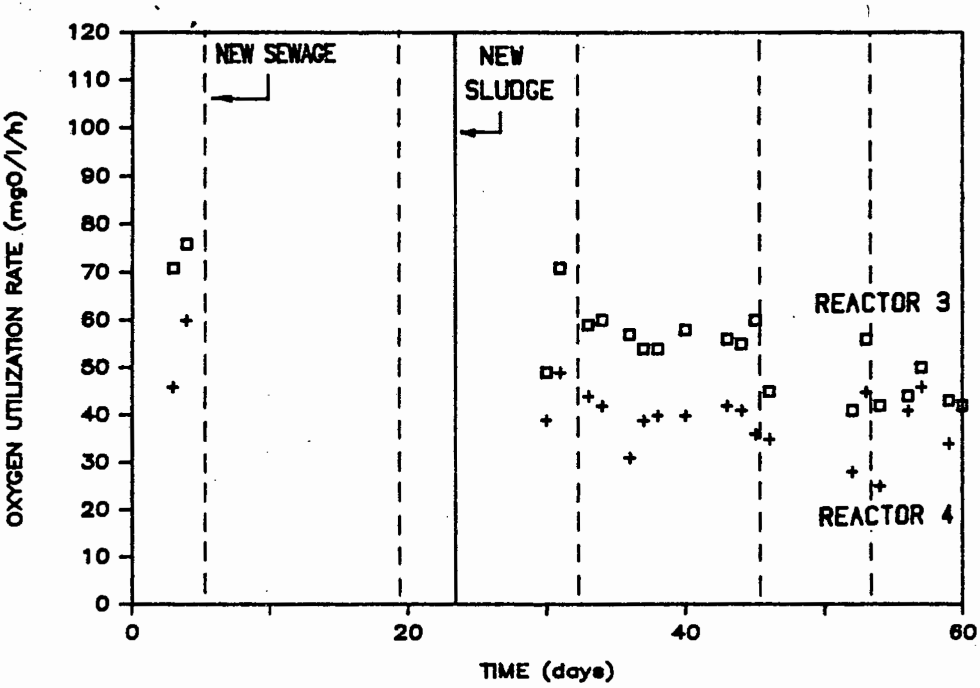


Fig 4.58: Daily performance of the oxygen utilisation rates in the aerobic reactors of the 3 day sludge age Phoredox system (repeat investigation).

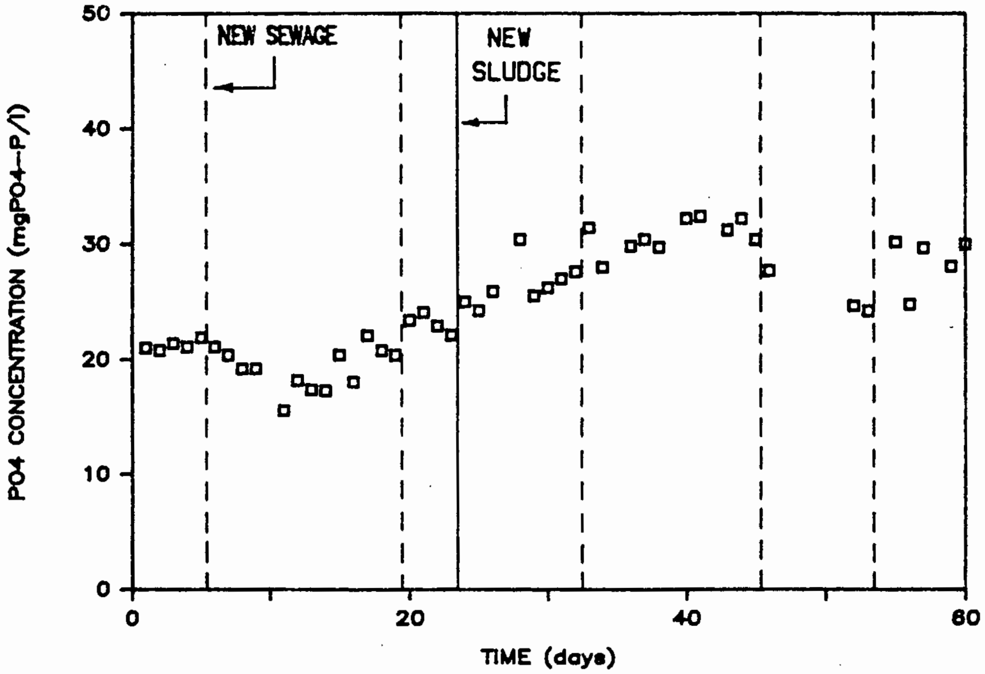


Fig 4.59: Daily performance of the phosphorus concentration in the first reactor of the 3 day sludge age Phoredox system (repeat investigation).

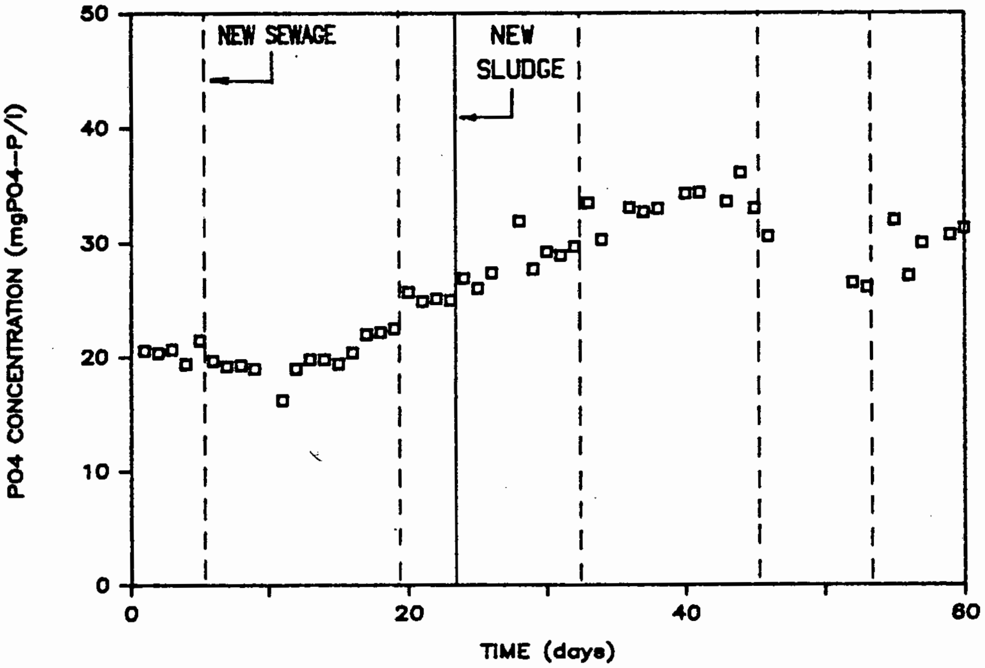


Fig 4.60: Daily performance of the phosphorus concentration in the second reactor of the 3 day sludge age Phoredox system (repeat investigation).

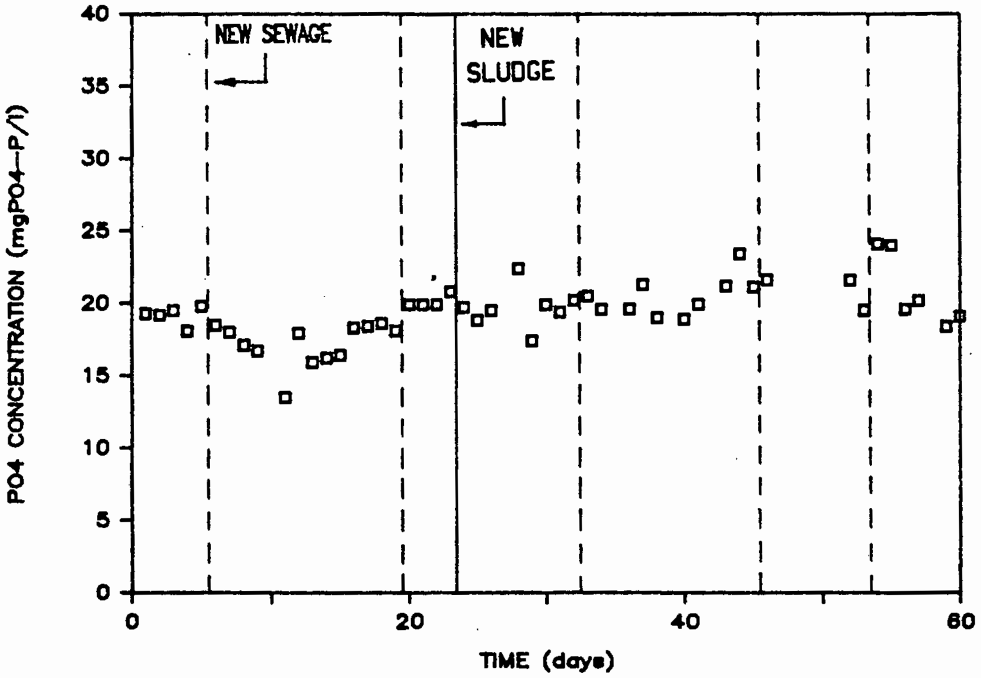


Fig 4.61: Daily performance of the phosphorus concentration in the third reactor of the 3 day sludge age Phoredox system (repeat investigation).

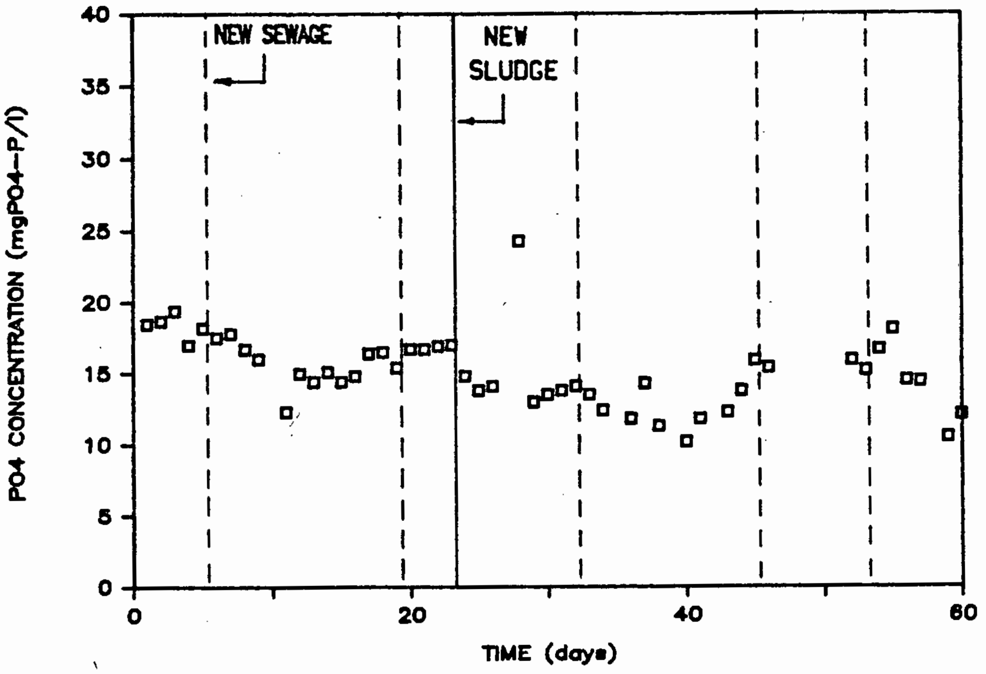


Fig 4.62: Daily performance of the phosphorus concentration in the fourth reactor of the 3 day sludge age Phoredox system (repeat investigation).

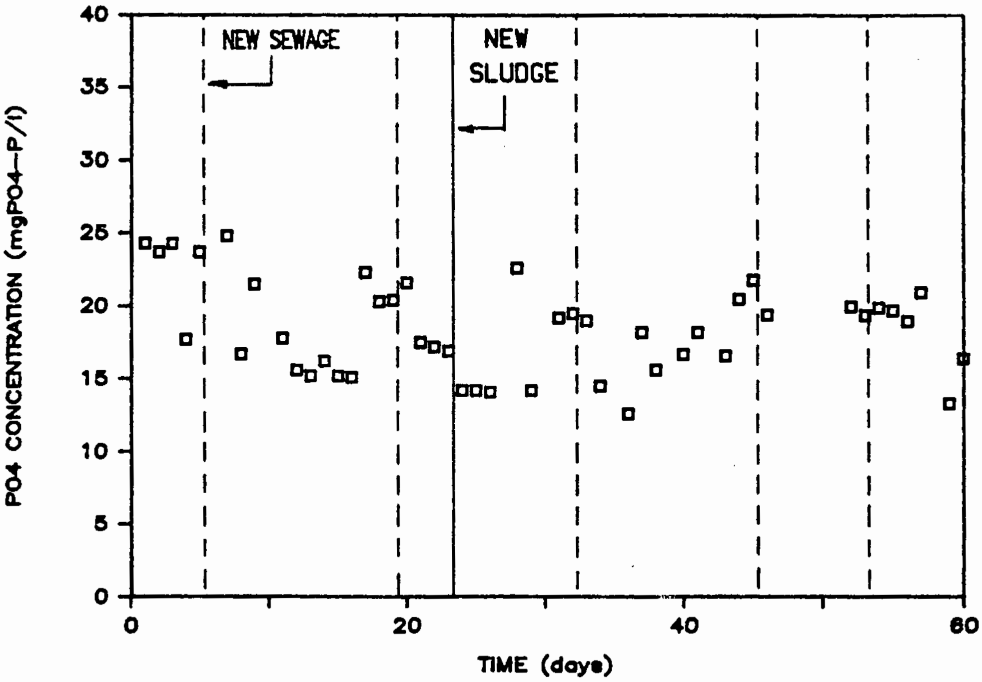


Fig 4.63: Daily performance of the phosphorus concentration in the filtered effluent from the 3 day sludge age Phoredox system (repeat investigation).

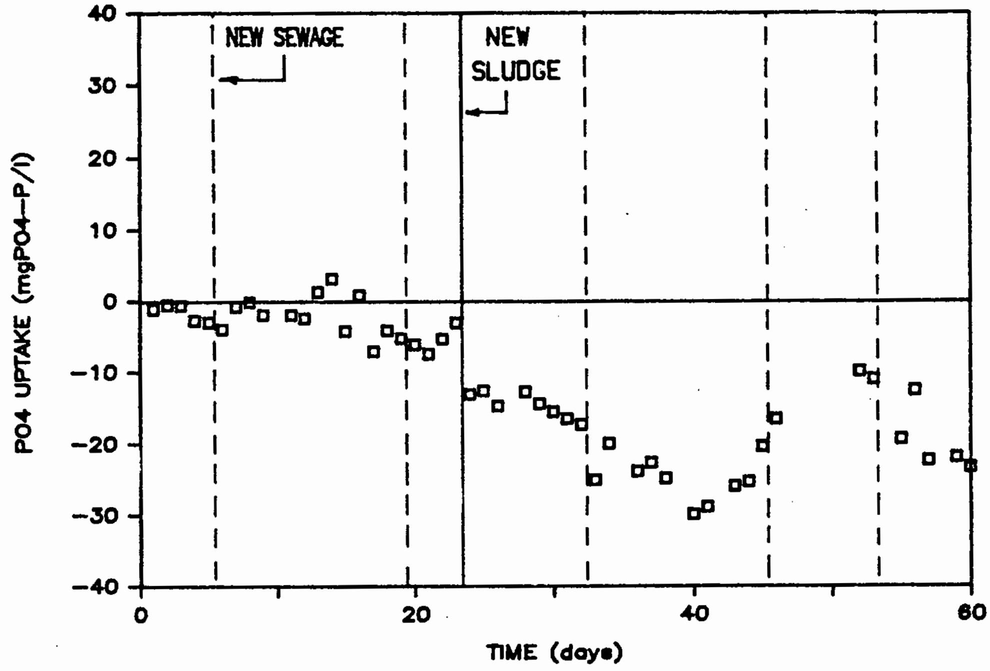


Fig 4.64: Daily performance of the phosphorus uptake in the first reactor of the 3 day sludge age Phoredox system (repeat investigation).

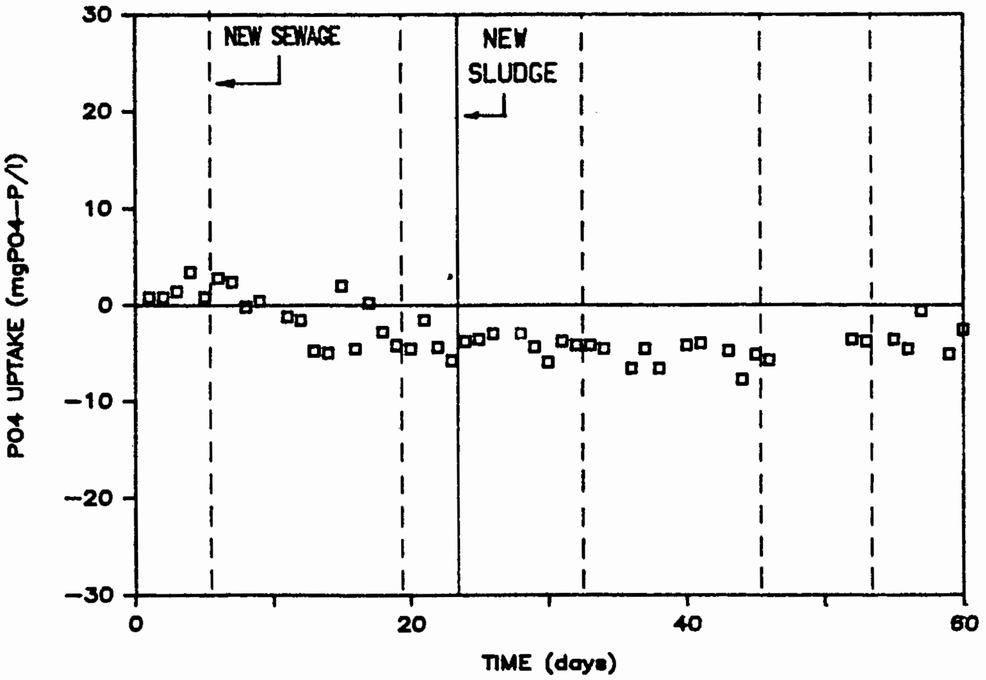


Fig 4.65: Daily performance of the phosphorus uptake in the second reactor of the 3 day sludge age Phoredox system (repeat investigation).

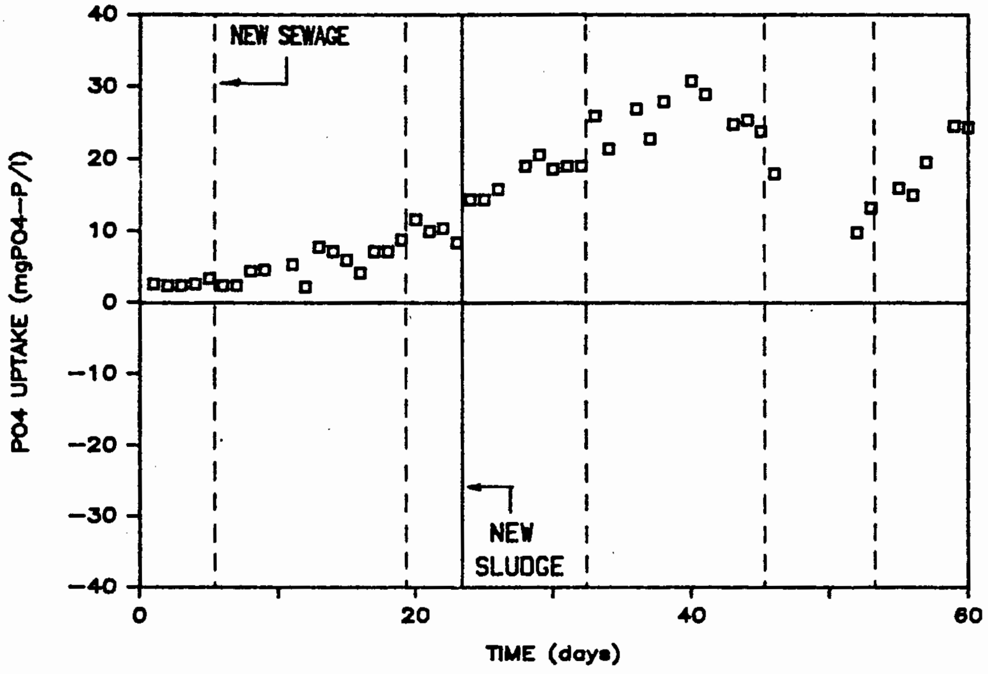


Fig 4.66: Daily performance of the phosphorus uptake in the third reactor of the 3 day sludge age Phoredox system (repeat investigation).

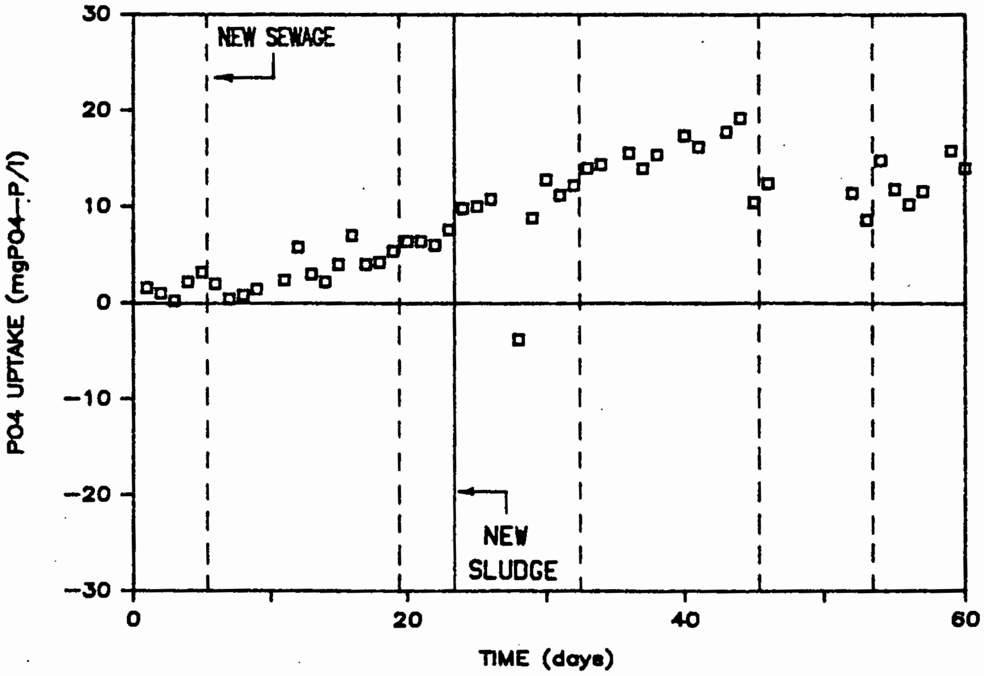


Fig 4.67: Daily performance of the phosphorus uptake in the fourth reactor of the 3 day sludge age Phoredox system (repeat investigation).

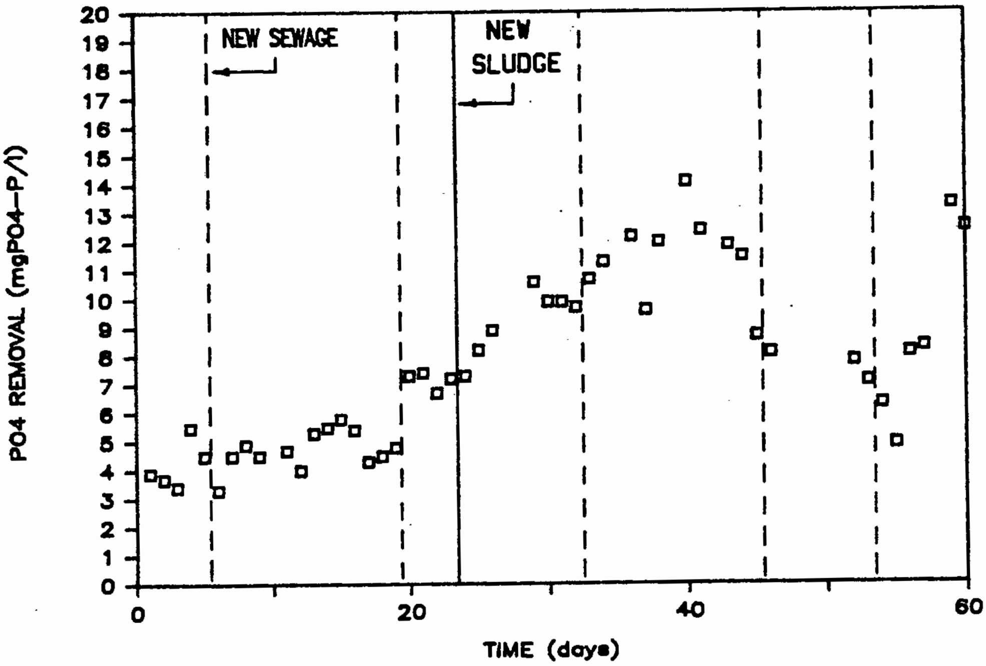


Fig 4.68: Daily performance of the phosphorus removal in the 3 day sludge age Phoredox system (repeat investigation).

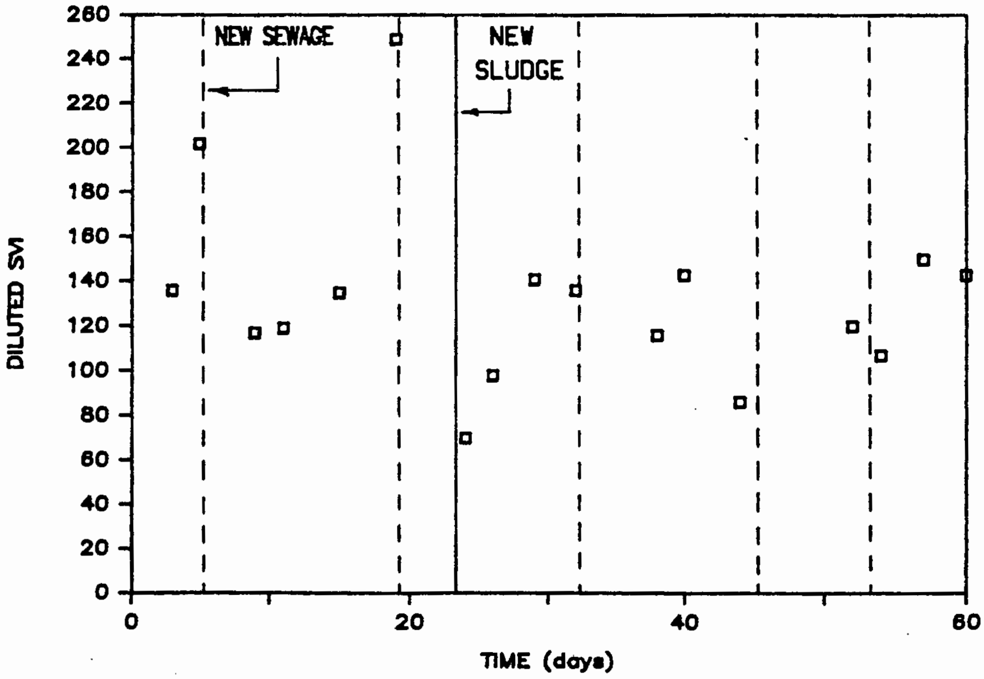


Fig 4.69: Daily performance of the Diluted Sludge Volume Index for the 3 day sludge age Phoredox system (repeat investigation).

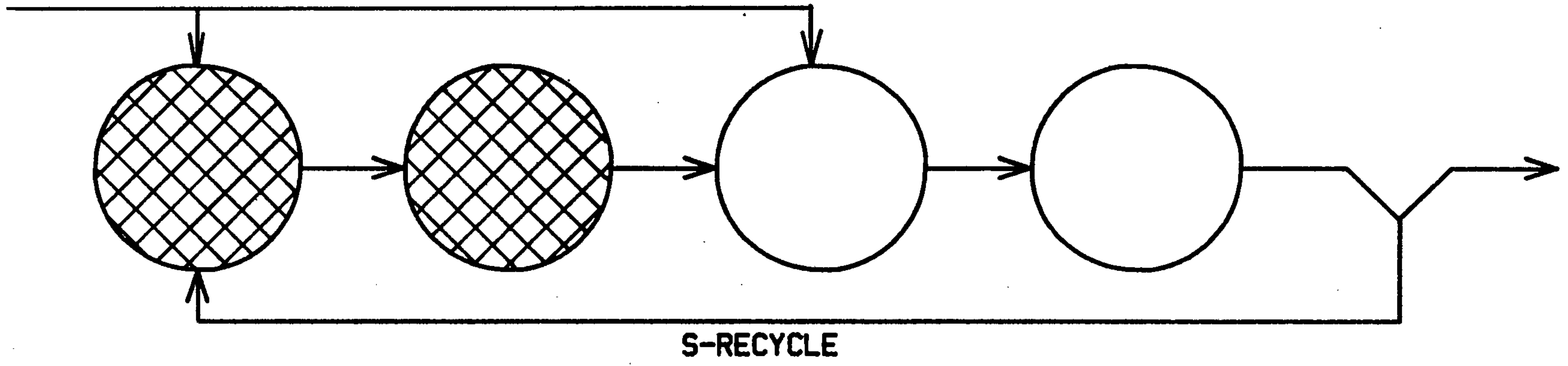


Fig 4.70: Schematic diagram of the Split-feed configuration without the selector reactor.

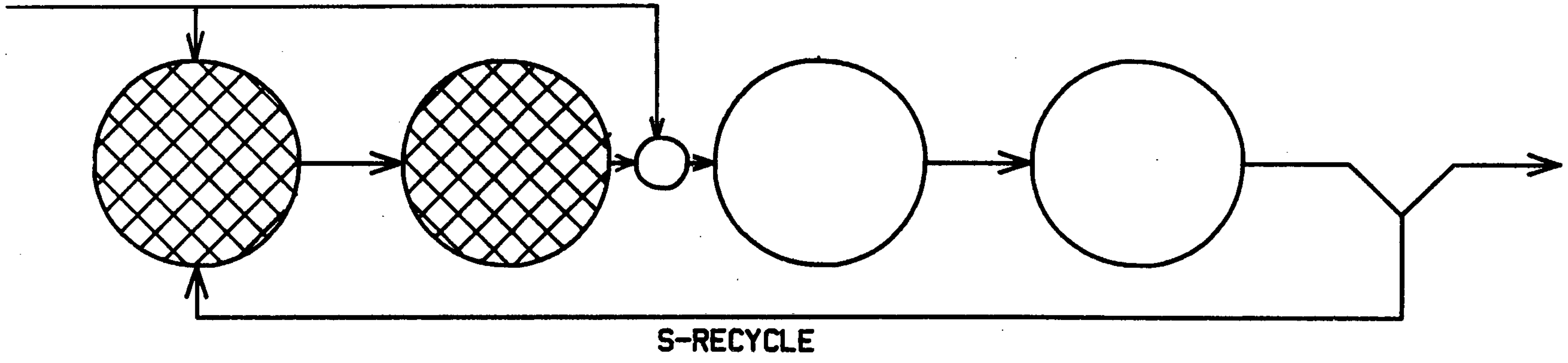


Fig 4.71: Schematic diagram of the Split-feed configuration with the selector reactor.

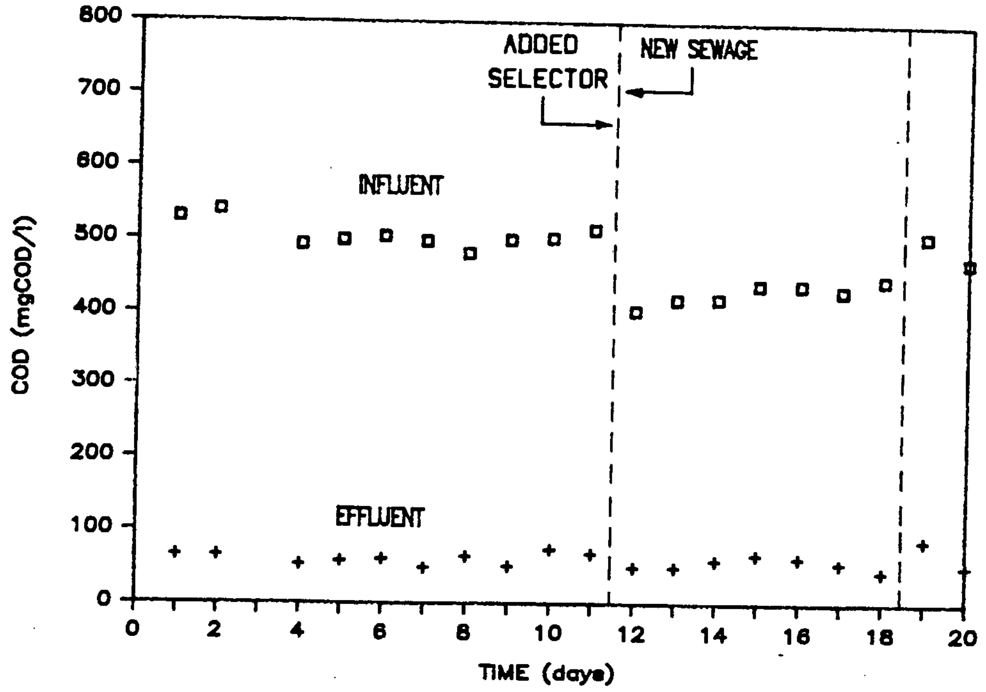


Fig 4.72: Daily performance of the unfiltered influent and filtered effluent COD concentrations for the 3 day sludge age Split-feed system.

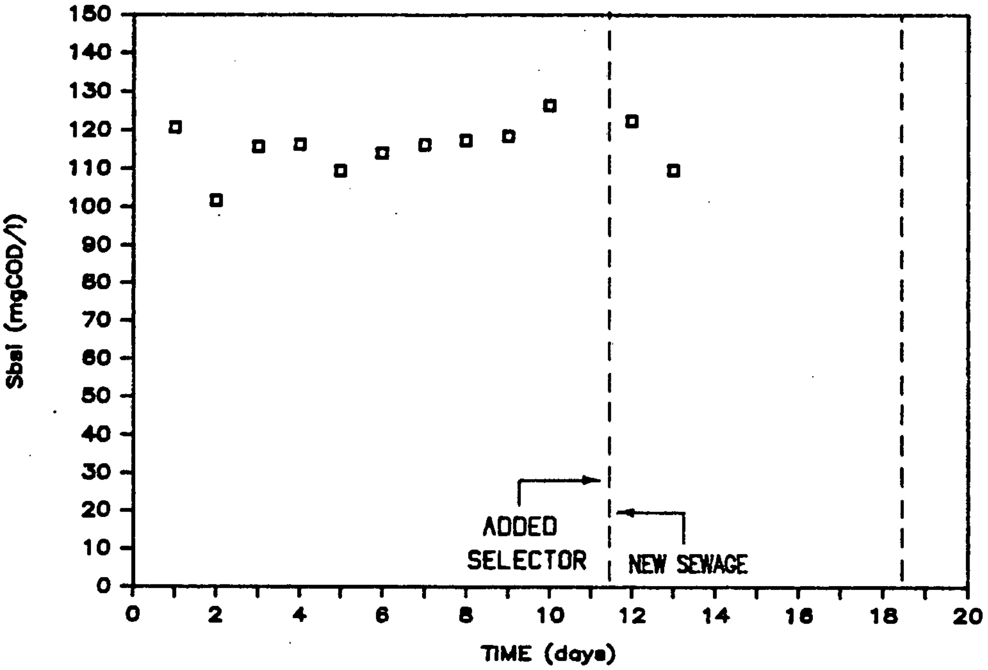


Fig 4.73: Daily performance of the influent readily biodegradable COD concentration for the 3 day sludge age Split-feed system.

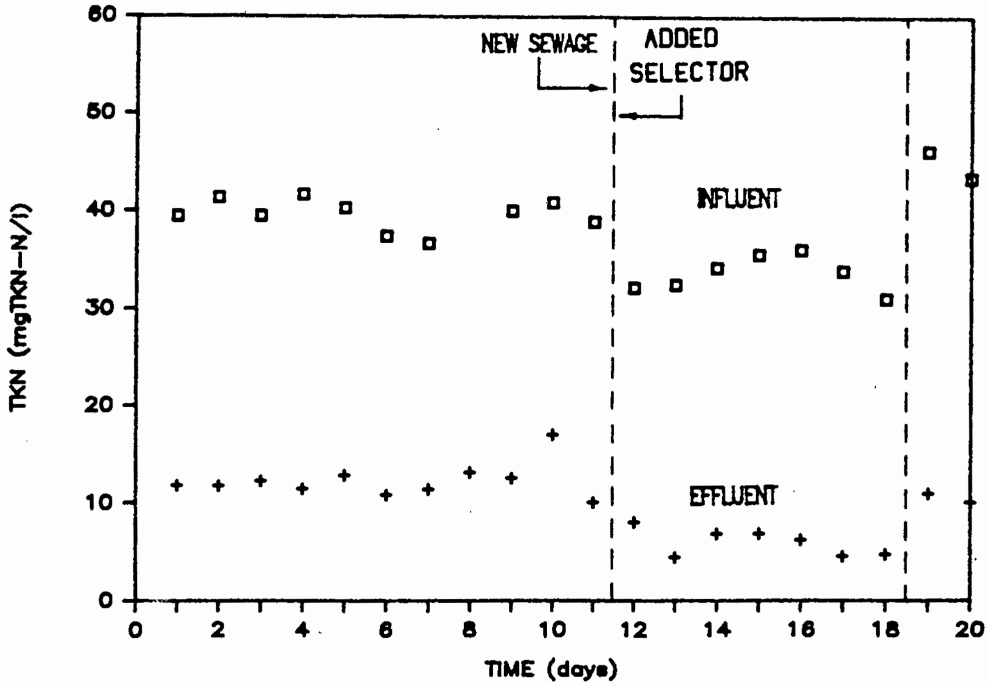


Fig 4.74: Daily performance of the unfiltered influent and filtered effluent TKN concentrations for the 3 day sludge age Split-feed system.

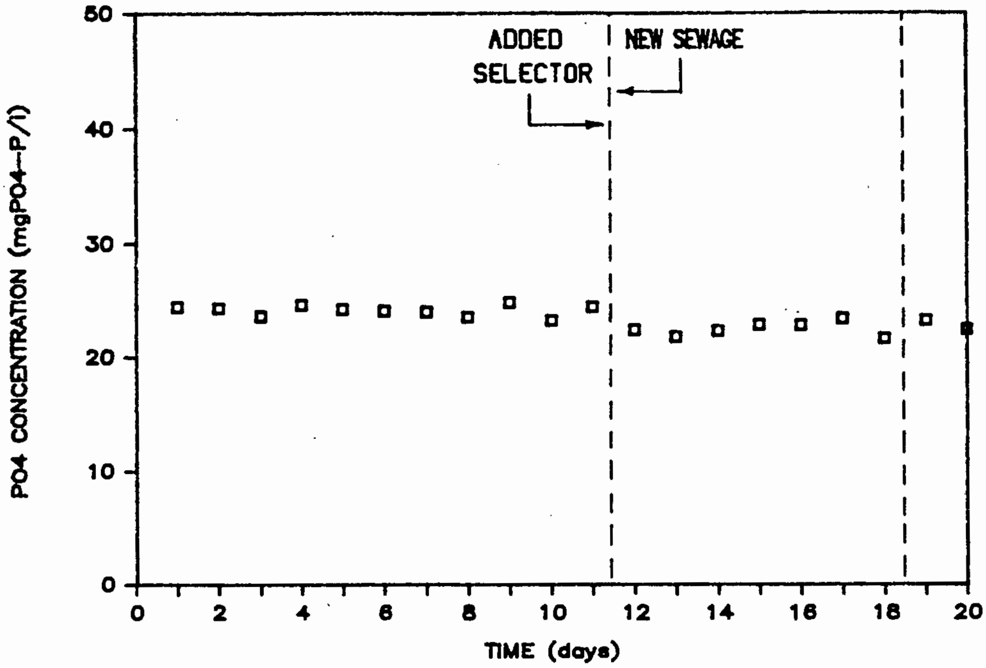


Fig 4.75: Daily performance of the phosphorus concentration in the influent to the 3 day sludge age Split-feed system.

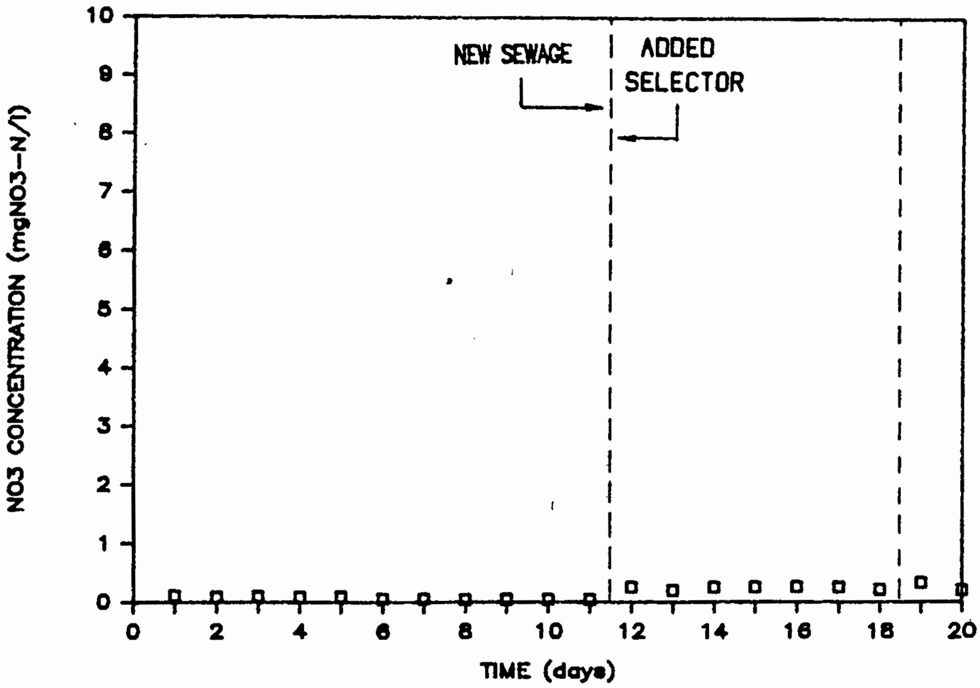


Fig 4.76: Daily performance of the nitrate concentration in the first reactor of the 3 day sludge age Split-feed system.

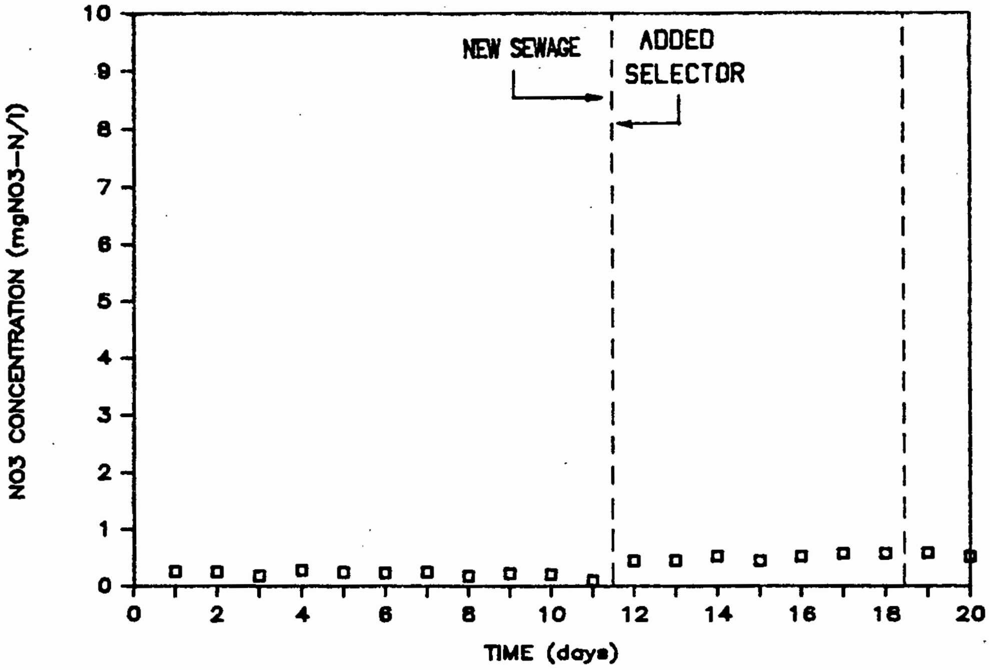


Fig 4.77: Daily performance of the nitrate concentration in the second reactor of the 3 day sludge age Split-feed system.

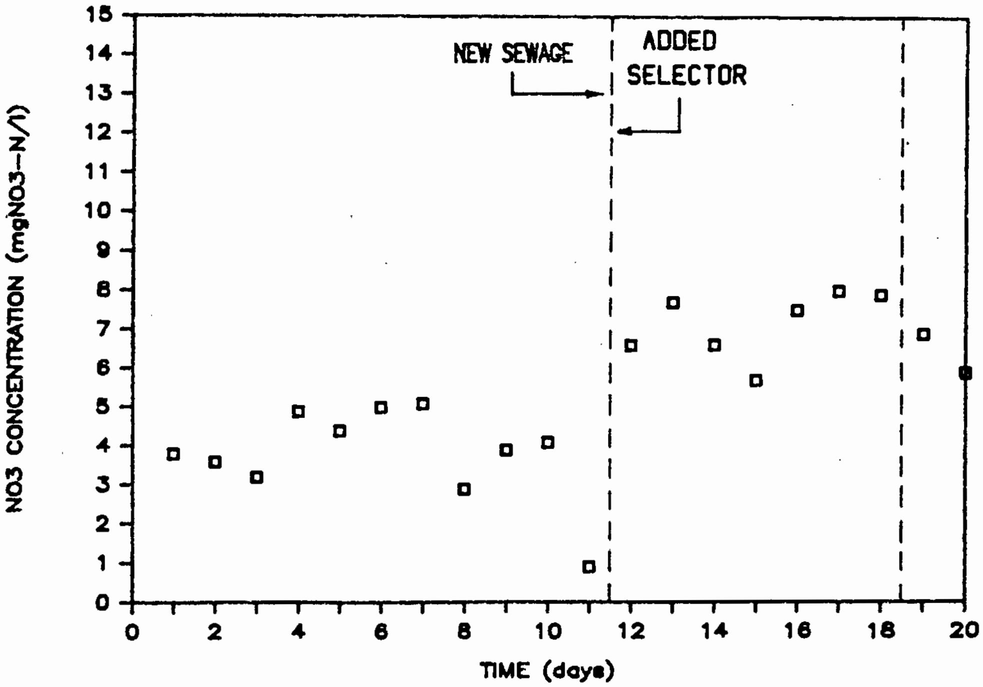


Fig 4.78: Daily performance of the nitrate concentration in the third reactor of the 3 day sludge age Split-feed system.

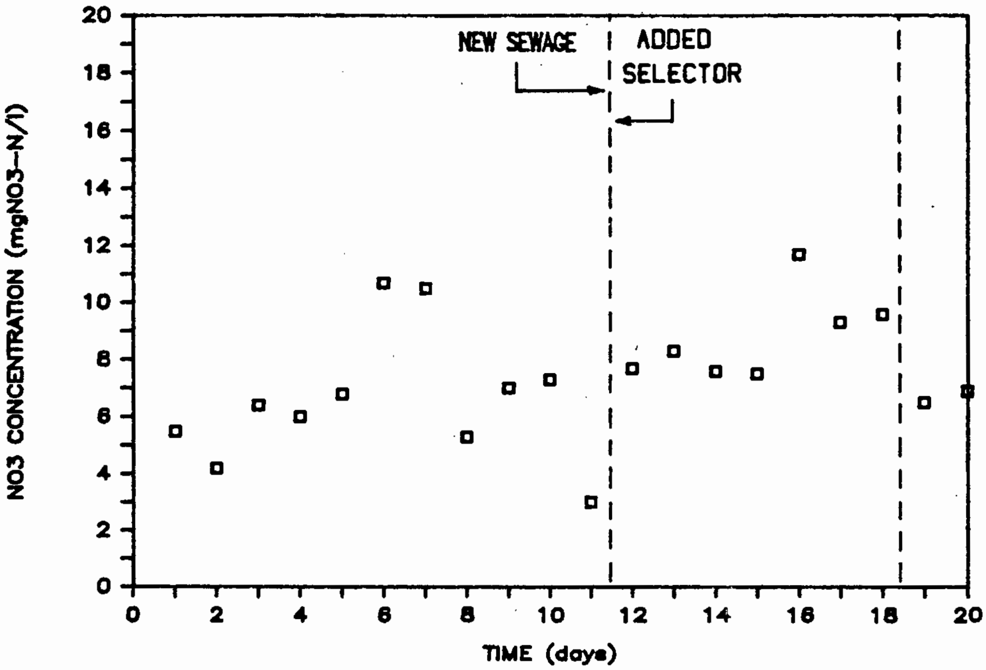
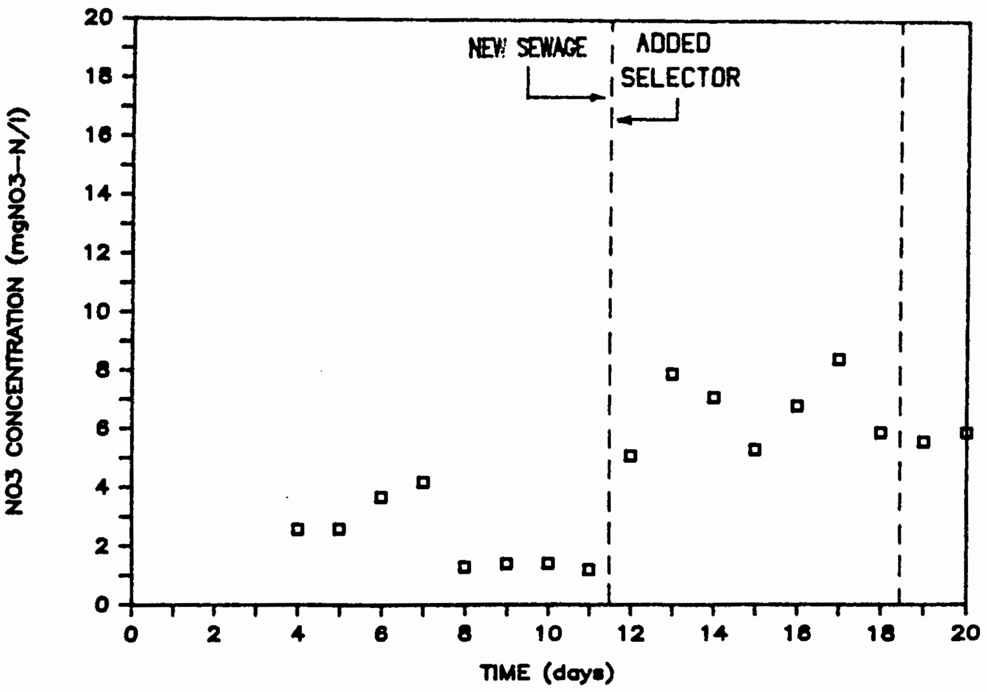
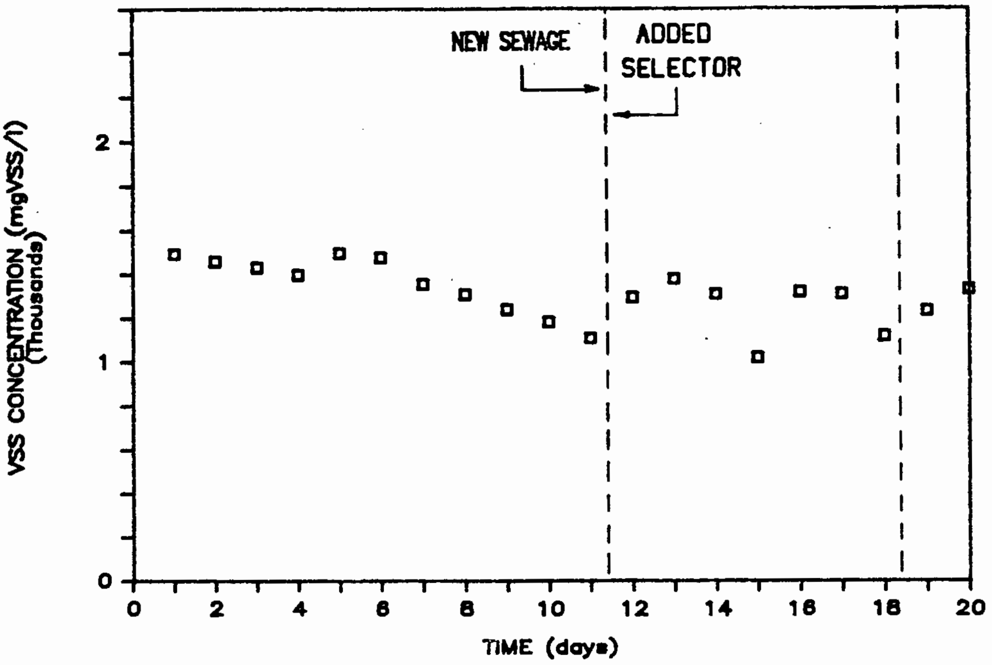


Fig 4.79: Daily performance of the nitrate concentration in the fourth reactor of the 3 day sludge age Split-feed system.



<u>Fig 4.80</u>: **Daily performance of the nitrate concentration in the effluent from the 3 day sludge age Split-feed system.**



<u>Fig 4.81</u>: **Daily performance of the volatile suspended solids in the first reactor of the 3 day sludge age Split-feed system.**

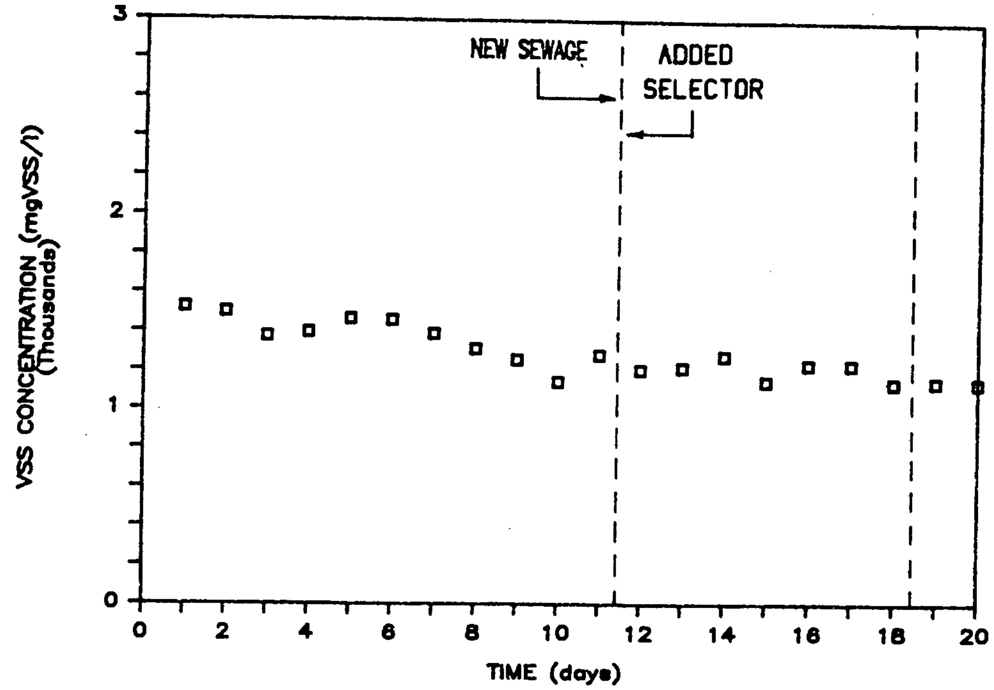


Fig 4.82: Daily performance of the volatile suspended solids in the second reactor of the 3 day sludge age Split-feed system.

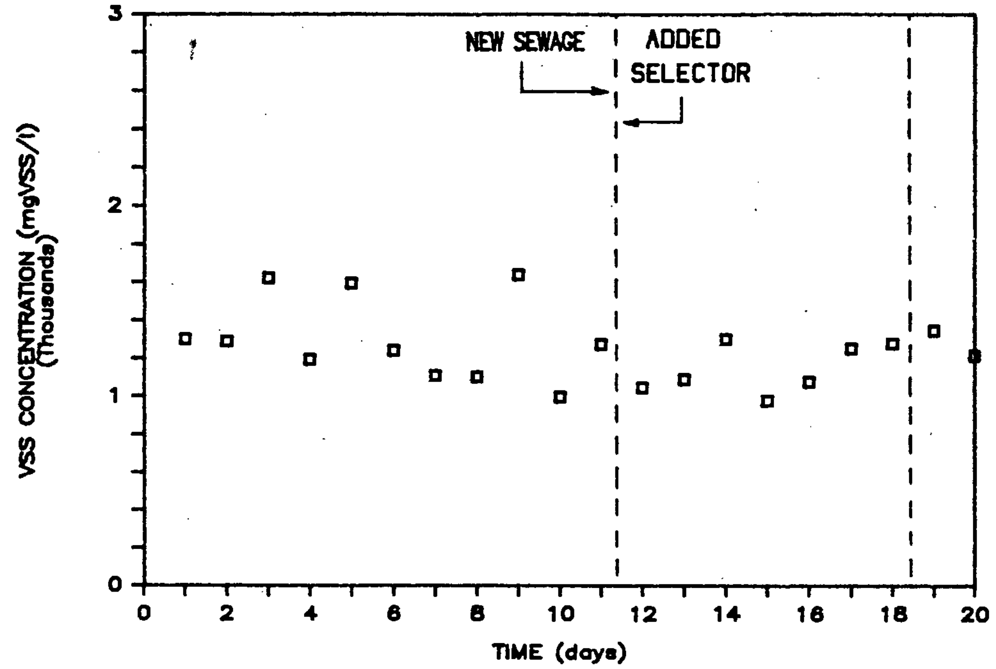


Fig 4.83: Daily performance of the volatile suspended solids in the third reactor of the 3 day sludge age Split-feed system.

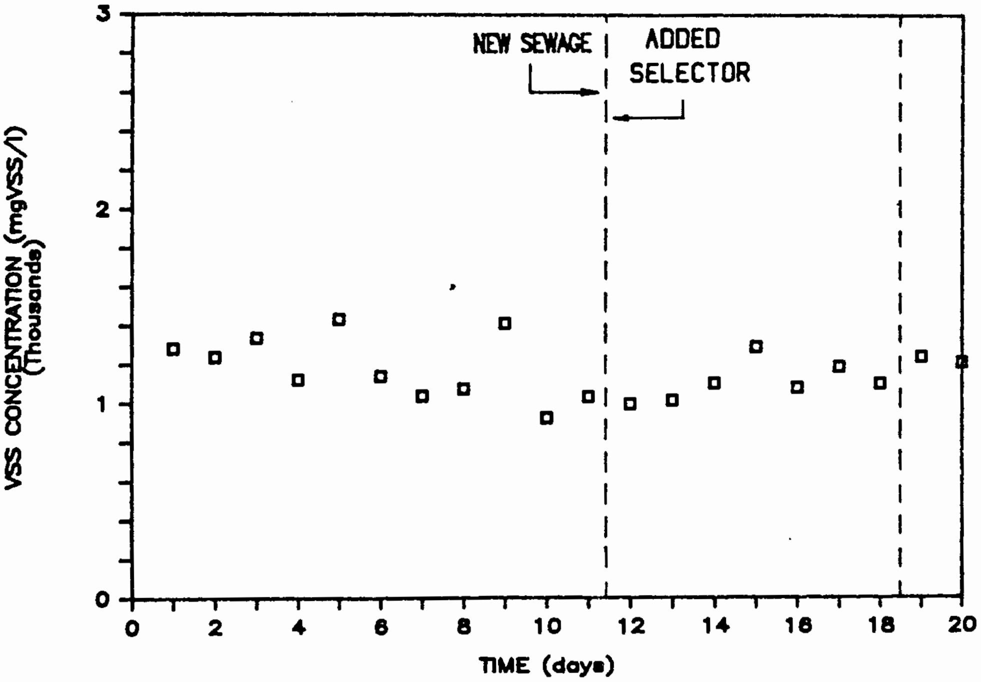


Fig 4.84: Daily performance of the volatile suspended solids in the fourth reactor of the 3 day sludge age Split-feed system.

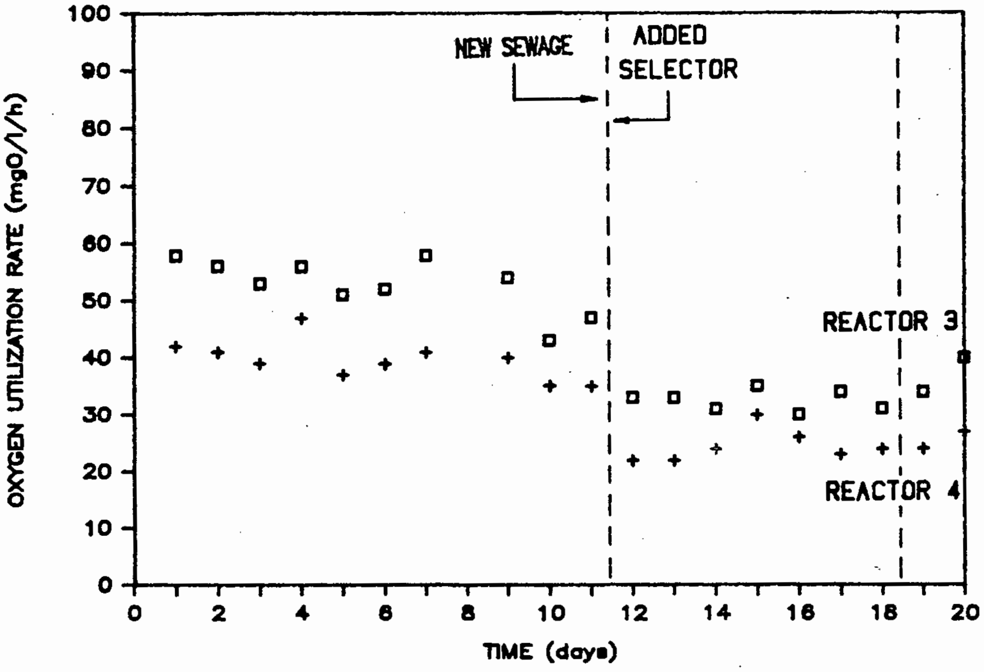


Fig 4.85: Daily performance of the oxygen utilisation rates in the aerobic reactors of the 3 day sludge age Split-feed system.

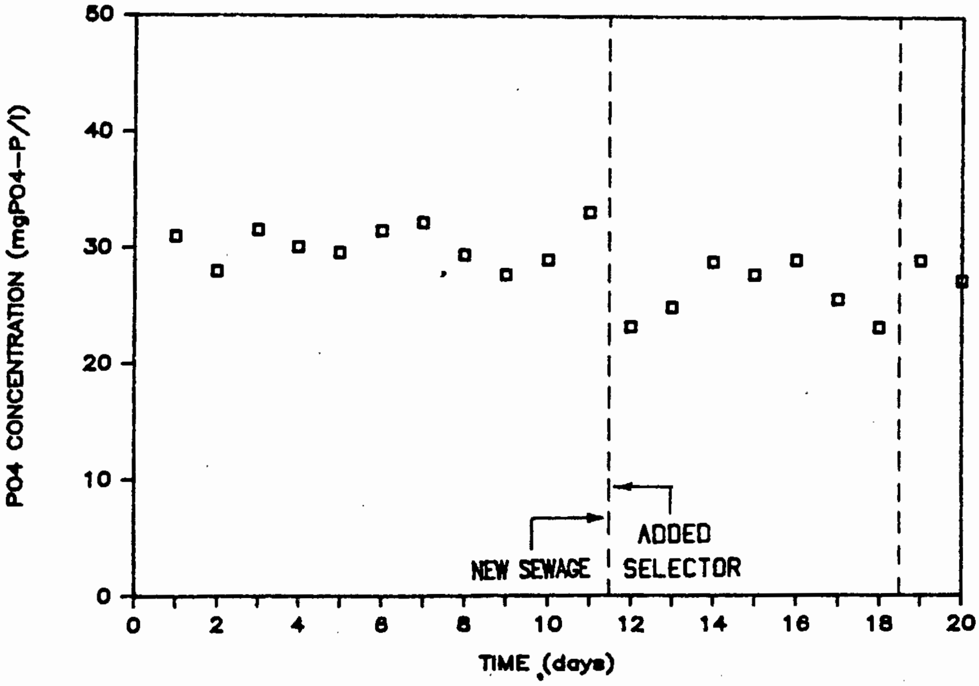


Fig 4.86: Daily performance of the phosphorus concentration in the first reactor of the 3 day sludge age Split-feed system.

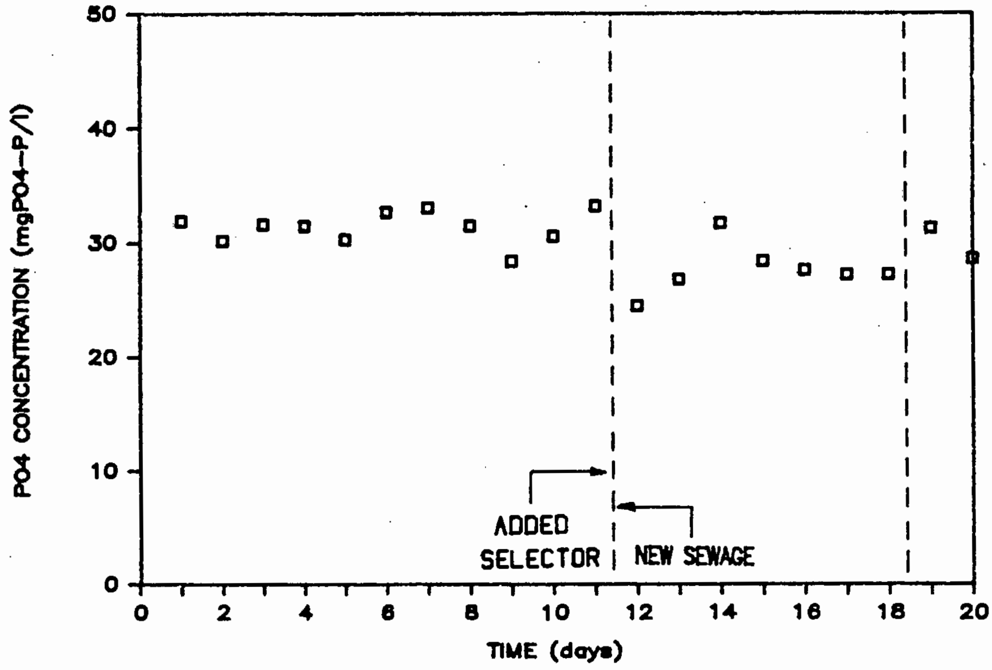


Fig 4.87: Daily performance of the phosphorus concentration in the second reactor of the 3 day sludge age Split-feed system.

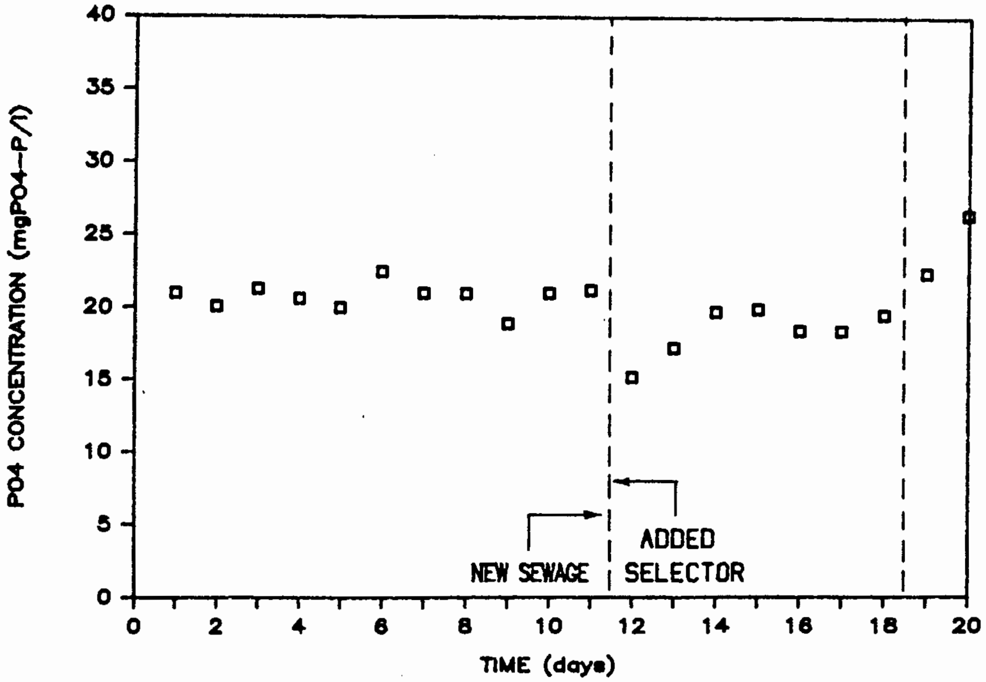


Fig 4.88: Daily performance of the phosphorus concentration in the third reactor of the 3 day sludge age Split-feed system.

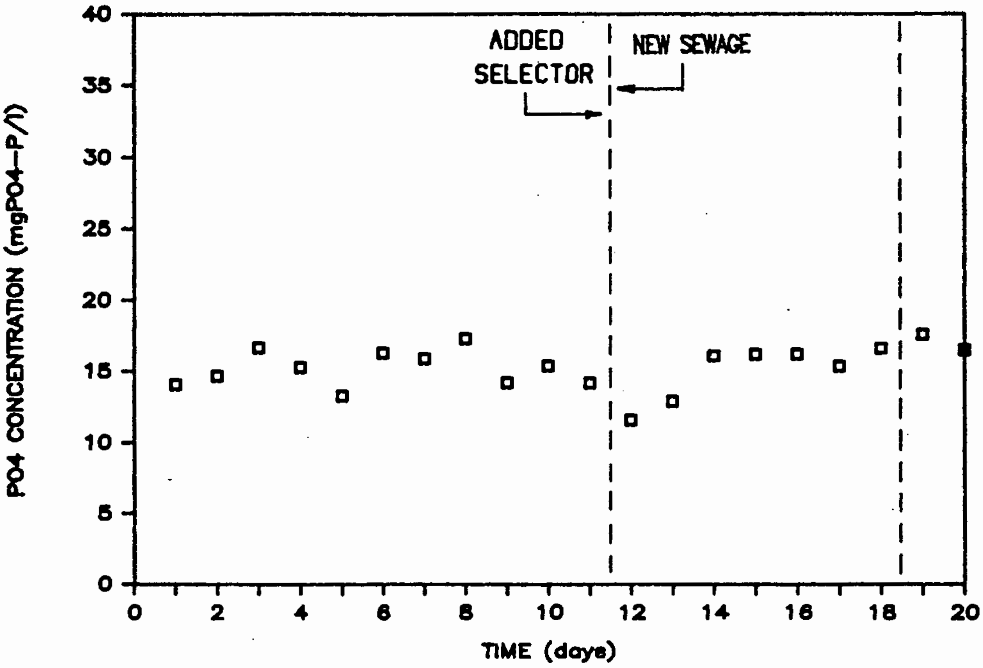


Fig 4.89: Daily performance of the phosphorus concentration in the fourth reactor of the 3 day sludge age Split-feed system.

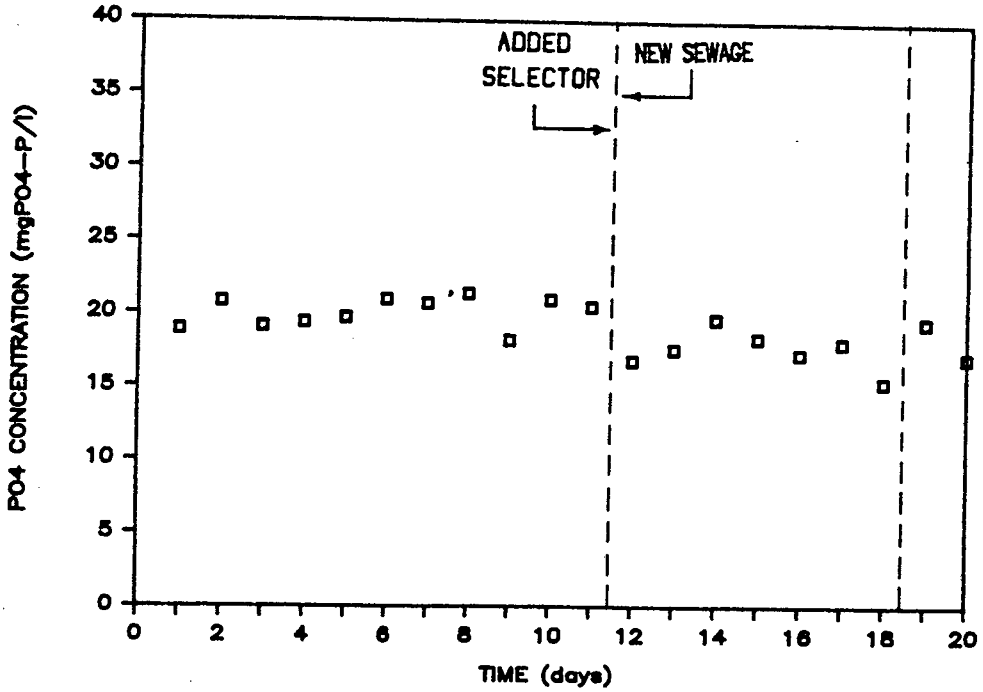


Fig 4.90: Daily performance of the phosphorus concentration in the filtered effluent from the 3 day sludge age Split-feed system.

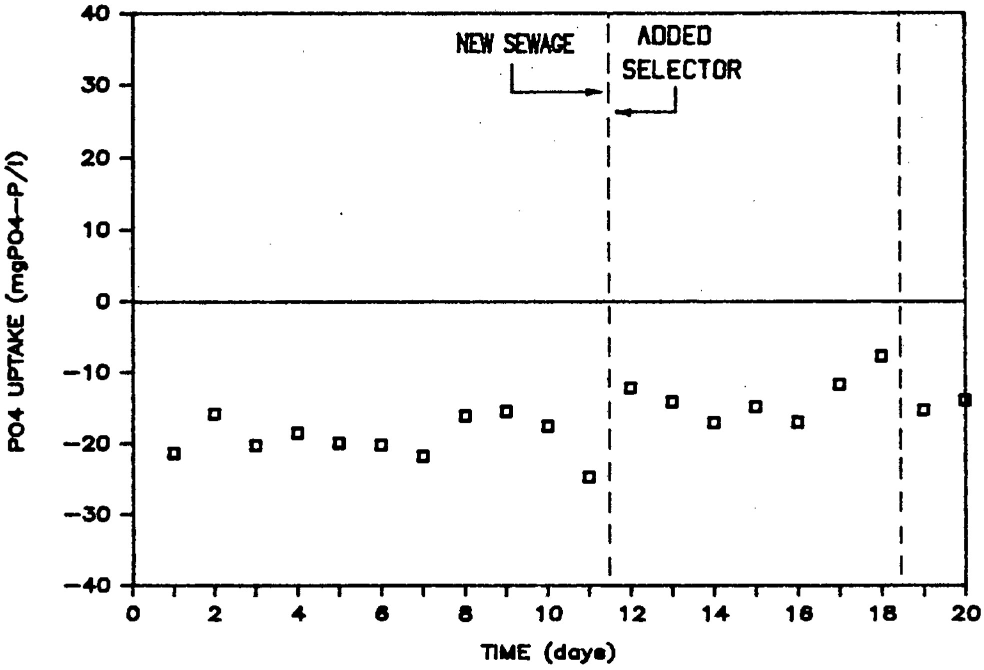


Fig 4.91: Daily performance of the phosphorus uptake in the first reactor of the 3 day sludge age Split-feed system.

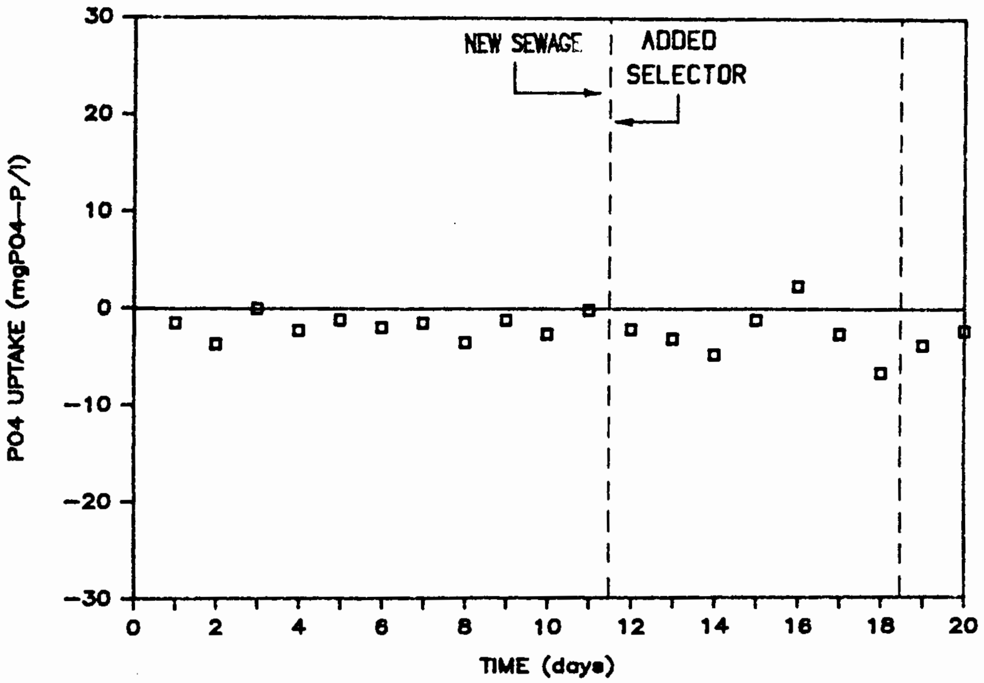


Fig 4.92: Daily performance of the phosphorus uptake in the second reactor of the 3 day sludge age Split-feed system.

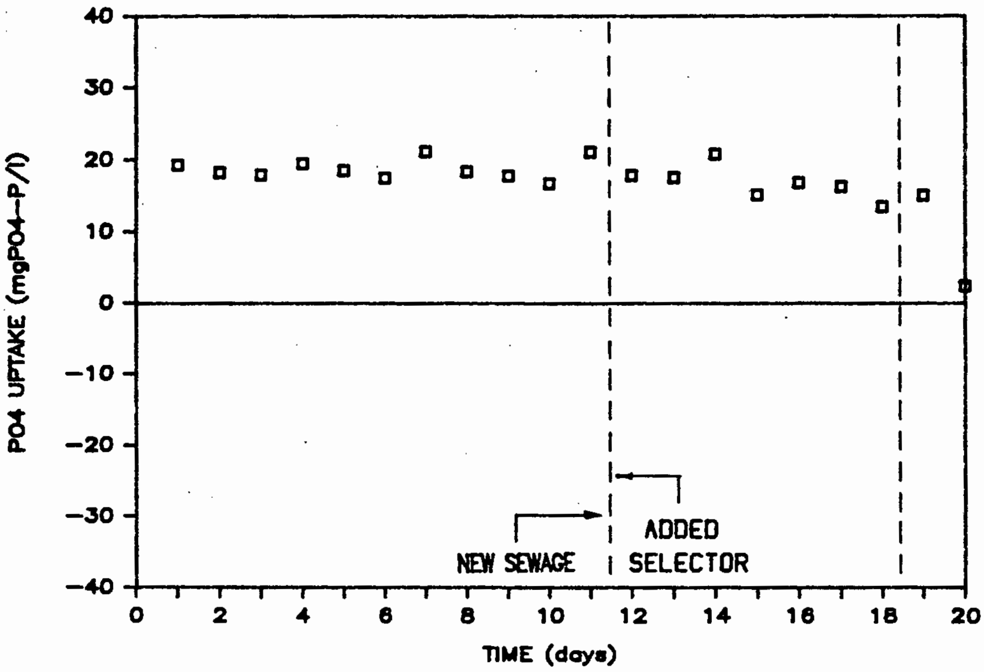


Fig 4.93: Daily performance of the phosphorus uptake in the third reactor of the 3 day sludge age Split-feed system.

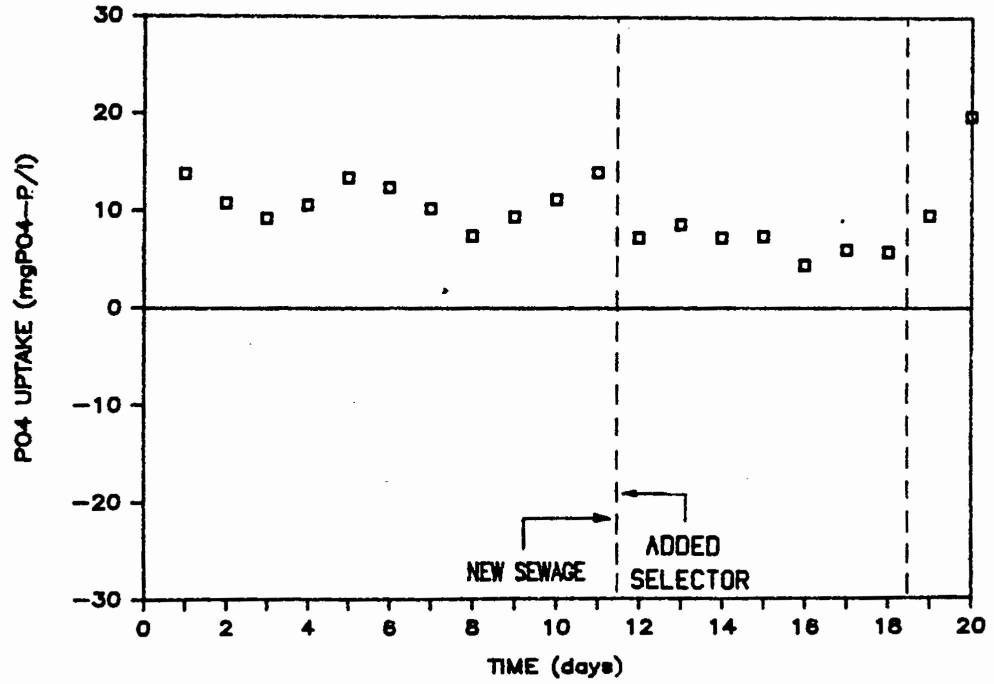


Fig 4.94: Daily performance of the phosphorus uptake in the fourth reactor of the 3 day sludge age Split-feed system.

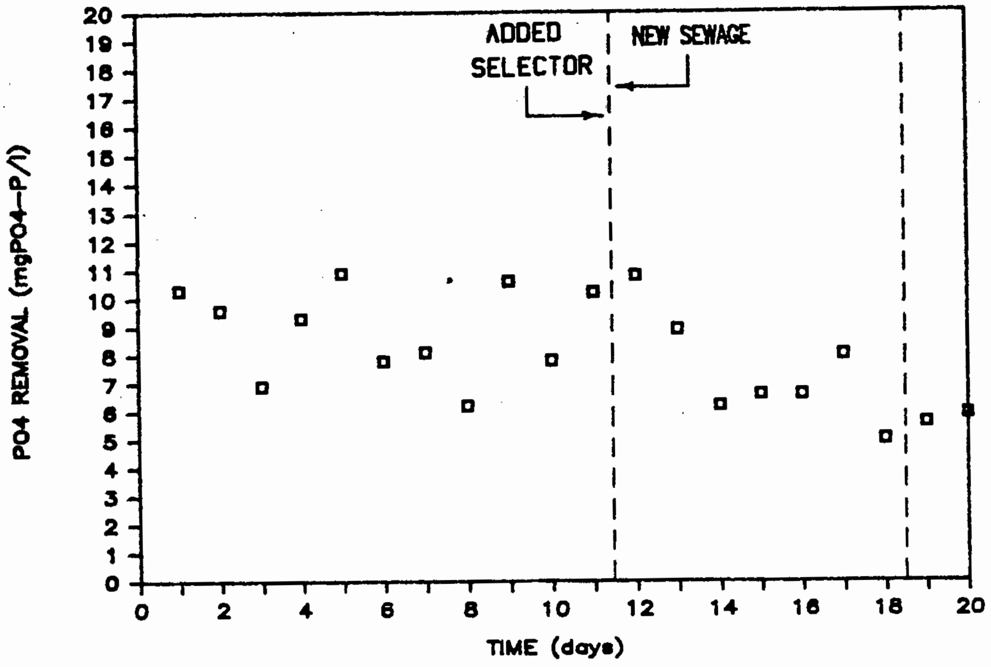


Fig 4.95: Daily performance of the phosphorus removal in the 3 day sludge age Split-feed system.

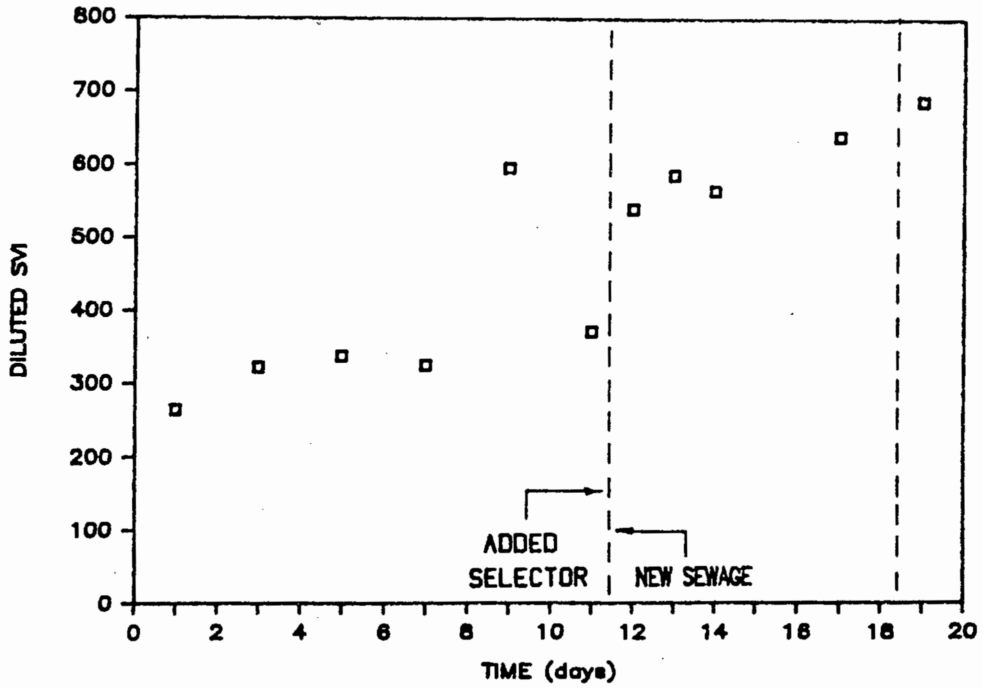
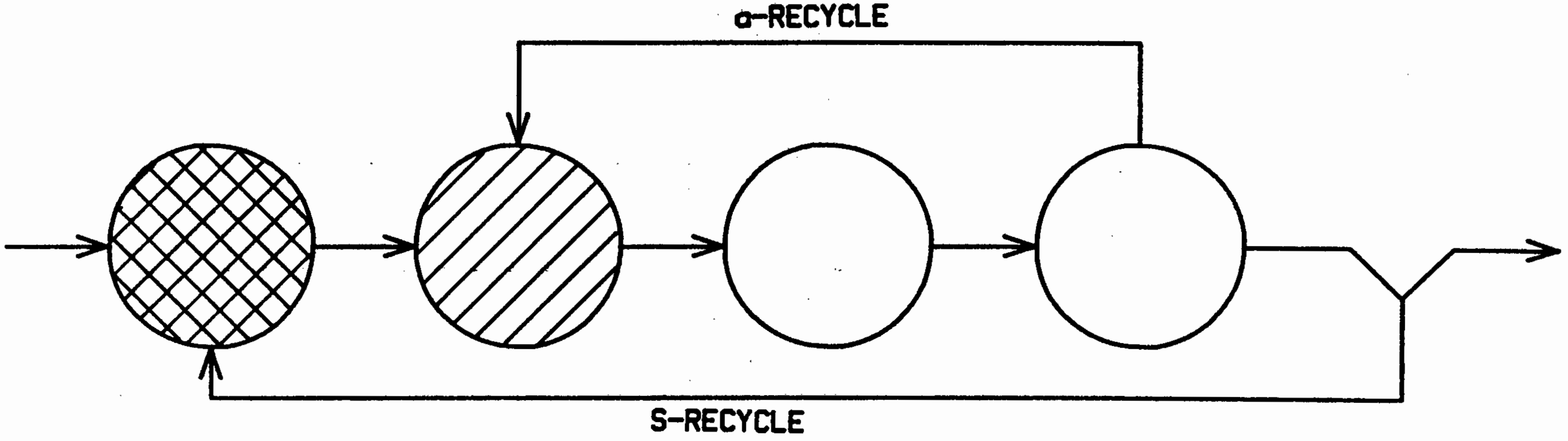


Fig 4.96: Daily performance of the Diluted Sludge Volume Index for the 3 day sludge age Split-feed system.



<u>Fig 4.97</u>: Schematic diagram of the 3-stage Bardenpho configuration.

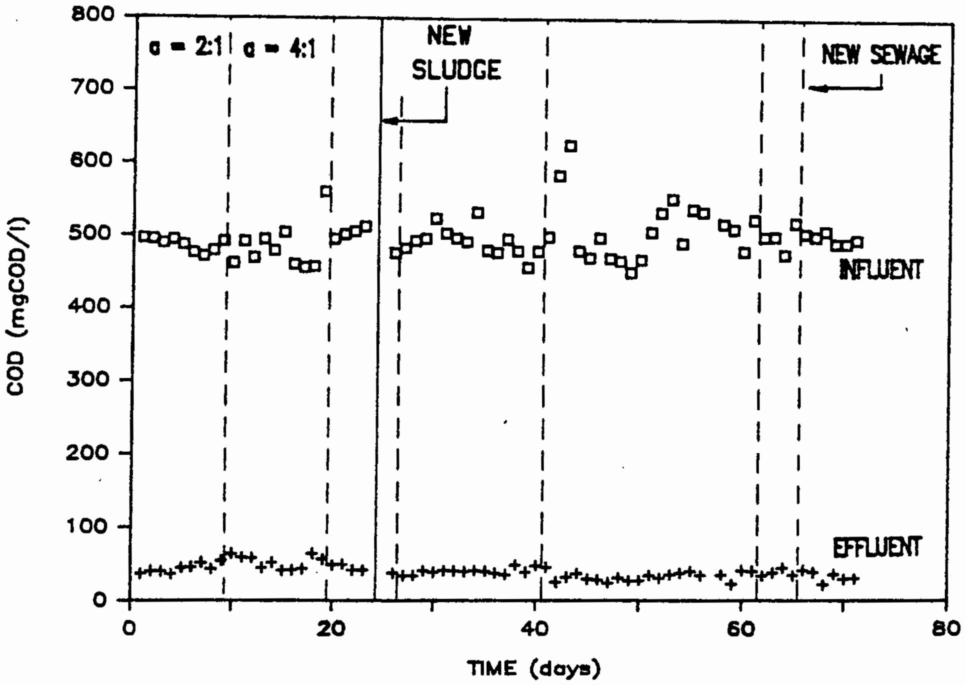


Fig 4.98: Daily performance of the unfiltered influent and filtered effluent COD concentrations for the 6 day sludge age 3-stage Bardenpho system.

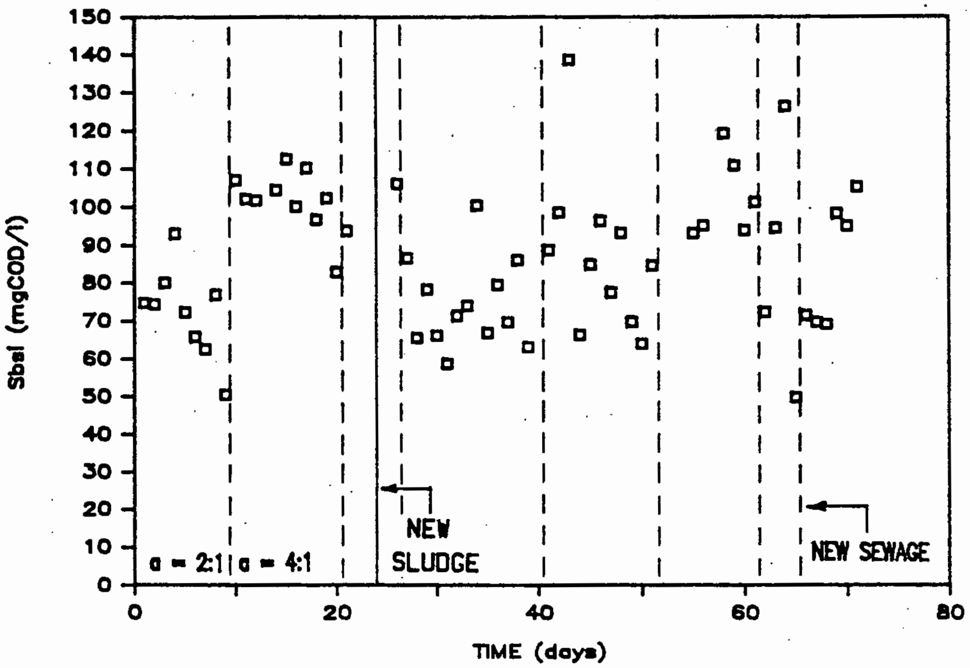


Fig 4.99: Daily performance of the influent readily biodegradable COD concentration for the 6 day sludge age 3-stage Bardenpho system.

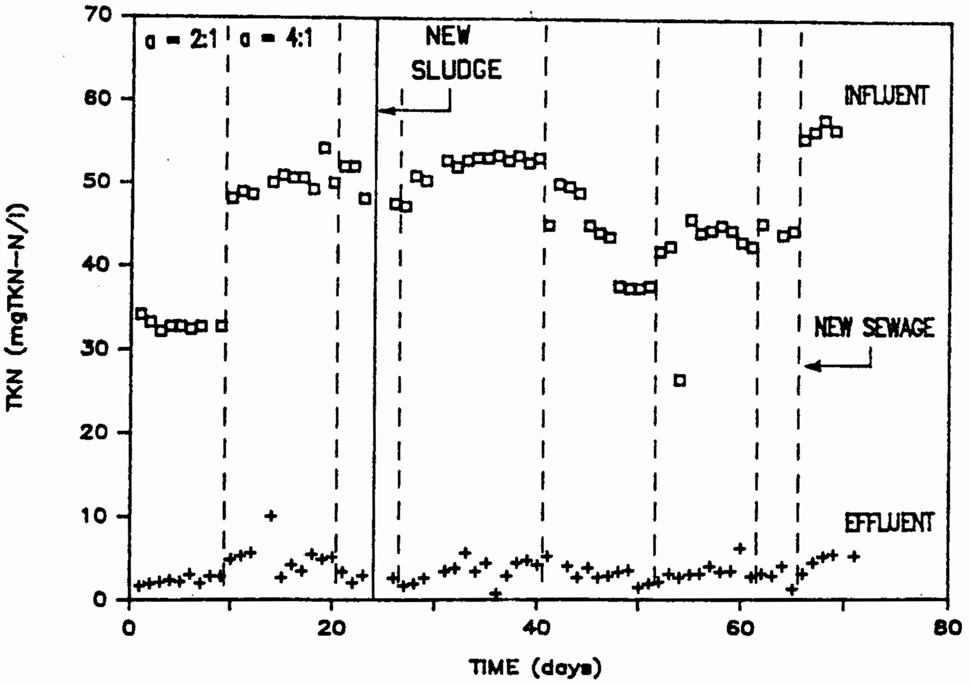


Fig 4.100: Daily performance of the unfiltered influent and filtered effluent TKN concentrations for the 6 day sludge age 3-stage Bardenpho process.

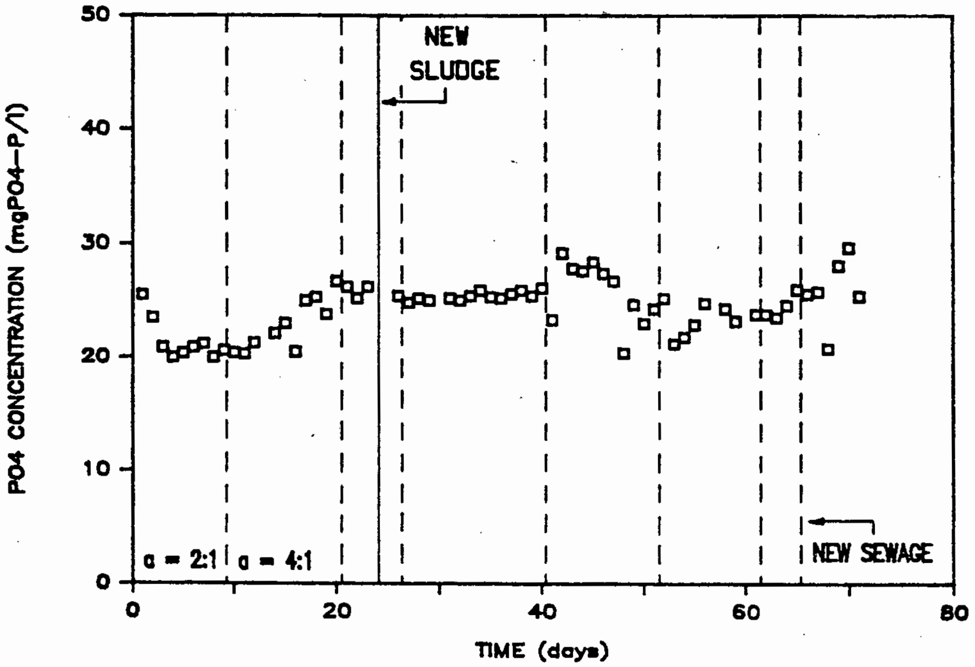


Fig 4.101: Daily performance of the phosphorus concentration in the influent to the 6 day sludge age 3-stage Bardenpho system.

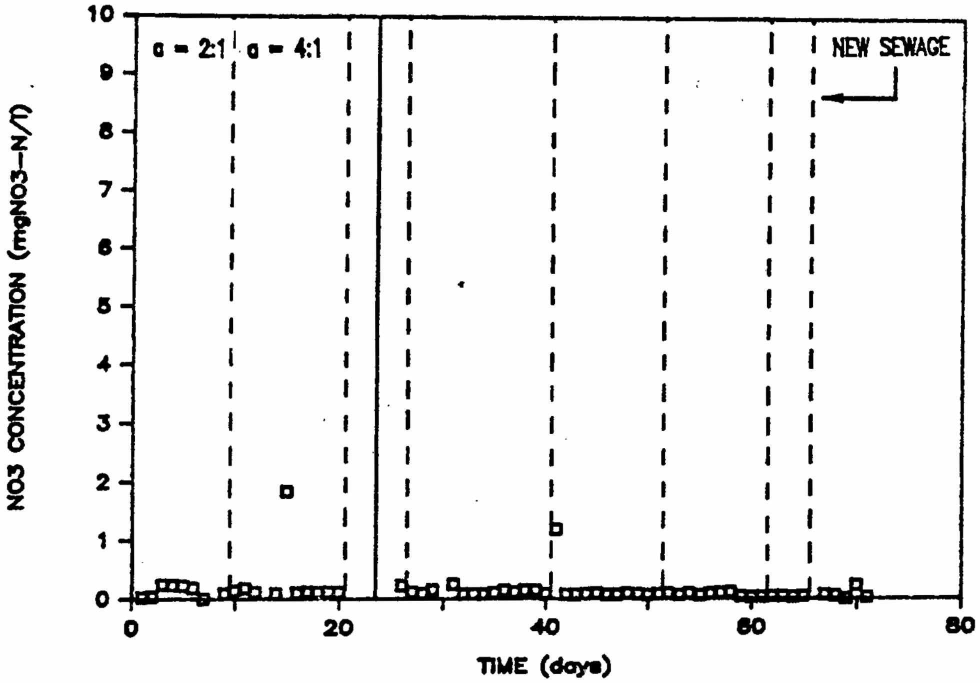


Fig 4.102: Daily performance of the nitrate concentration in the first reactor of the 6 day sludge age 3-stage Bardenpho system.

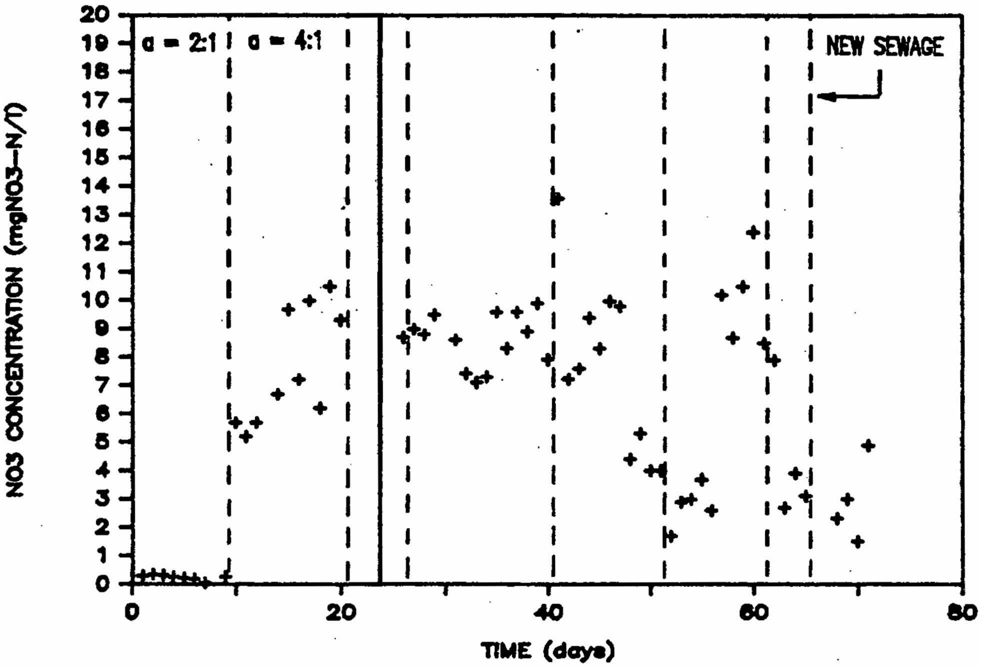


Fig 4.103: Daily performance of the nitrate concentration in the second reactor of the 6 day sludge age 3-stage Bardenpho system.

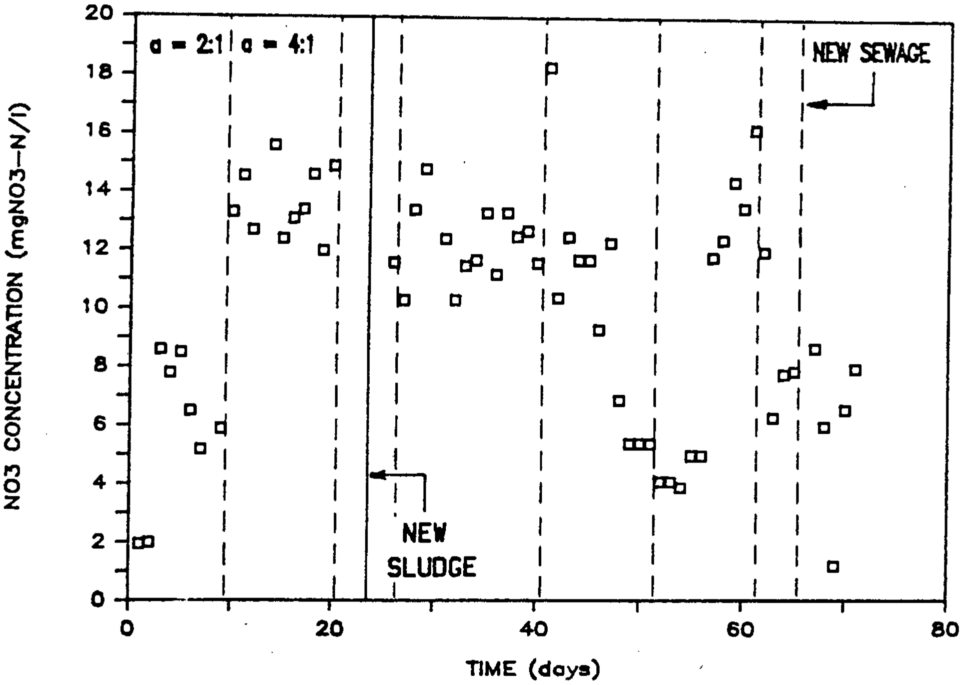


Fig 4.104: Daily performance of the nitrate concentration in the third reactor of the 6 day sludge age 3-stage Bardenpho system.

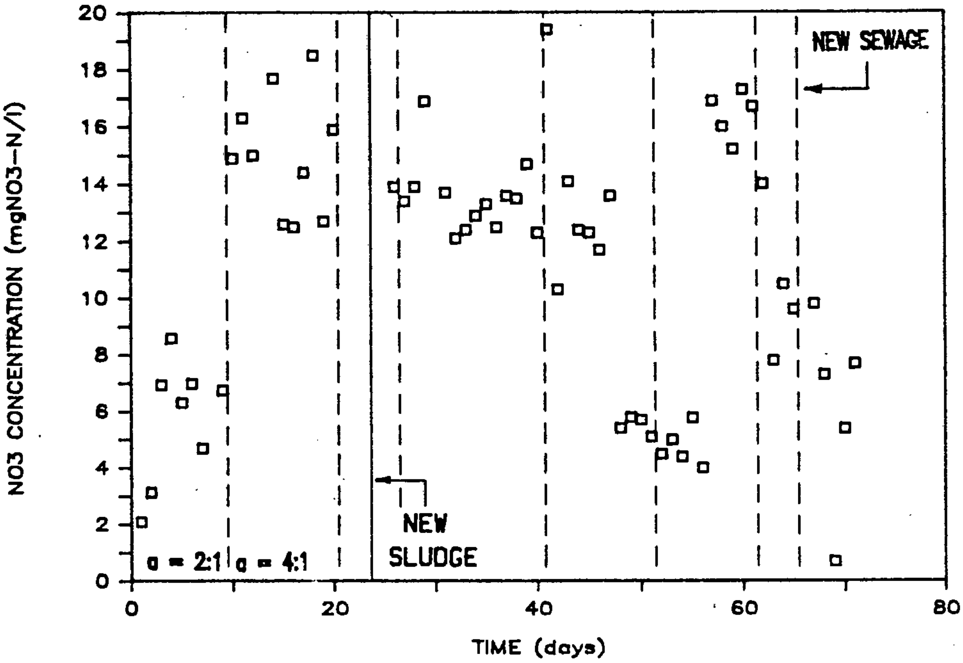


Fig 4.105: Daily performance of the nitrate concentration in the fourth reactor of the 6 day sludge age 3-stage Bardenpho system.

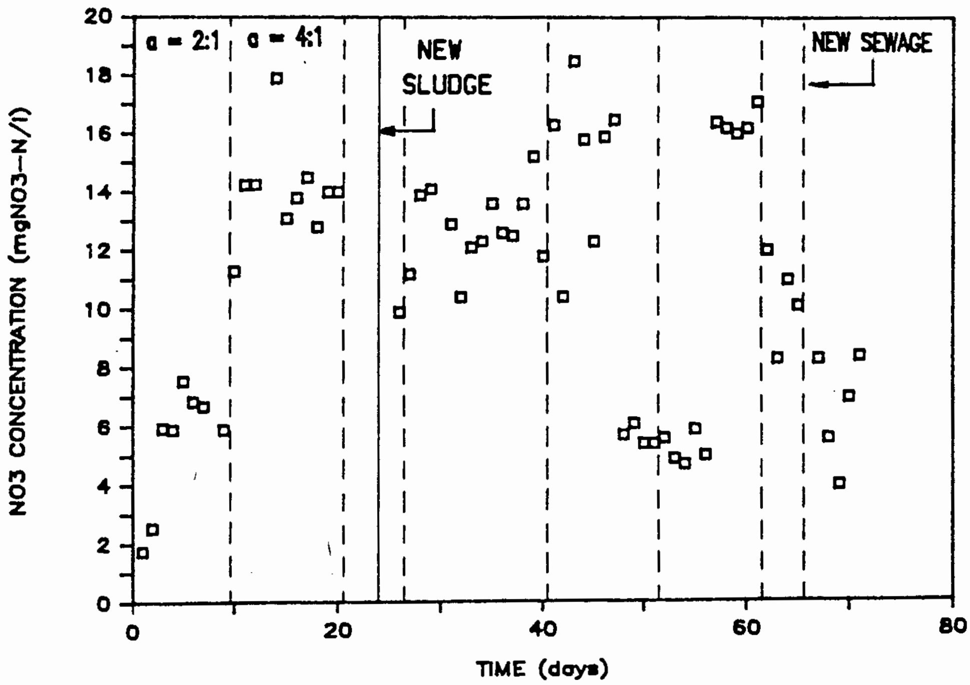


Fig 4.106: Daily performance of the nitrate concentration in the effluent from the 6 day sludge age 3-stage Bardenpho system.

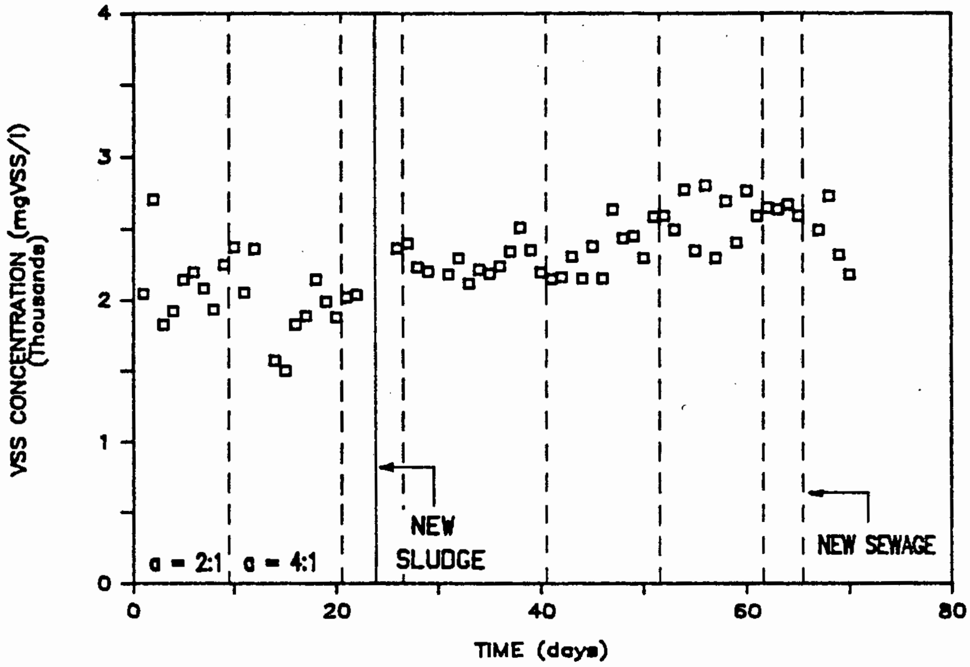


Fig 4.107: Daily performance of the volatile suspended solids in the first reactor of the 6 day sludge age 3-stage Bardenpho system.

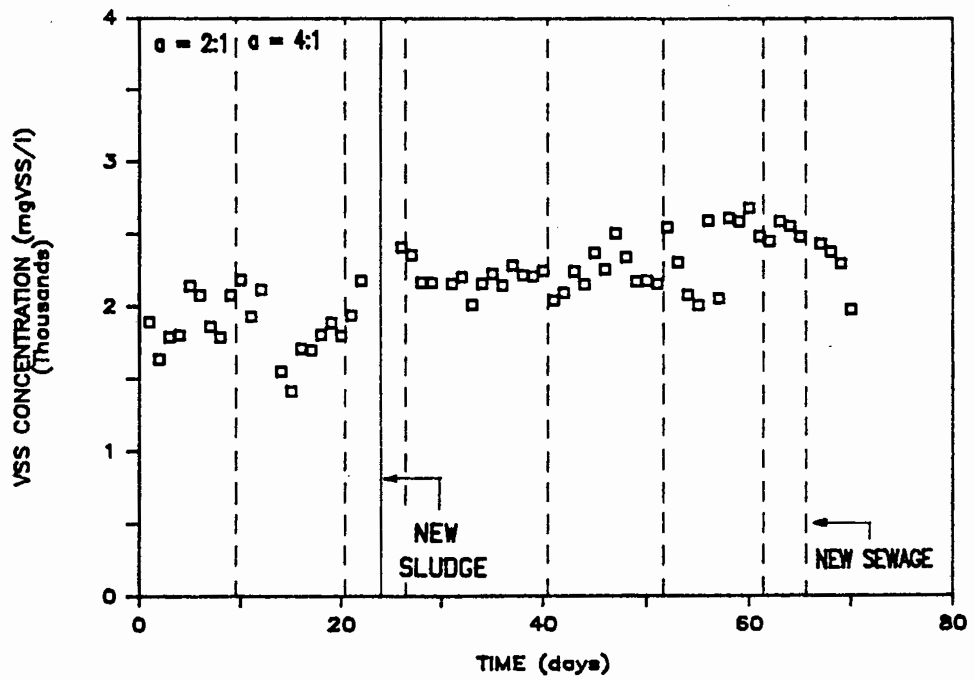


Fig 4.108: Daily performance of the volatile suspended solids in the second reactor of the 6 day sludge age 3-stage Bardenpho system.

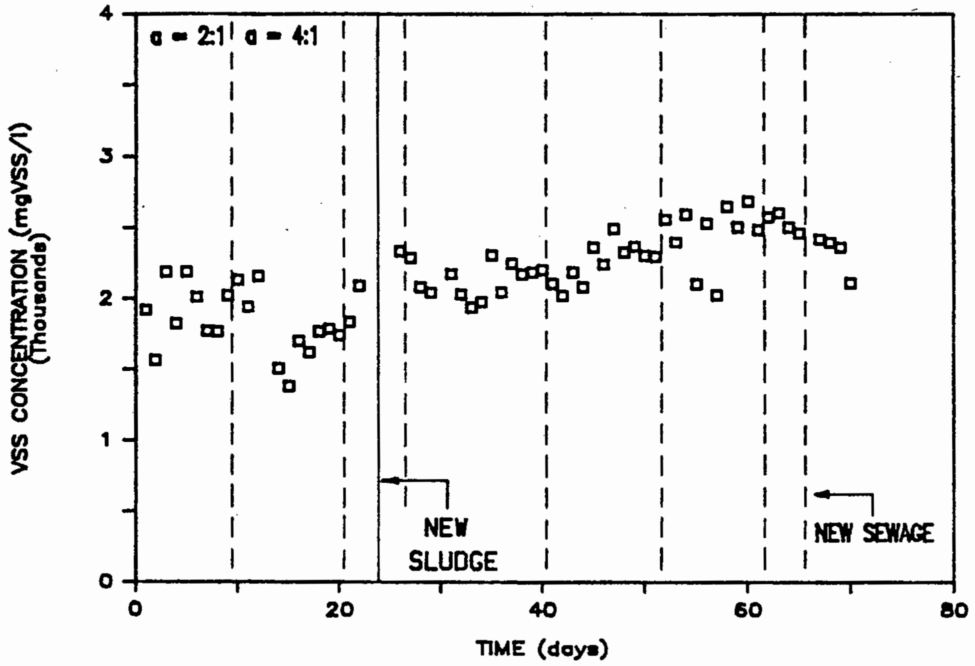


Fig 4.109: Daily performance of the volatile suspended solids in the third reactor of the 6 day sludge age 3-stage Bardenpho system.

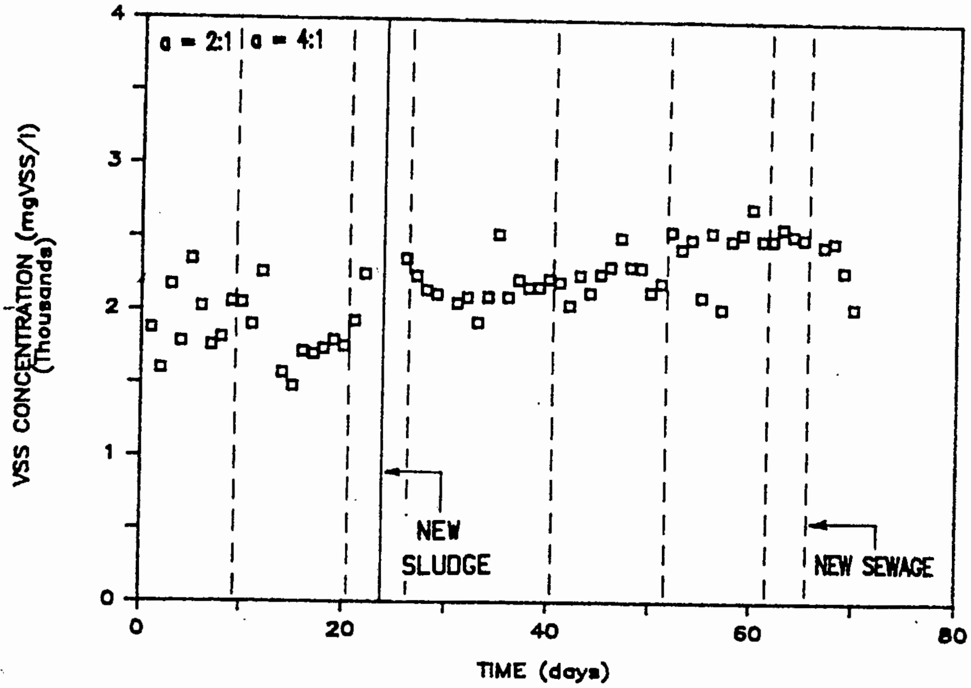


Fig 4.110: Daily performance of the volatile suspended solids in the fourth reactor of the 6 day sludge age 3-stage Bardenpho system.

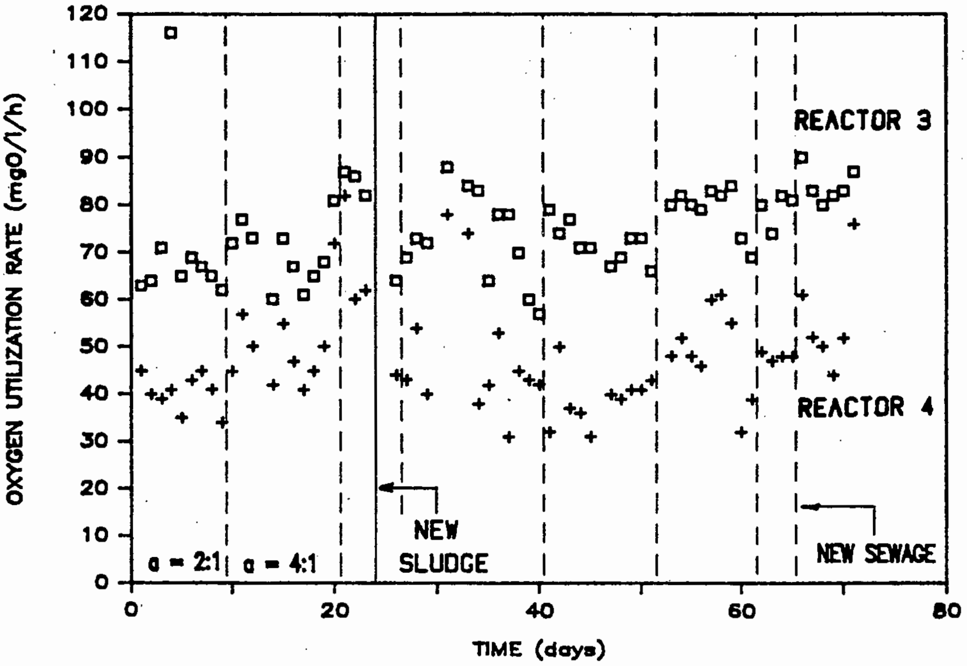


Fig 4.111: Daily performance of the oxygen utilisation rates in the aerobic reactors of the 6 day sludge age 3-stage Bardenpho system.

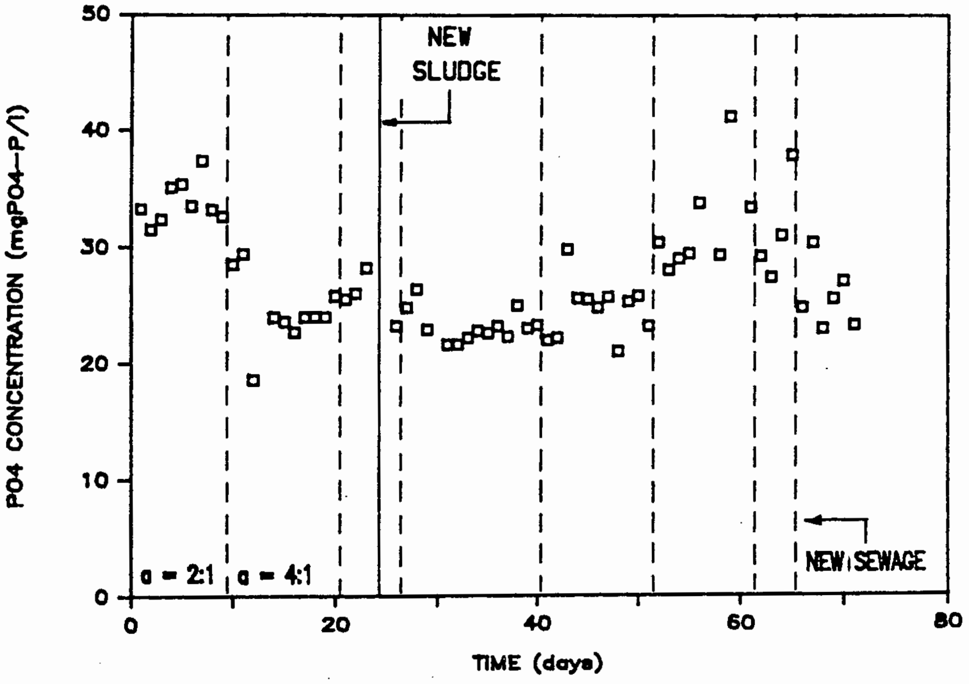


Fig 4.112: Daily performance of the phosphorus concentration in the first reactor of the 6 day sludge age 3-stage Bardenpho system.

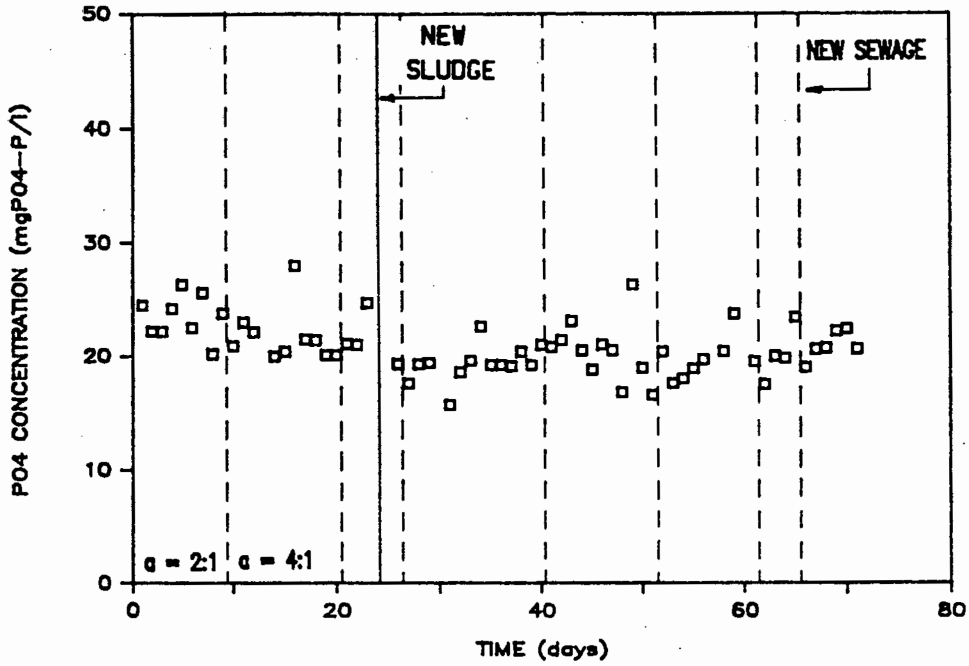


Fig 4.113: Daily performance of the phosphorus concentration in the second reactor of the 6 day sludge age 3-stage Bardenpho system.

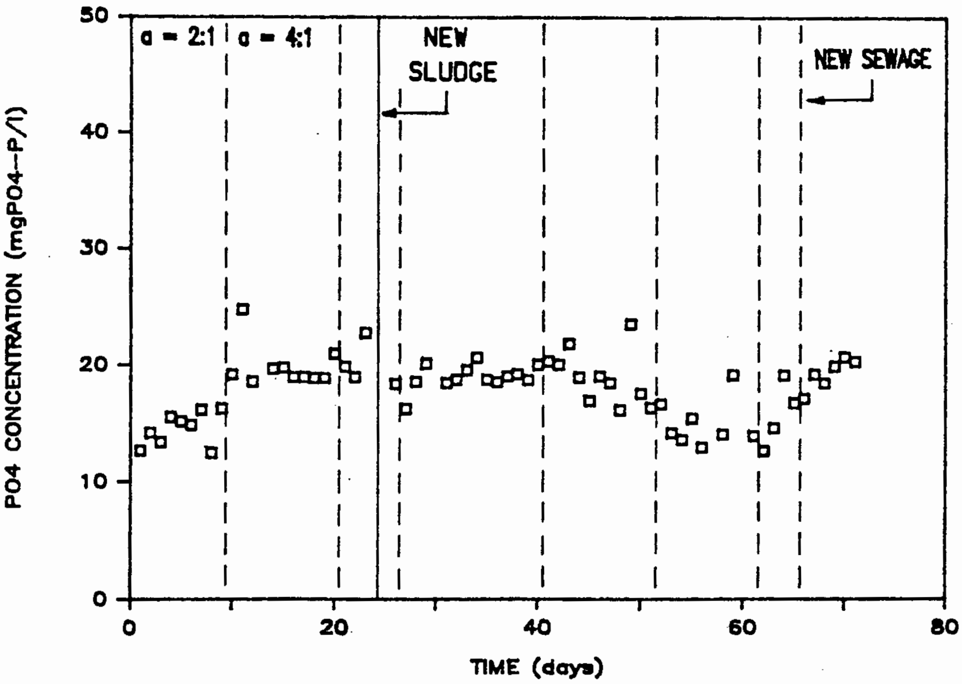


Fig 4.114: Daily performance of the phosphorus concentration in the third reactor of the 6 day sludge age 3-stage Bardenpho system.

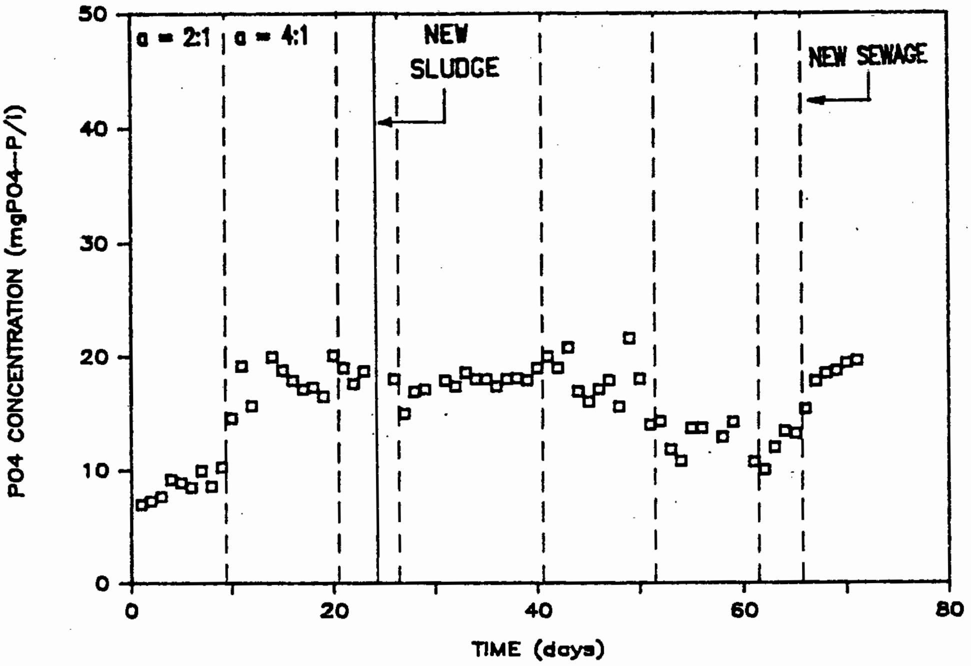


Fig 4.115: Daily performance of the phosphorus concentration in the fourth reactor of the 6 day sludge age 3-stage Bardenpho system.

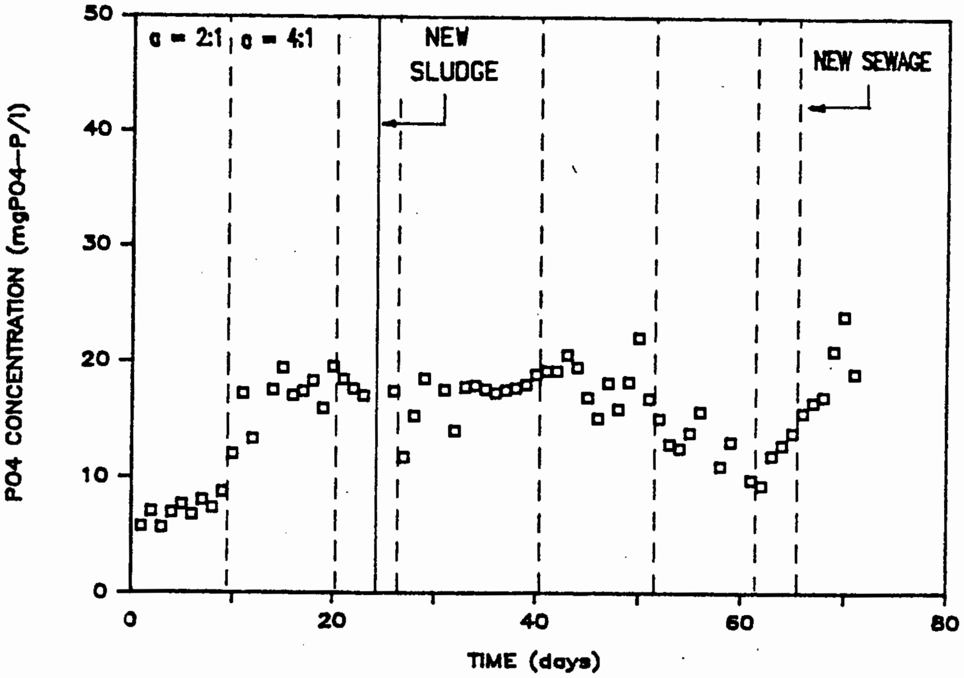


Fig 4.116: Daily performance of the phosphorus concentration in the filtered effluent from the 6 day sludge age 3-stage Bardenpho system.

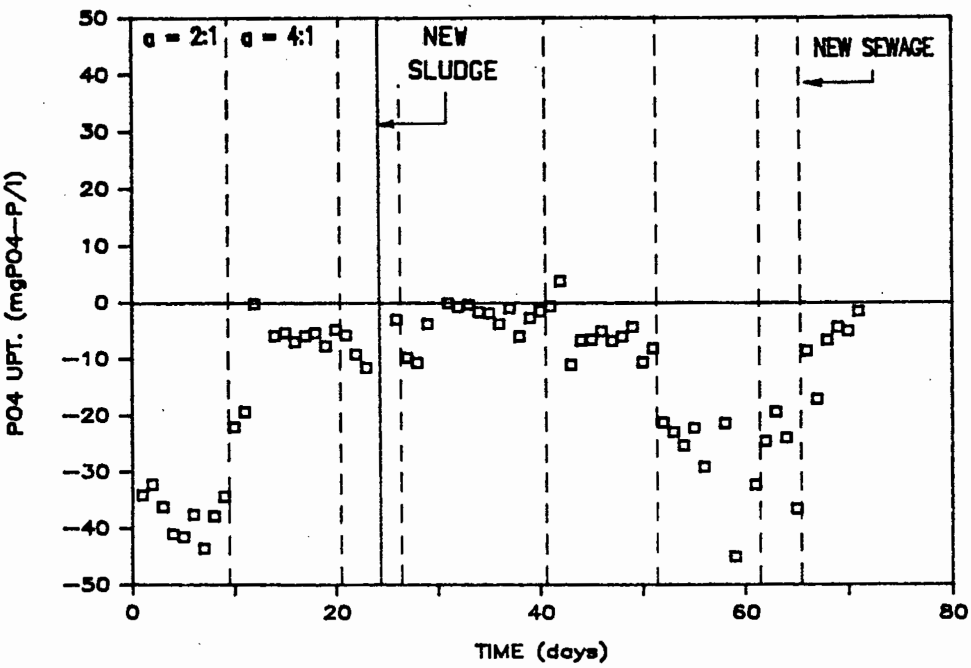


Fig 4.117: Daily performance of the phosphorus uptake in the first reactor of the 6 day sludge age 3-stage Bardenpho system.

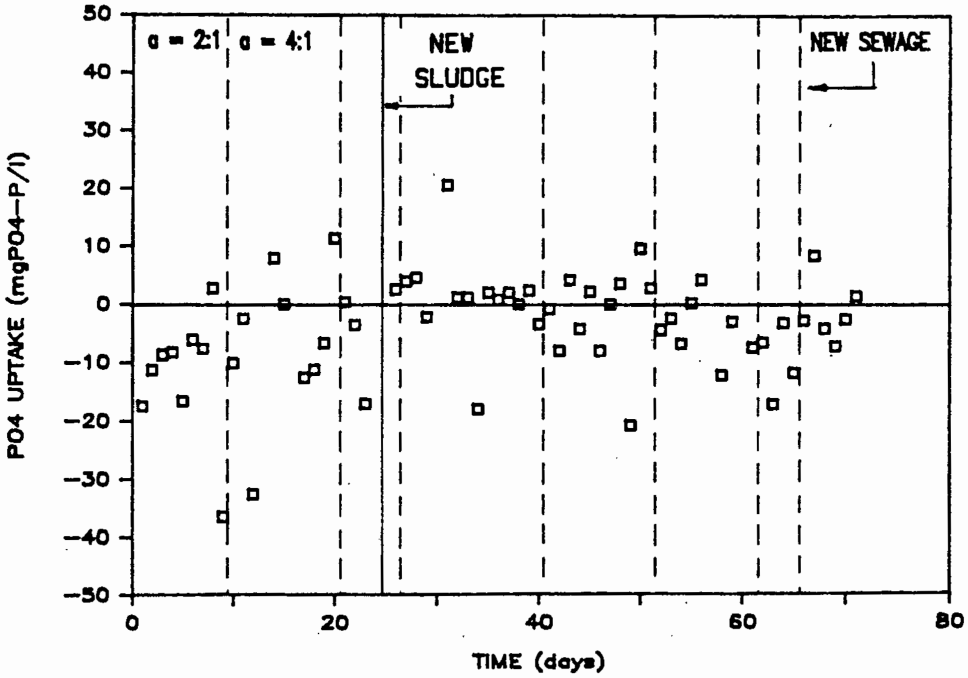


Fig 4.118: Daily performance of the phosphorus uptake in the second reactor of the 6 day sludge age 3-stage Bardenpho system.

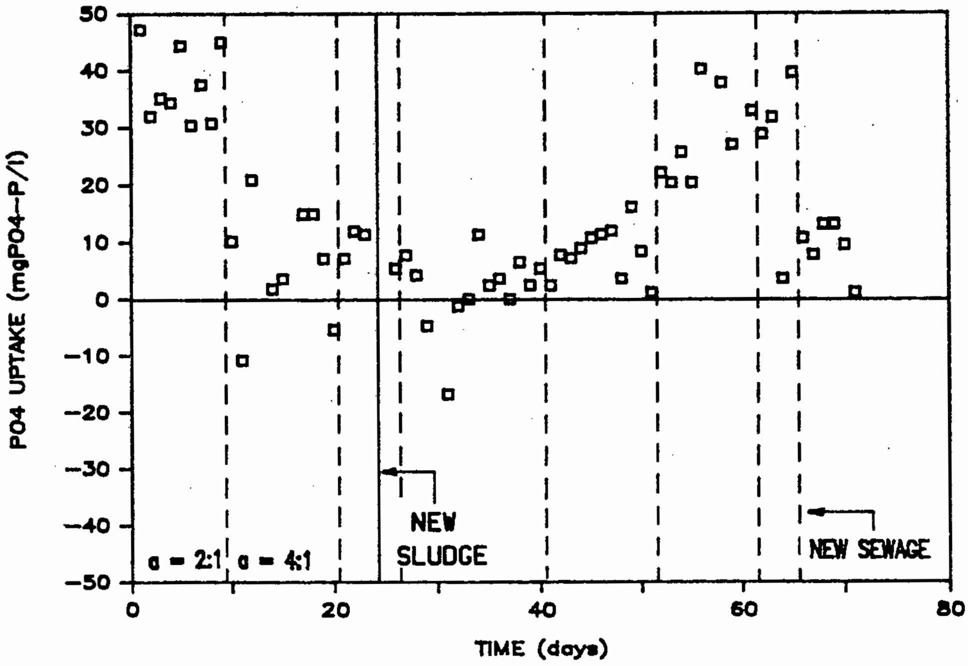


Fig 4.119: Daily performance of the phosphorus uptake in the third reactor of the 6 day sludge age 3-stage Bardenpho system.

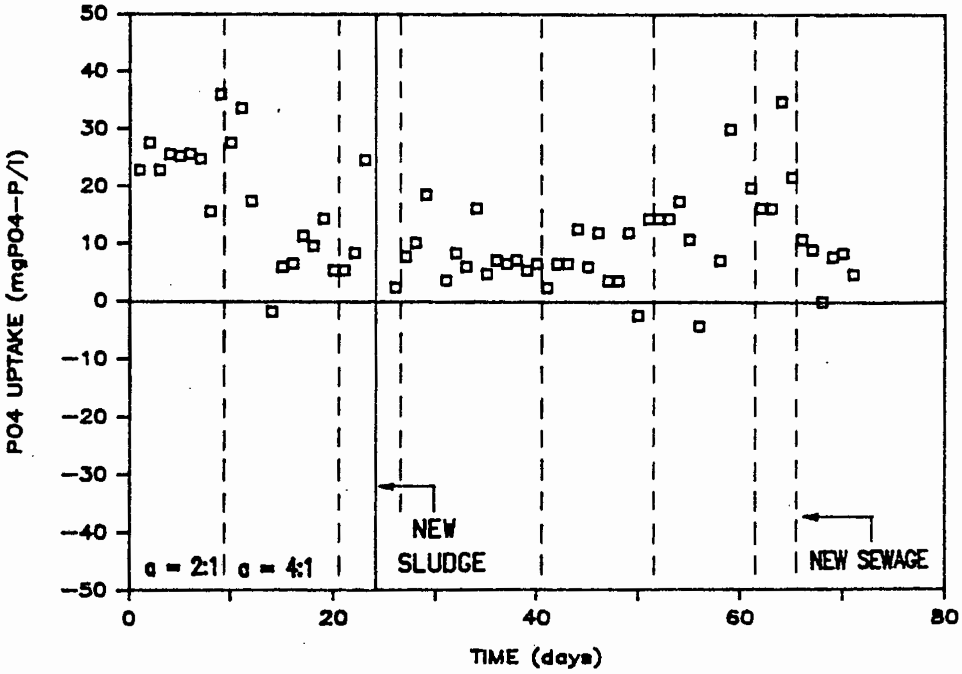


Fig 4.120: Daily performance of the phosphorus uptake in the fourth reactor of the 6 day sludge age 3-stage Bardenpho system.

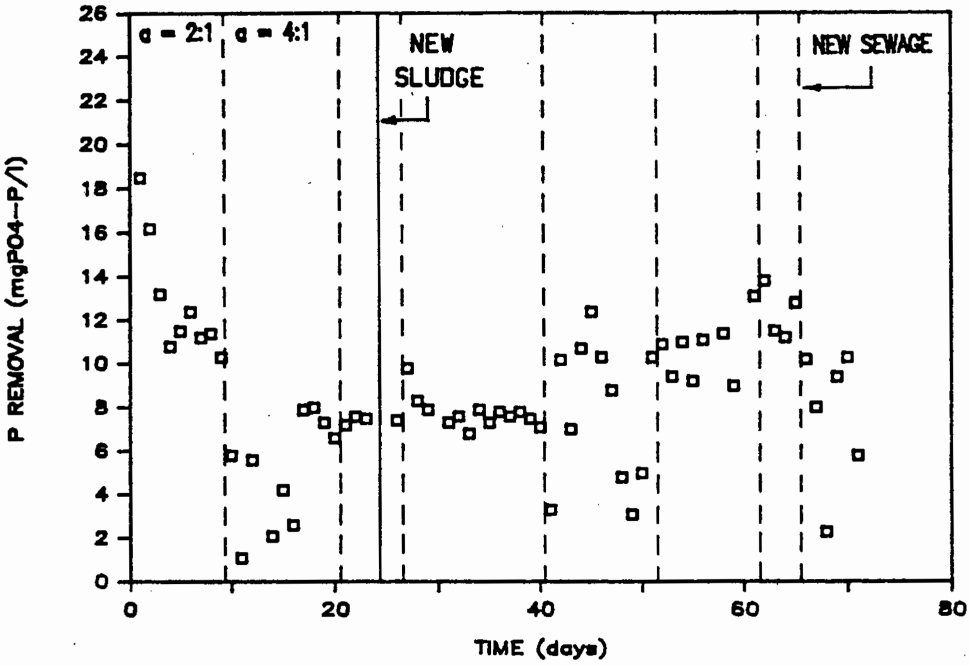


Fig 4.121: Daily performance of the phosphorus removal in the 6 day sludge age 3-stage Bardenpho system.

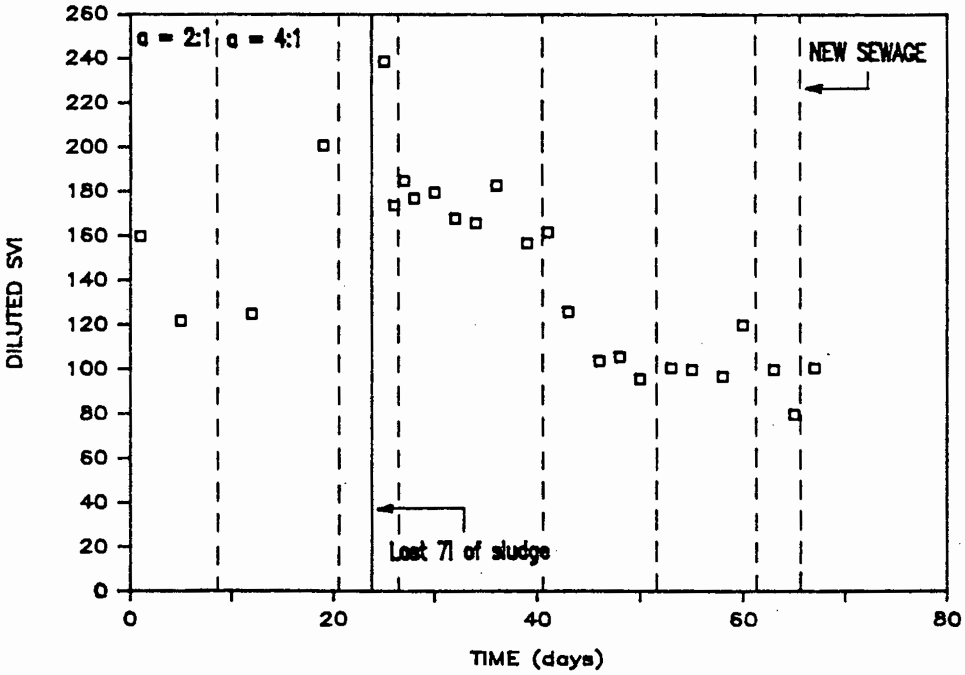
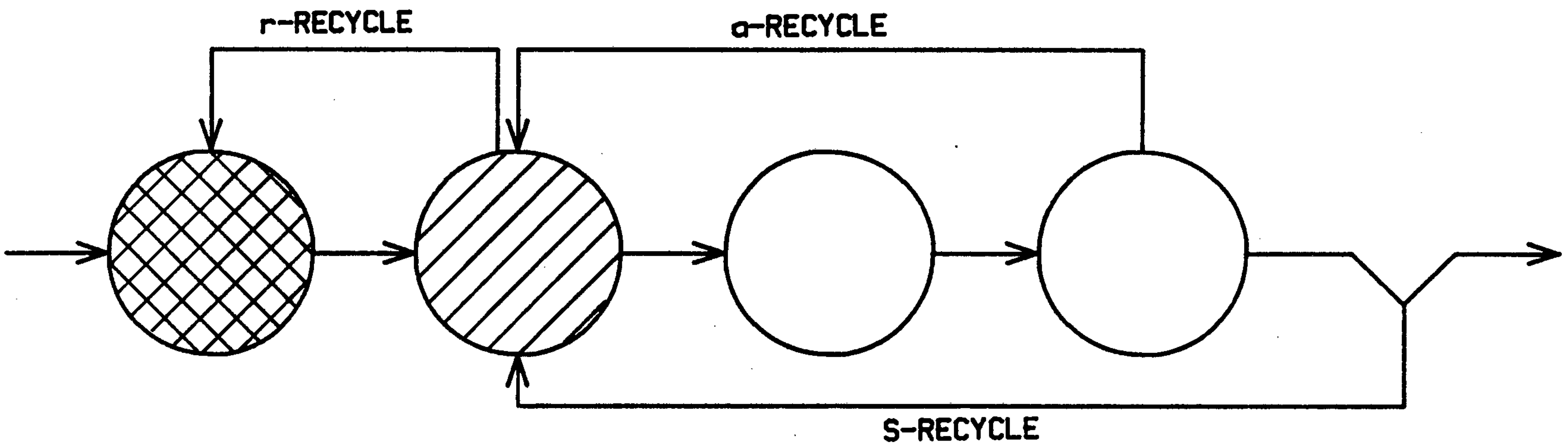


Fig 4.122: Daily performance of the Diluted Sludge Volume Index for the 6 day sludge age 3-stage Bardenpho System.



<u>Fig 4.123</u>: Schematic diagram of the UCT configuration.

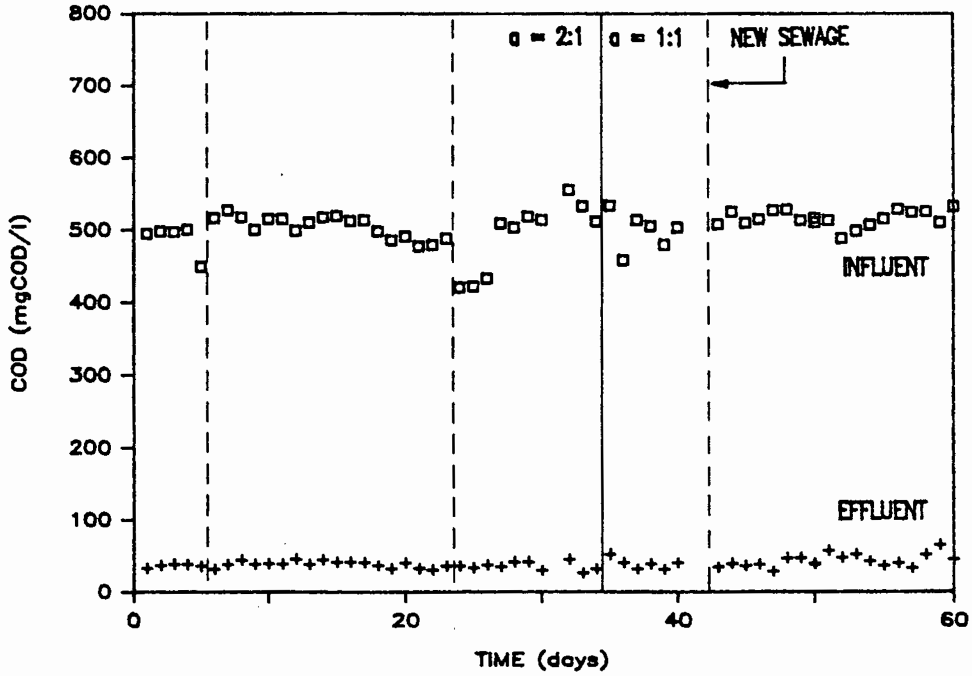


Fig 4.124: Daily performance of the unfiltered influent and filtered effluent COD concentrations for the 6 day sludge age UCT system.

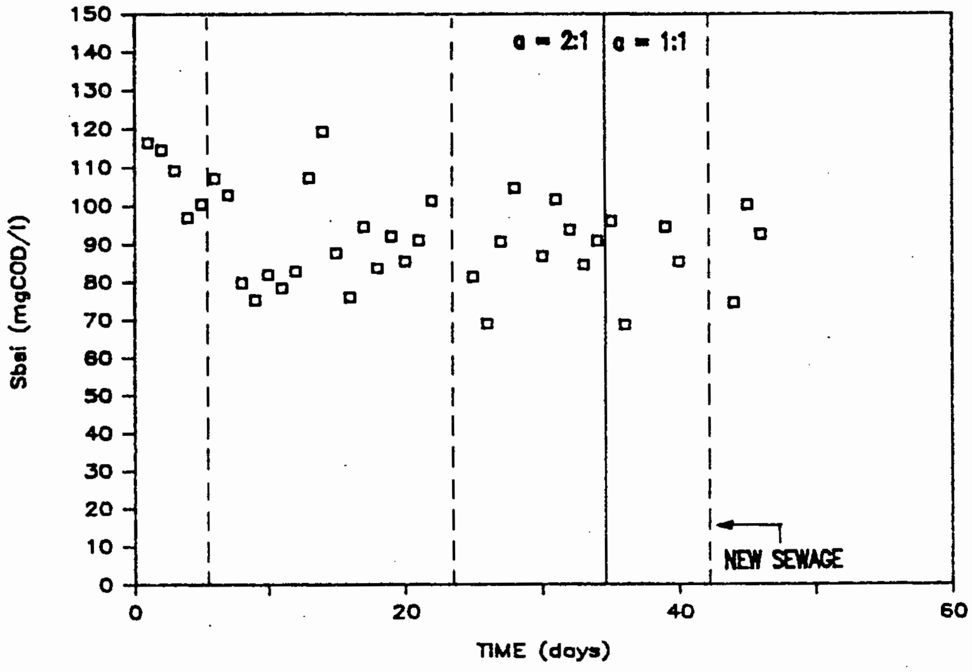


Fig 4.125: Daily performance of the influent readily biodegradable COD concentration for the 6 day sludge age UCT system.

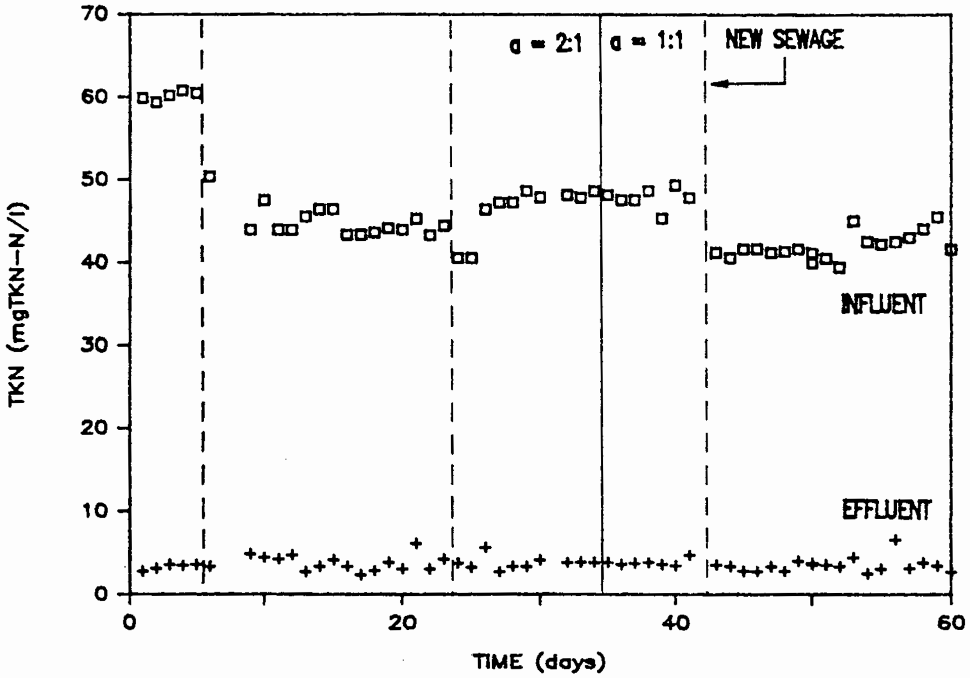


Fig 4.126: Daily performance of the unfiltered influent and filtered effluent TKN concentrations for the 6 day sludge age UCT system.

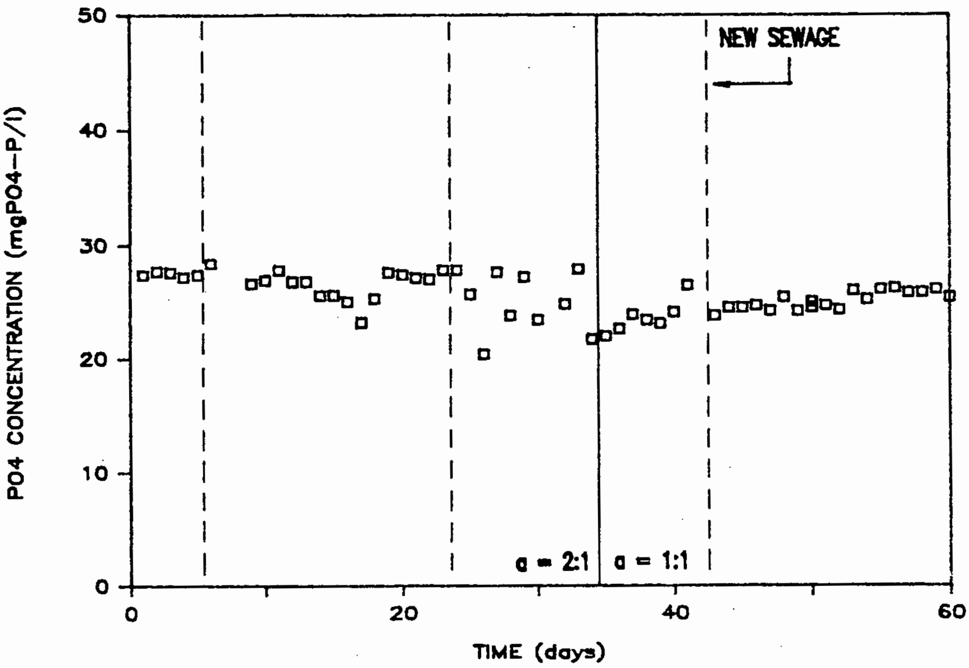


Fig 4.127: Daily performance of the phosphorus concentration in the influent to the 6 day sludge age UCT system.

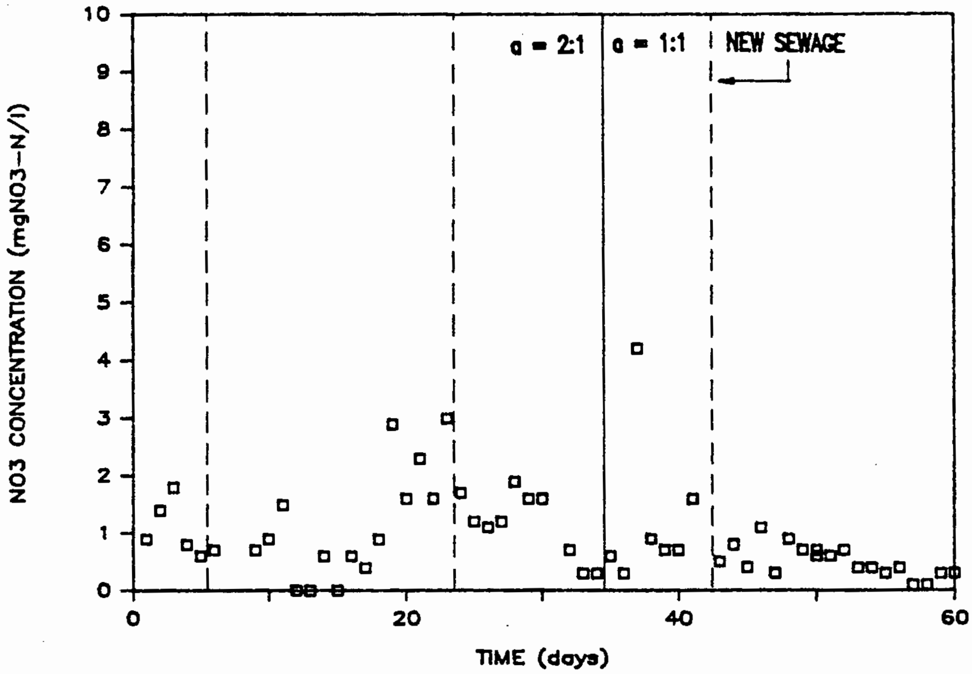


Fig 4.128: Daily performance of the nitrate concentration in the first reactor of the 6 day sludge age UCT system.

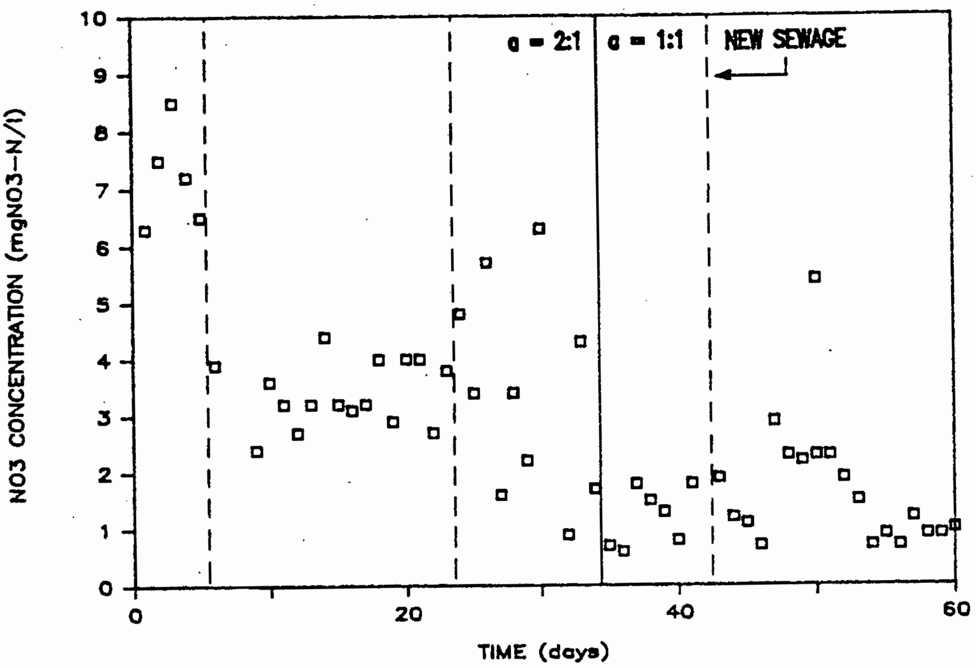


Fig 4.129: Daily performance of the nitrate concentration in the second reactor of the 6 day sludge age UCT system.

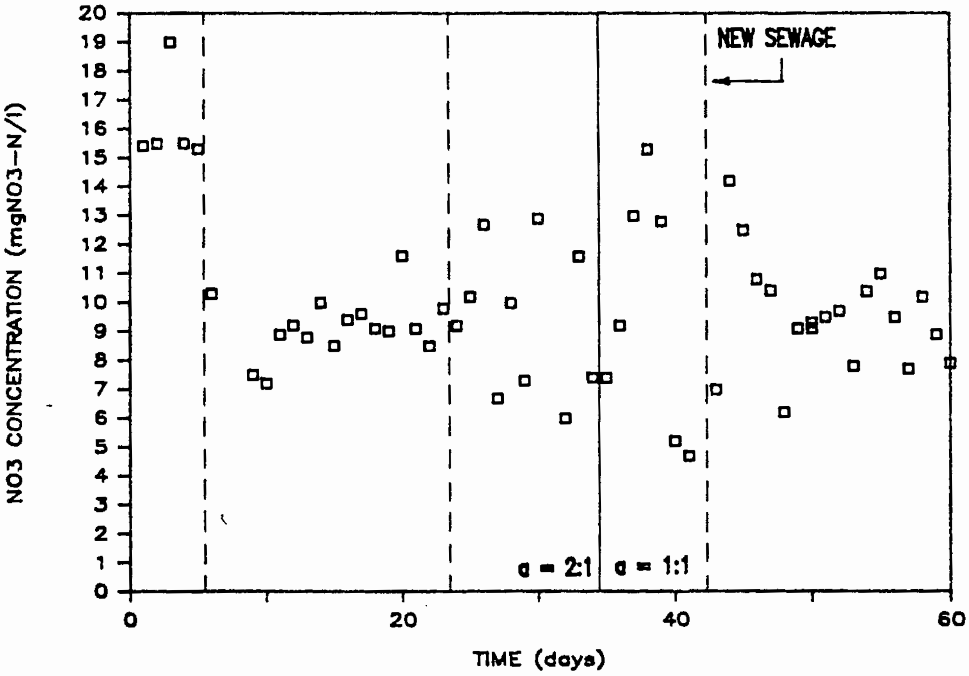


Fig 4.130: Daily performance of the nitrate concentration in the third reactor of the 6 day sludge age UCT system.

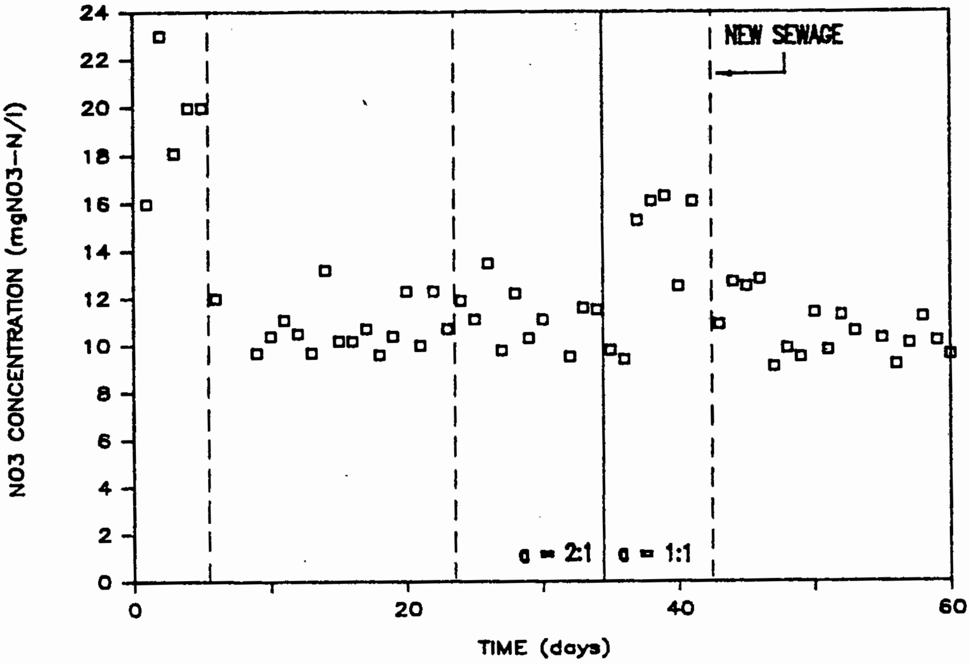


Fig 4.131: Daily performance of the nitrate concentration in the fourth reactor of the 6 day sludge age UCT system.

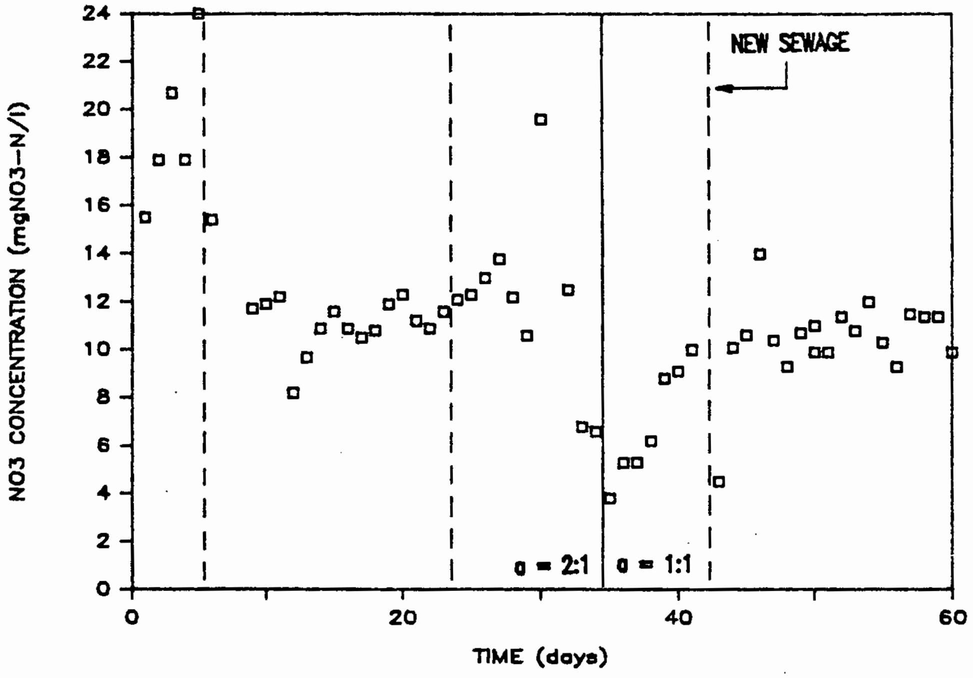


Fig 4.132: Daily performance of the nitrate concentration in the effluent from the 6 day sludge age UCT system.

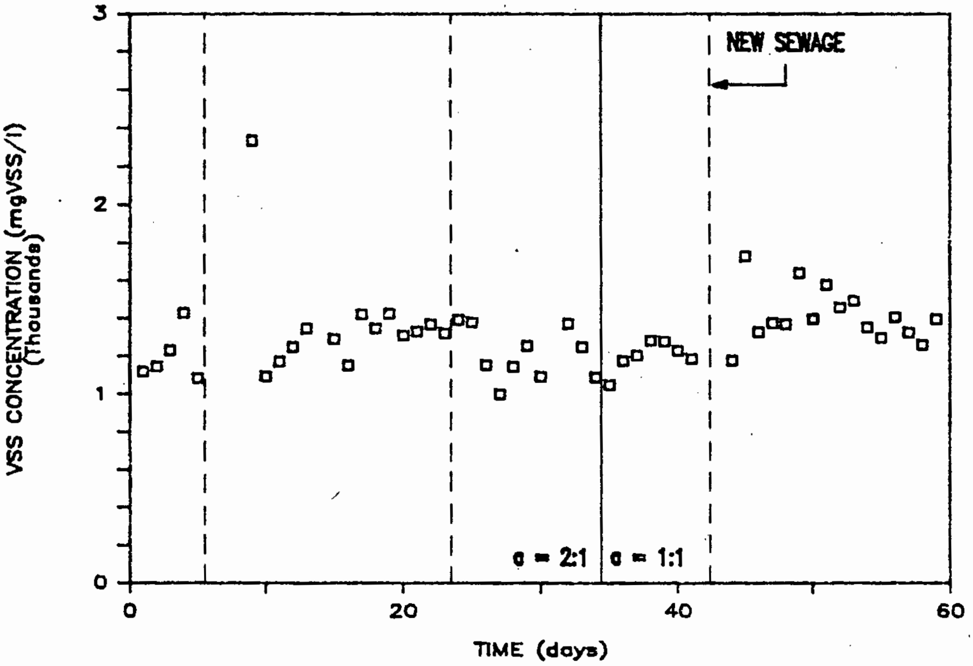


Fig 4.133: Daily performance of the volatile suspended solids in the first reactor of the 6 day sludge age UCT system.

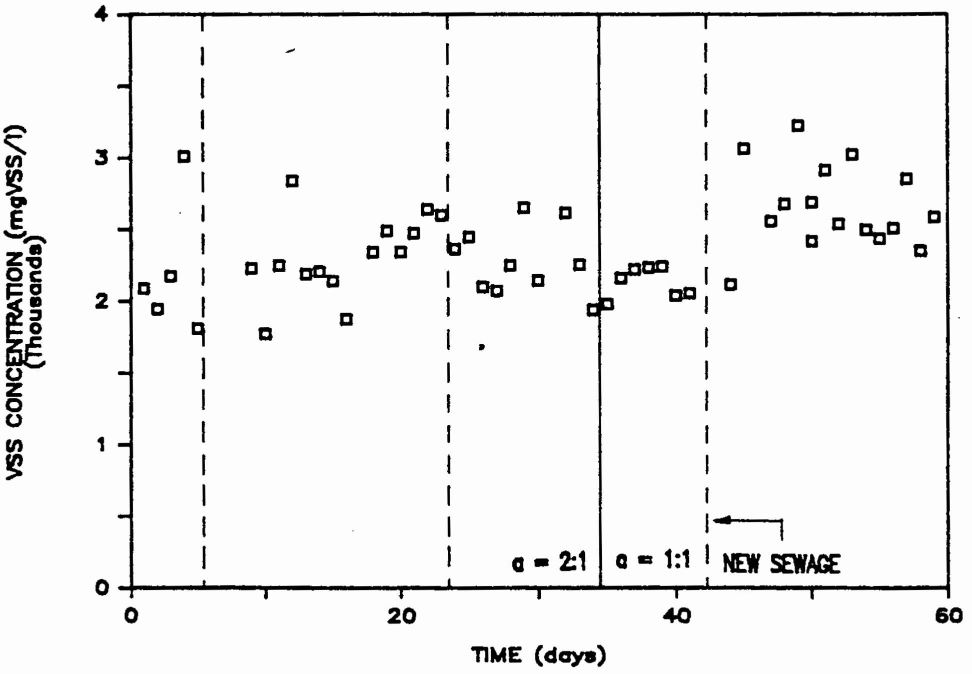


Fig 4.134: Daily performance of the volatile suspended solids in the second reactor of the 6 day sludge age UCT system.

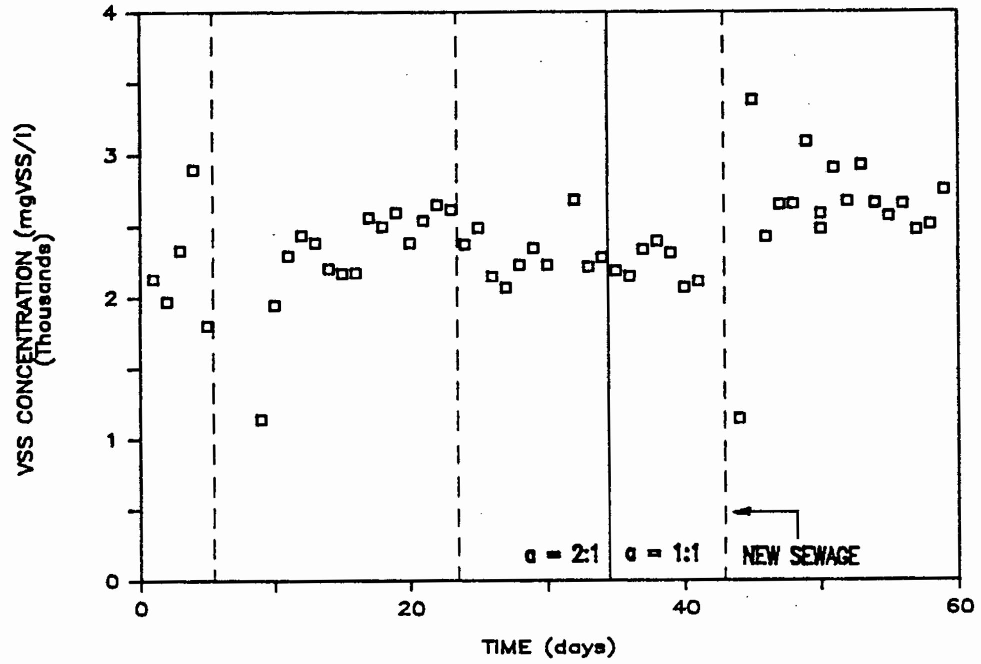


Fig 4.135: Daily performance of the volatile suspended solids in the third reactor of the 6 day sludge age UCT system.

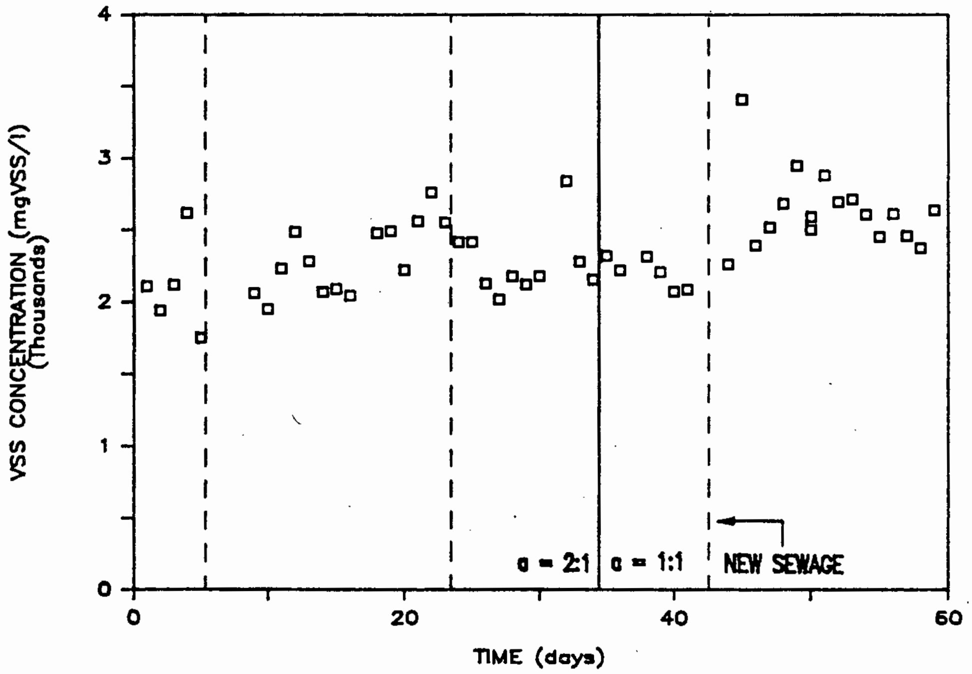


Fig 4.136: Daily performance of the volatile suspended solids in the fourth reactor of the 6 day sludge age UCT system.

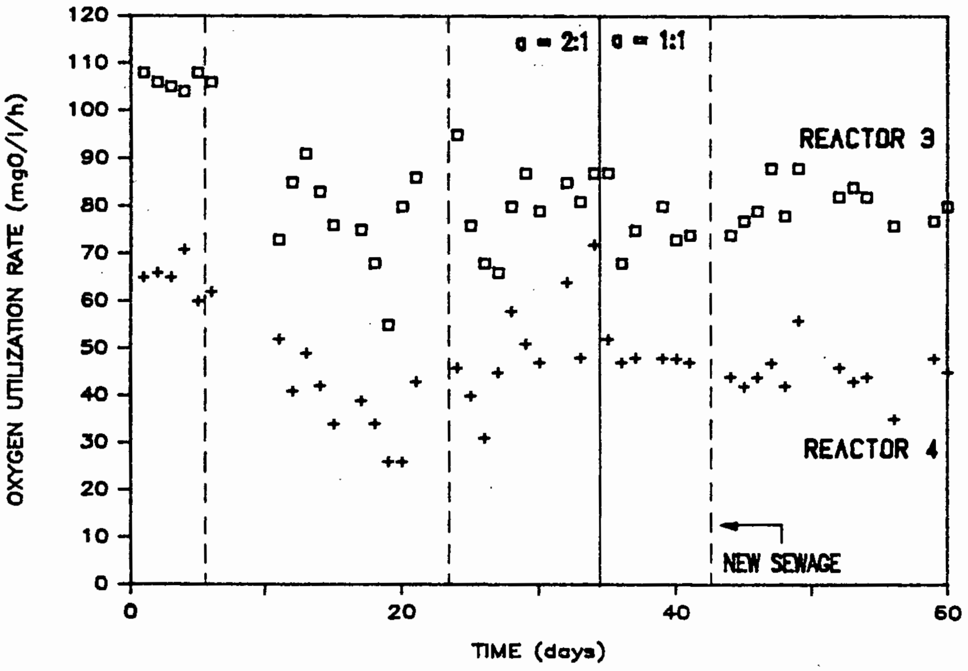


Fig 4.137: Daily performance of the oxygen utilisation rates in the aerobic reactors of the 6 day sludge age UCT system.

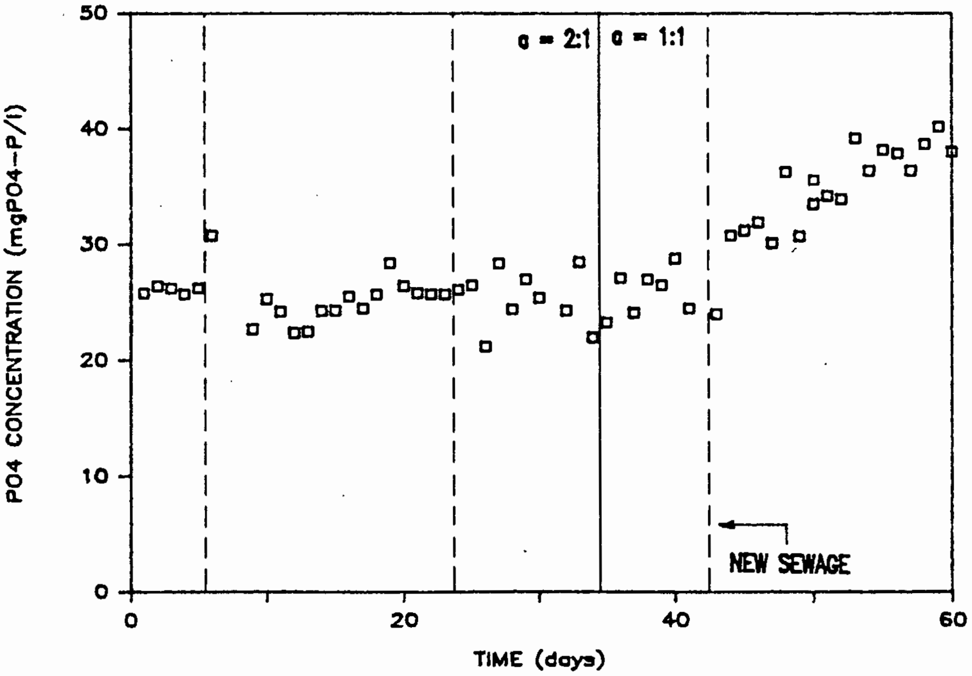


Fig 4.138: Daily performance of the phosphorus concentration in the first reactor of the 6 day sludge age UCT system.

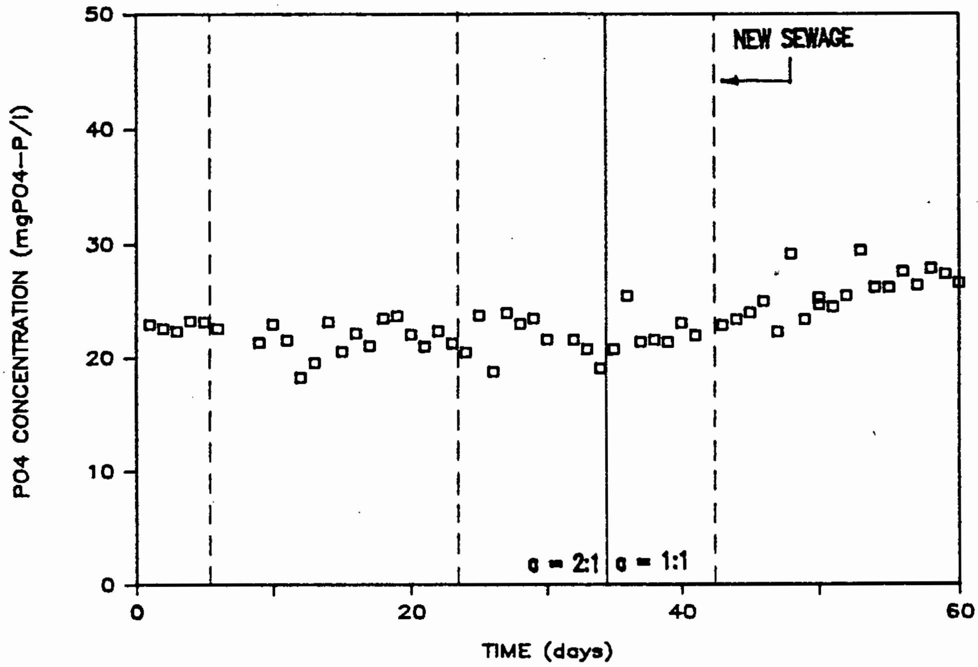


Fig 4.139: Daily performance of the phosphorus concentration in the second reactor of the 6 day sludge age UCT system.

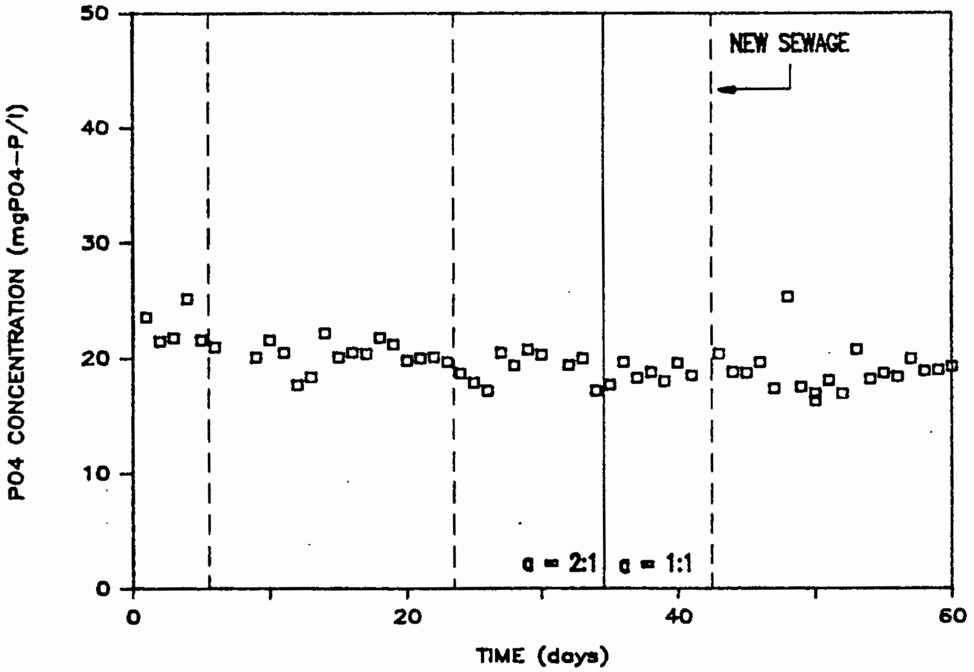


Fig 4.140: Daily performance of the phosphorus concentration in the third reactor of the 6 days ludge age UCT system.

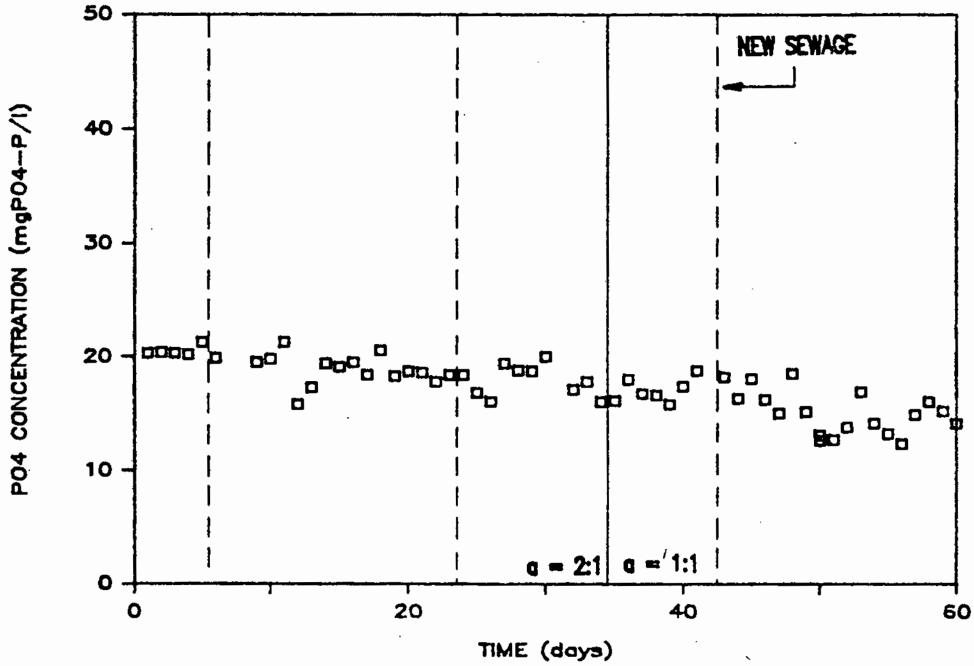


Fig 4.141: Daily performance of the phosphorus concentration in the fourth reactor of the 6 day sludge age UCT system.

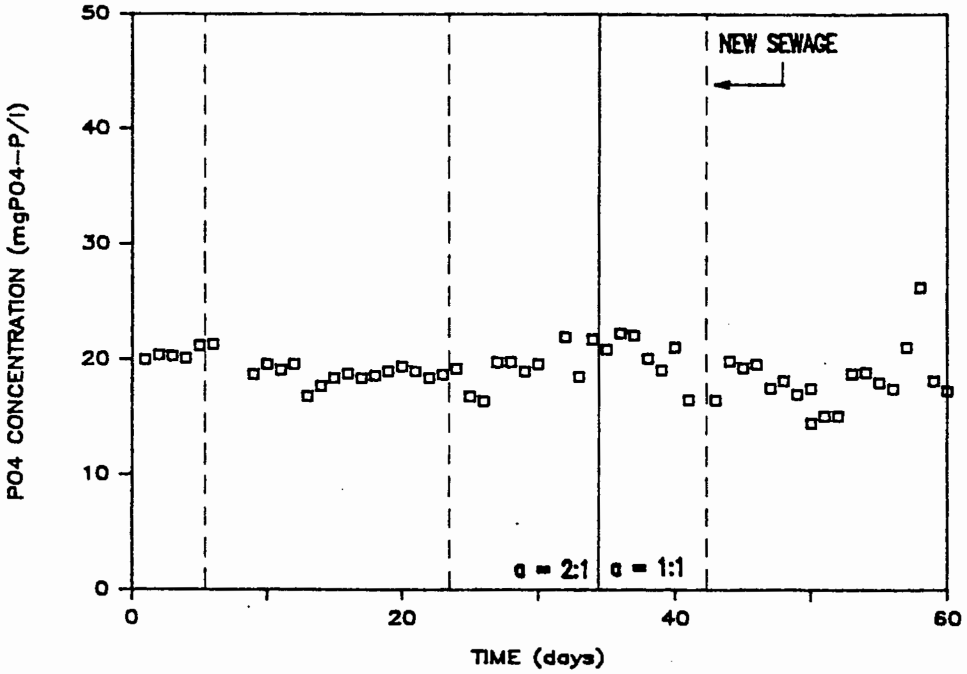


Fig 4.142: Daily performance of the phosphorus concentration in the filtered effluent from the 6 day sludge age UCT system.

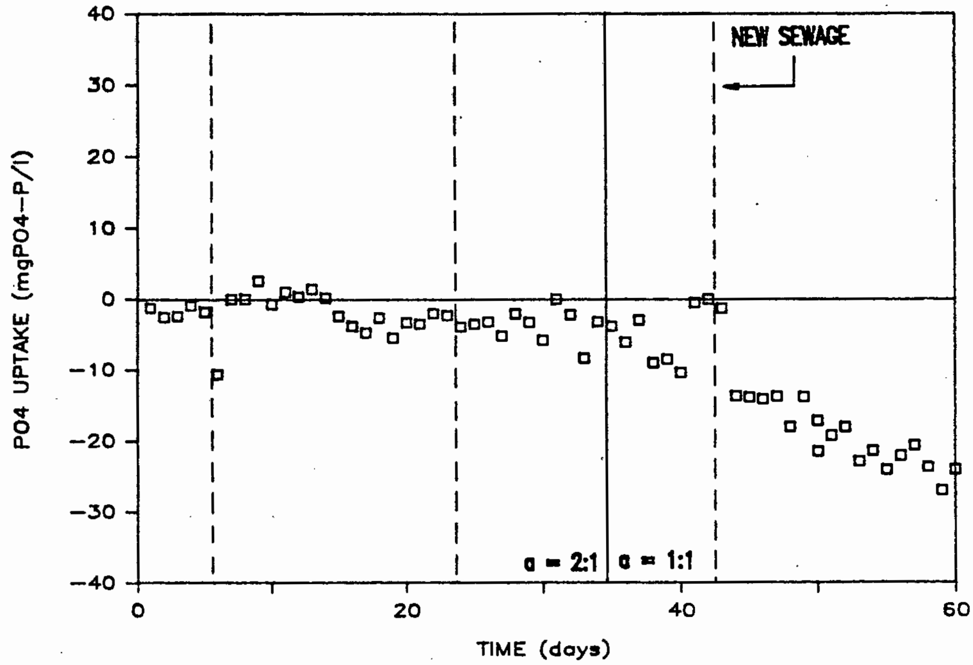


Fig 4.143: Daily performance of the phosphorus uptake in the first reactor of the 6 day sludge age UCT system.

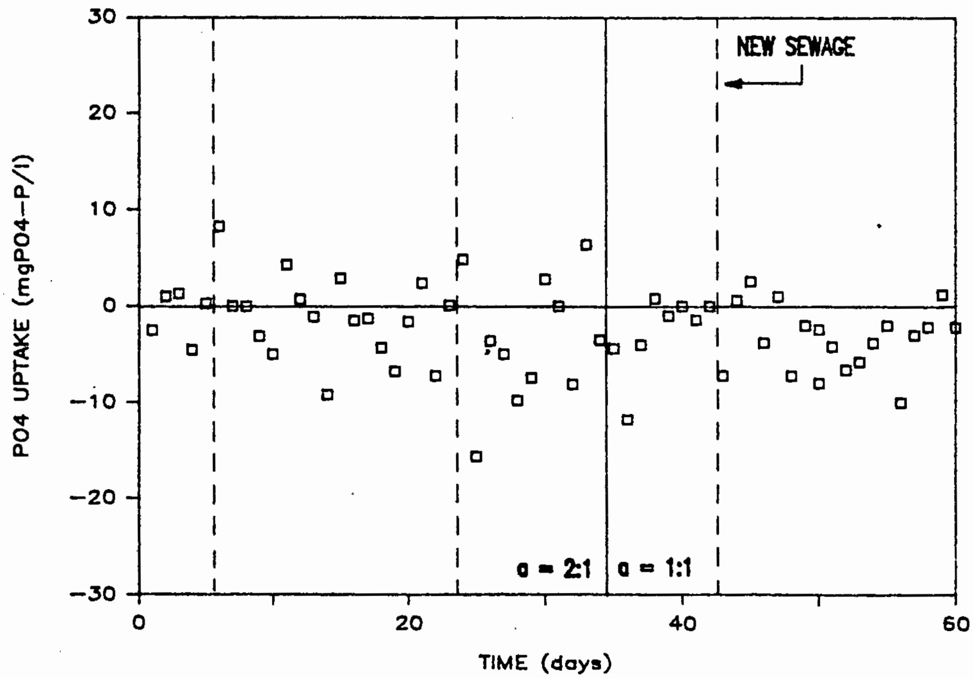


Fig 4.144: Daily performance of the phosphorus uptake in the second reactor of the 6 day sludge age UCT system.

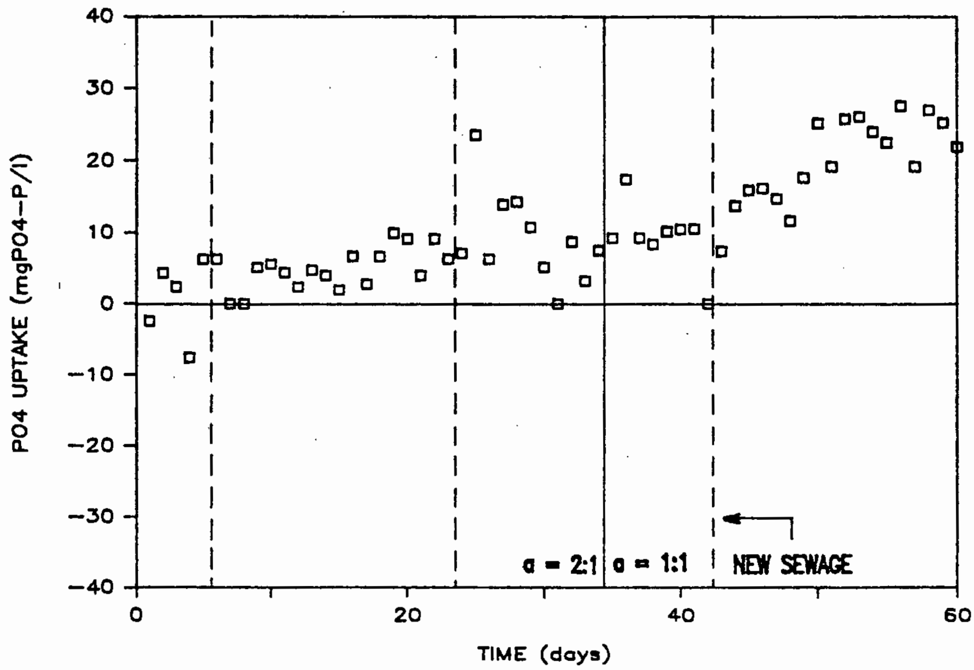


Fig 4.145: Daily performance of the phosphorus uptake in the third reactor of the 6 day sludge age UCT system.

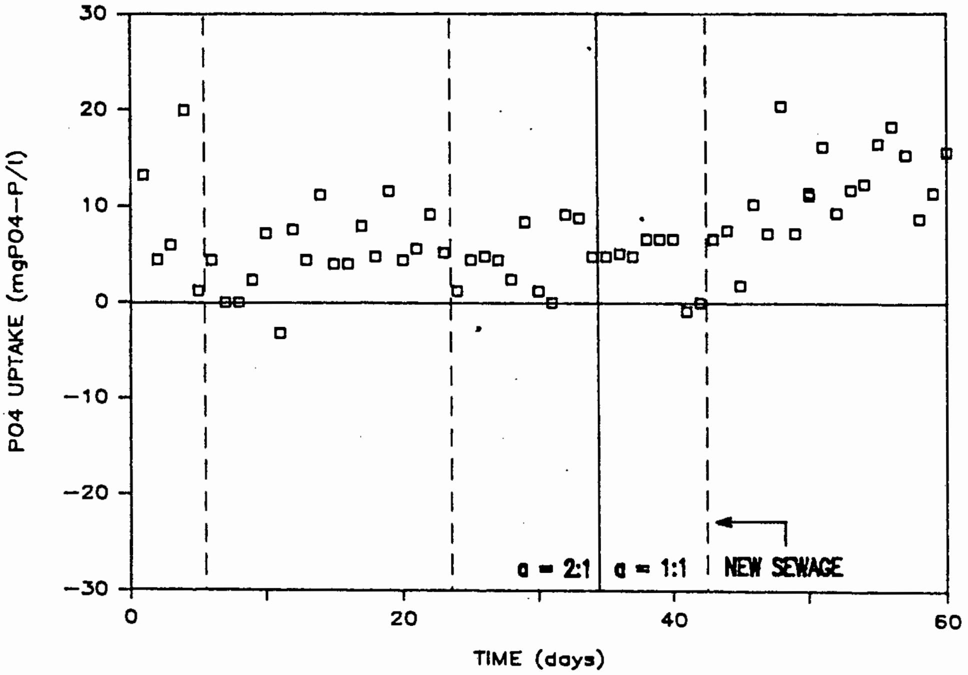


Fig 4.146: Daily performance of the phosphorus uptake in the fourth reactor of the 6 day sludge age UCT system.

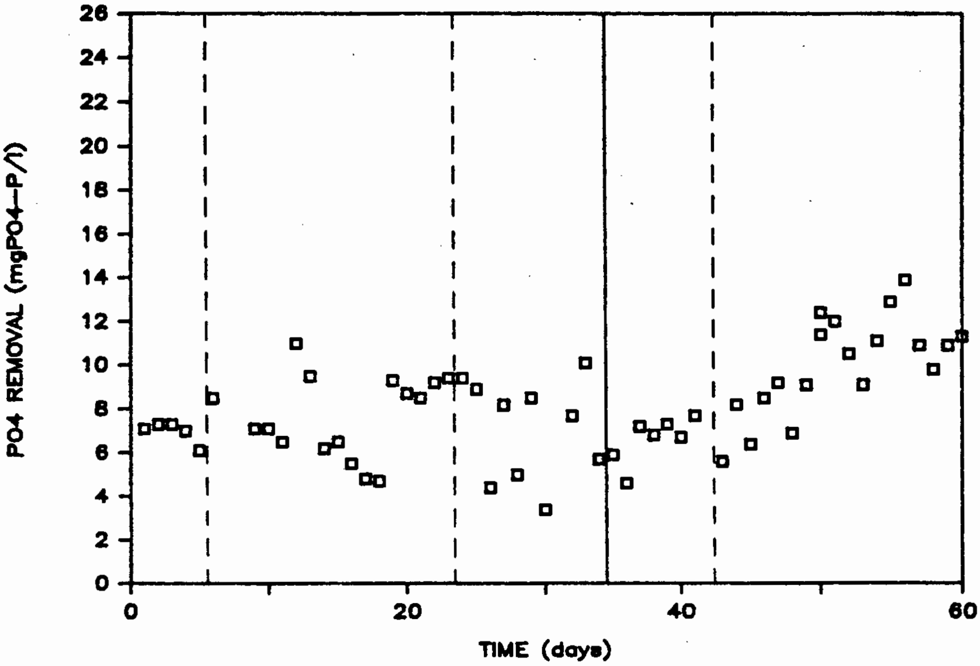


Fig 4.147: Daily performance of the phosphorus removal in the 6 day sludge age UCT system.

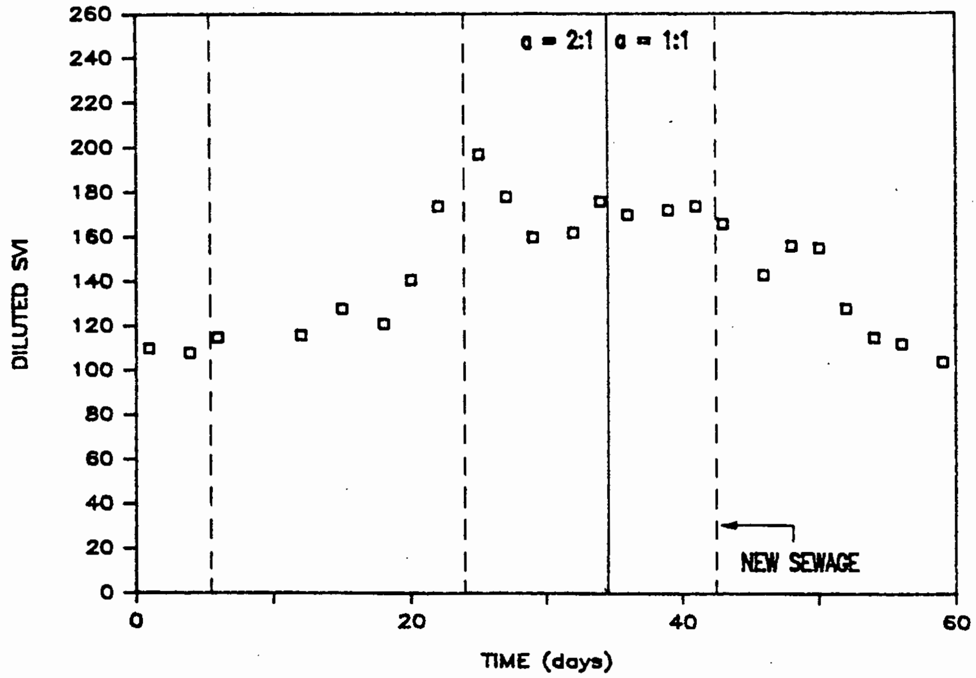


Fig 4.148: Daily performance of the Diluted Sludge Volume Index for the 6 day sludge age UCT system.

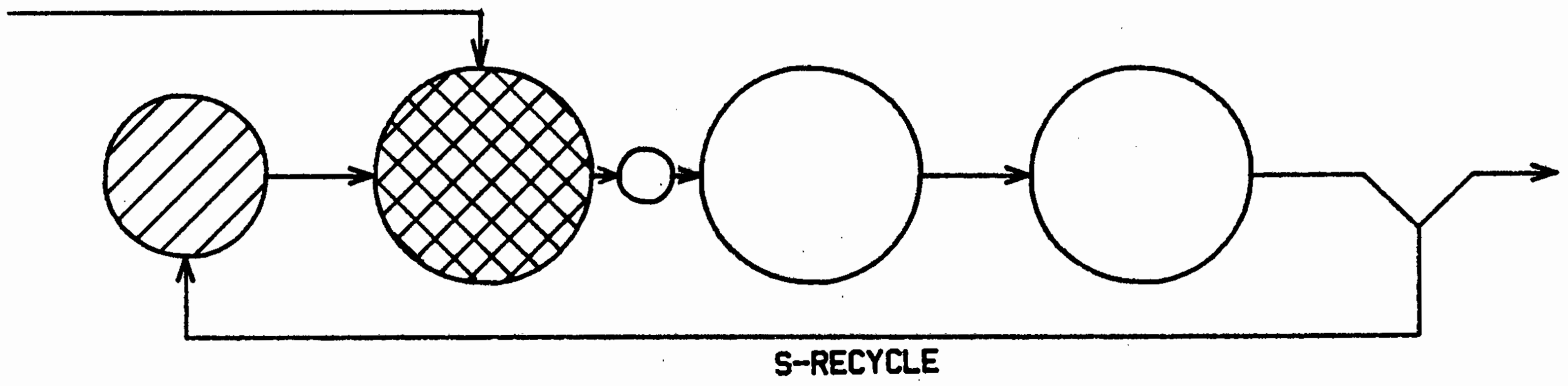


Fig 4.149: Schematic diagram of the Johannesburg configuration.

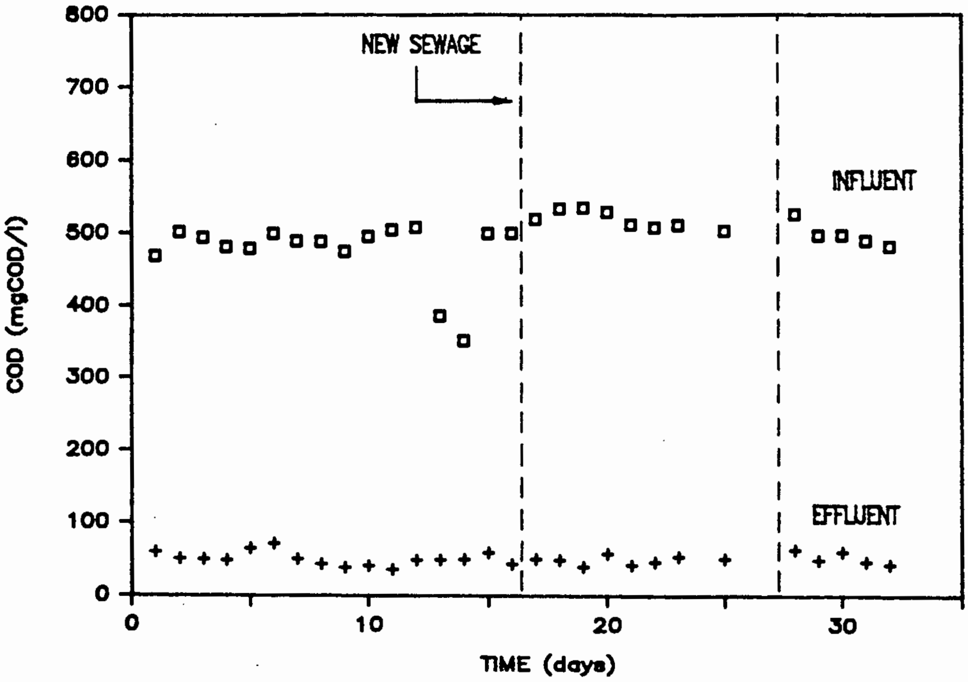


Fig 4.150: Daily performance of the unfiltered influent and filtered effluent COD concentrations for the 3 day sludge age Johannesburg system.

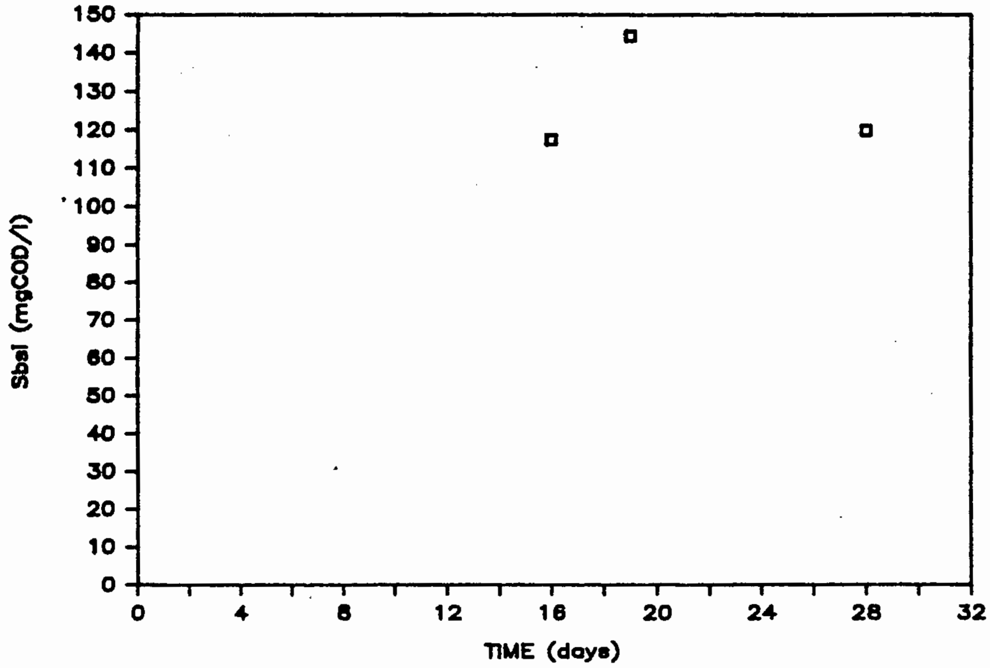
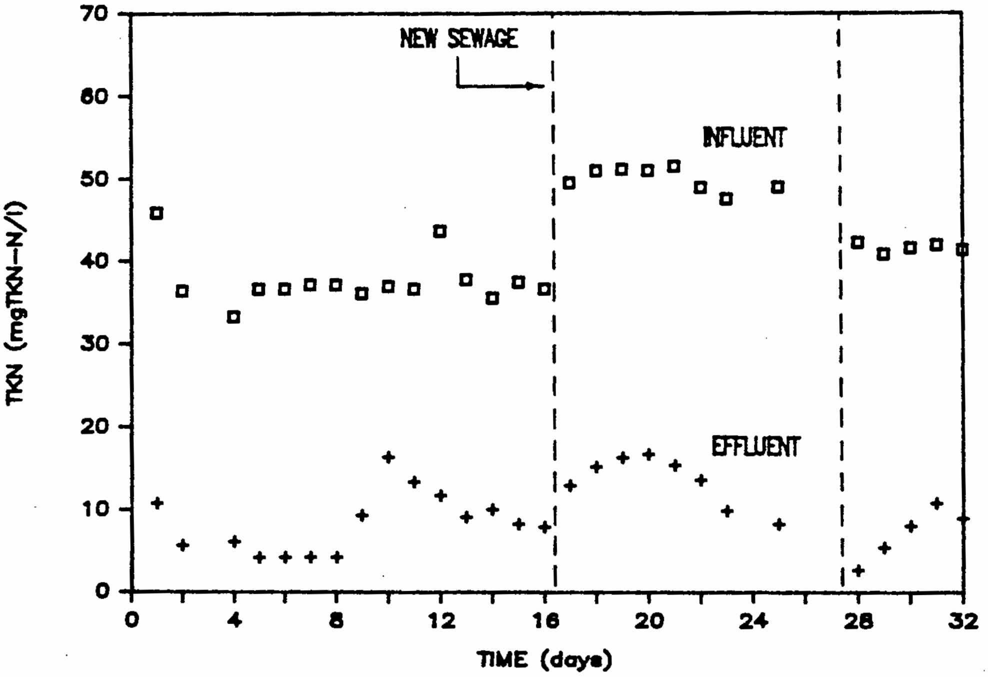
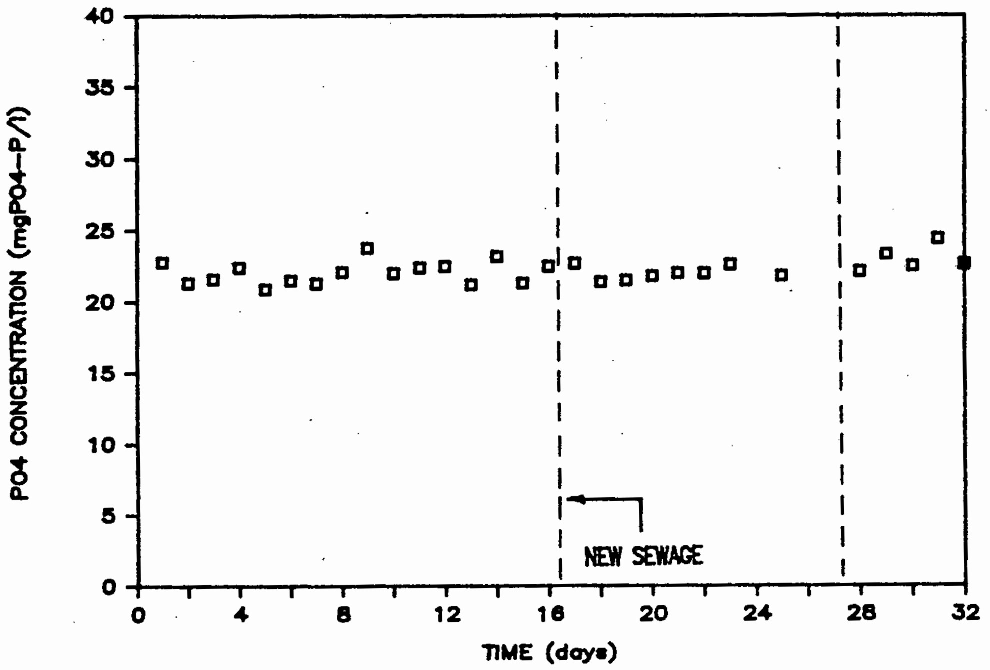


Fig 4.151: Daily performance of the influent readily biodegradable COD concentration for the 3 day sludge age Johannesburg system.



<u>Fig 4.152</u>: Daily performance of the unfiltered influent and filtered effluent TKN concentrations for the 3 day sludge age Johannesburg system.



<u>Fig 4.153</u>: Daily performance of the phosphorus concentration in the influent to the 3 day sludge age Johannesburg system.

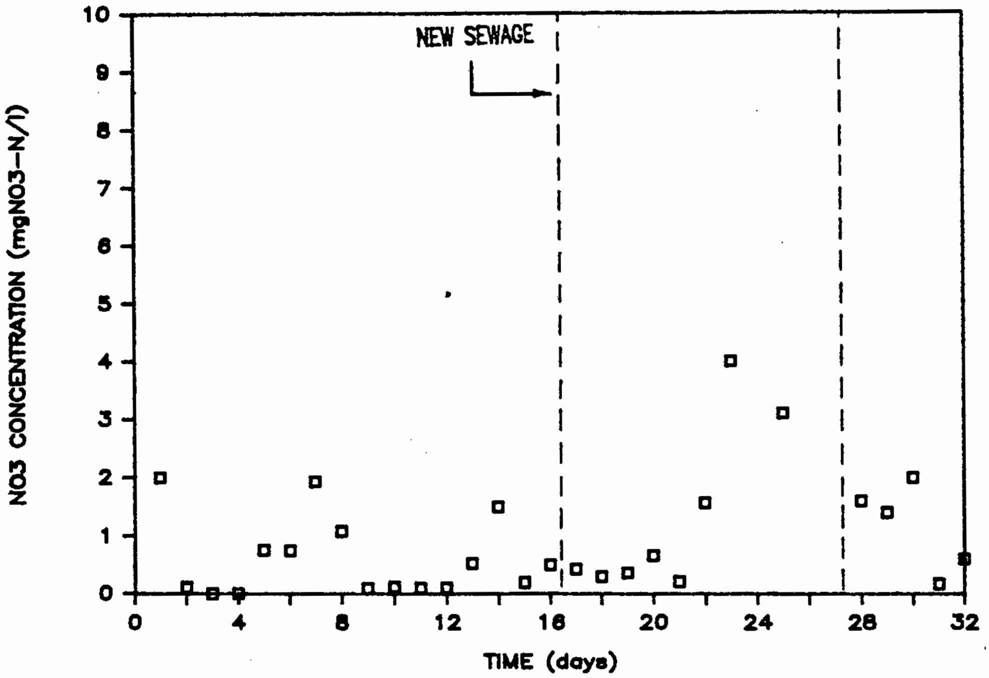


Fig 4.154: Daily performance of the nitrate concentration in the first reactor of the 3 day sludge age Johannesburg system.

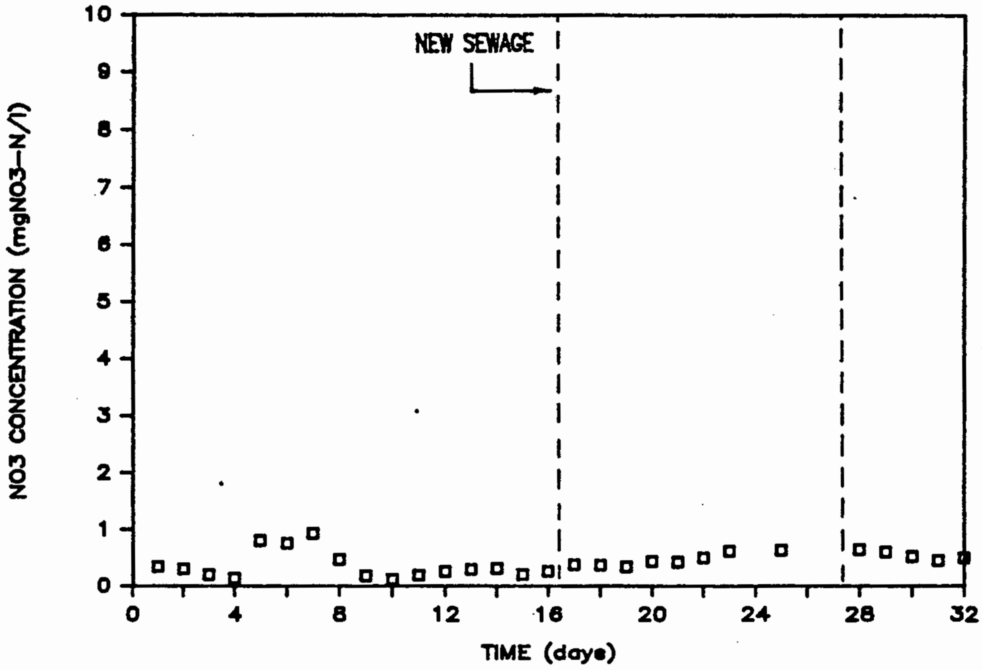


Fig 4.155: Daily performance of the nitrate concentration in the second reactor of the 3 day sludge age Johannesburg system.

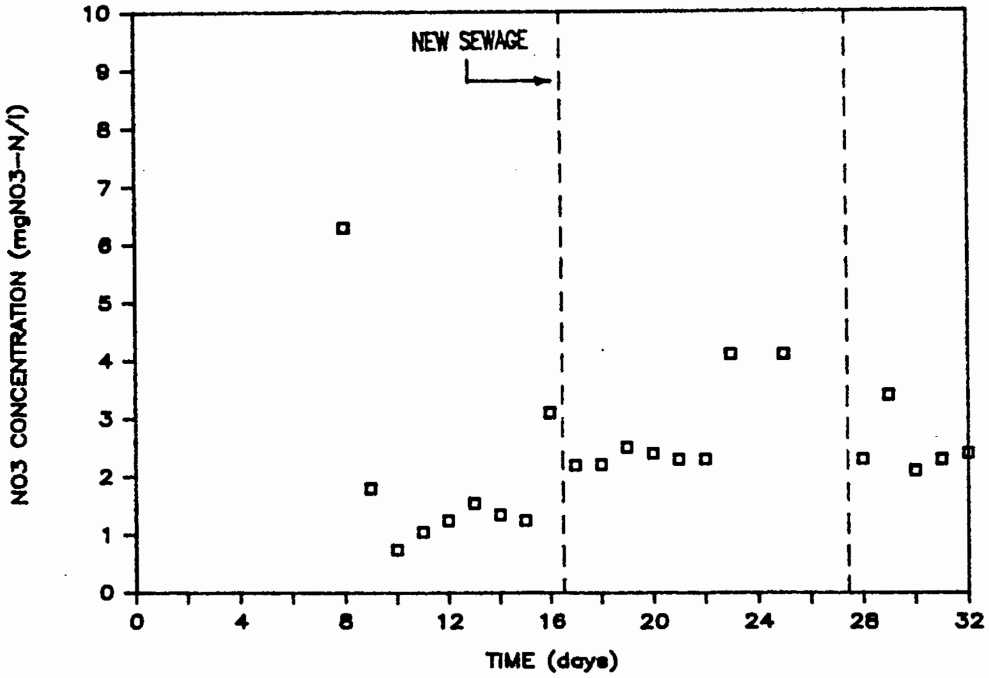


Fig 4.156: Daily performance of the nitrate concentration in the selector reactor of the 3 day sludge age Johannesburg system.

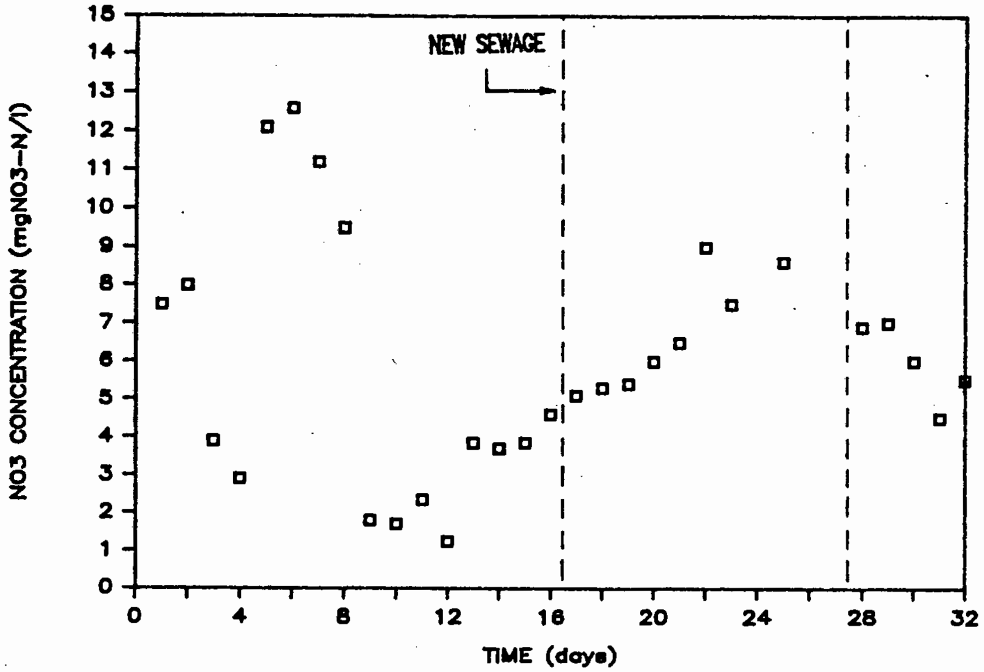


Fig 4.157: Daily performance of the nitrate concentration in the third reactor of the 3 day sludge age Johannesburg system.

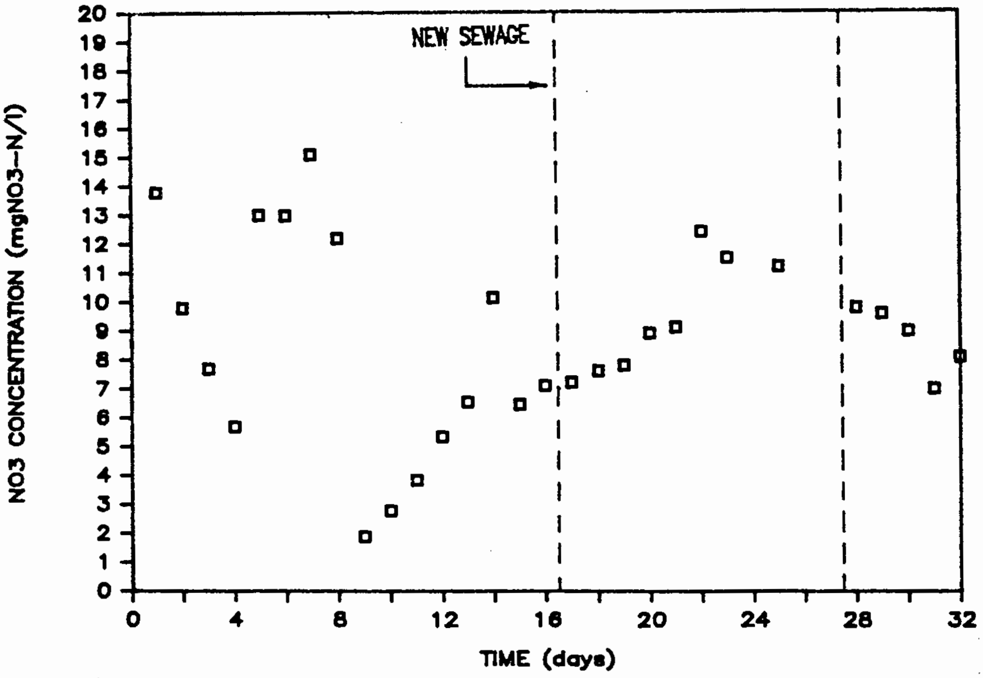


Fig 4.158: Daily performance of the nitrate concentration in the fourth reactor of the 3 day sludge age Johannesburg system.

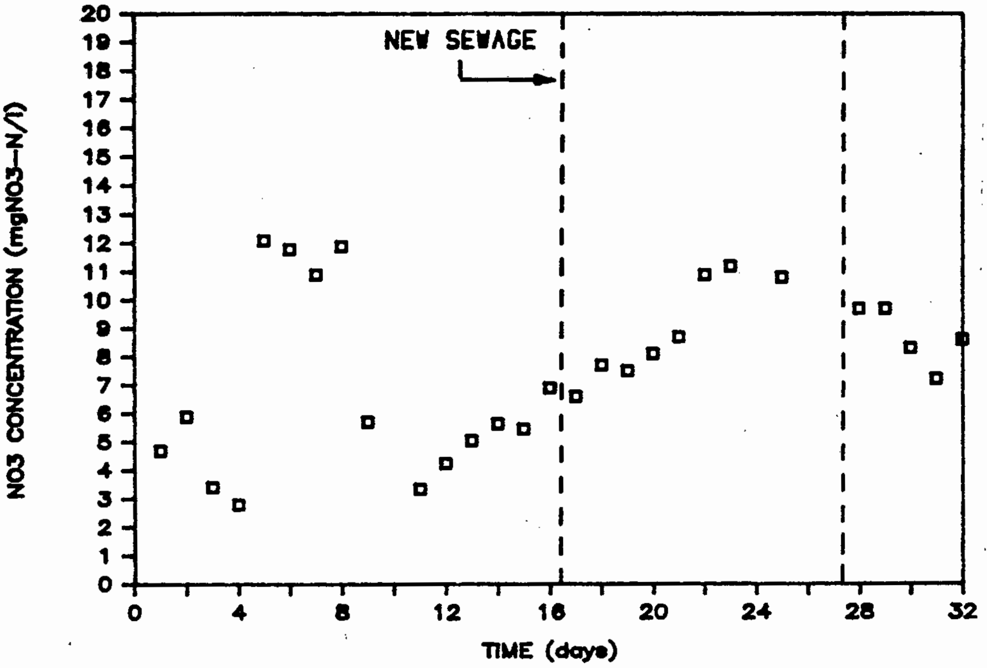


Fig 4.159: Daily performance of the nitrate concentration in the effluent from the 3 day sludge age Johannesburg system.

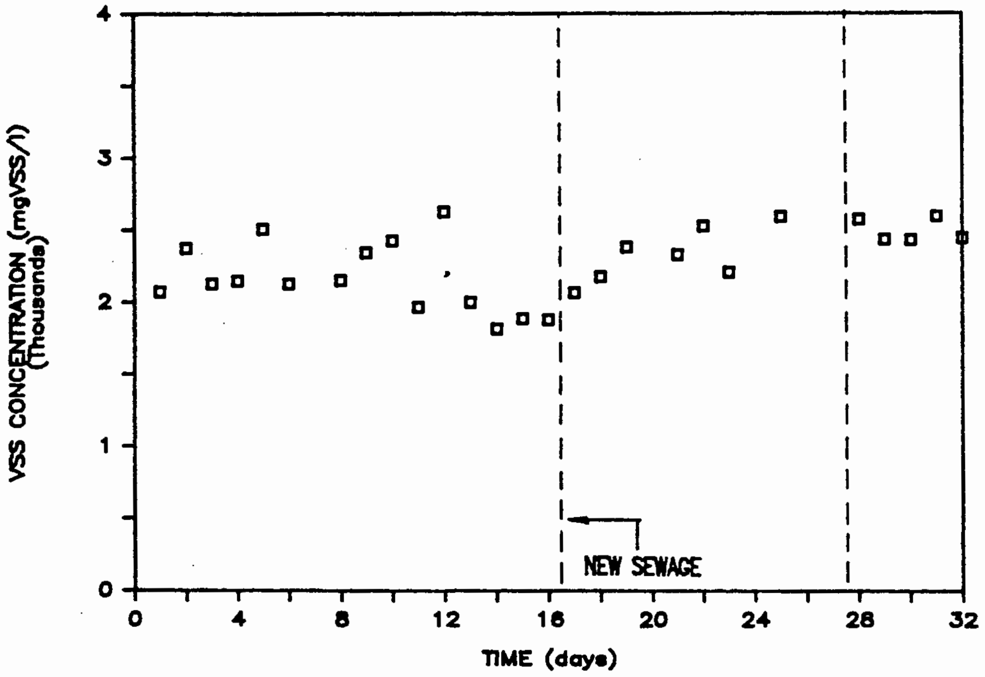


Fig 4.160: Daily performance of the volatile suspended solids in the first reactor of the 3 day sludge age Johannesburg system.

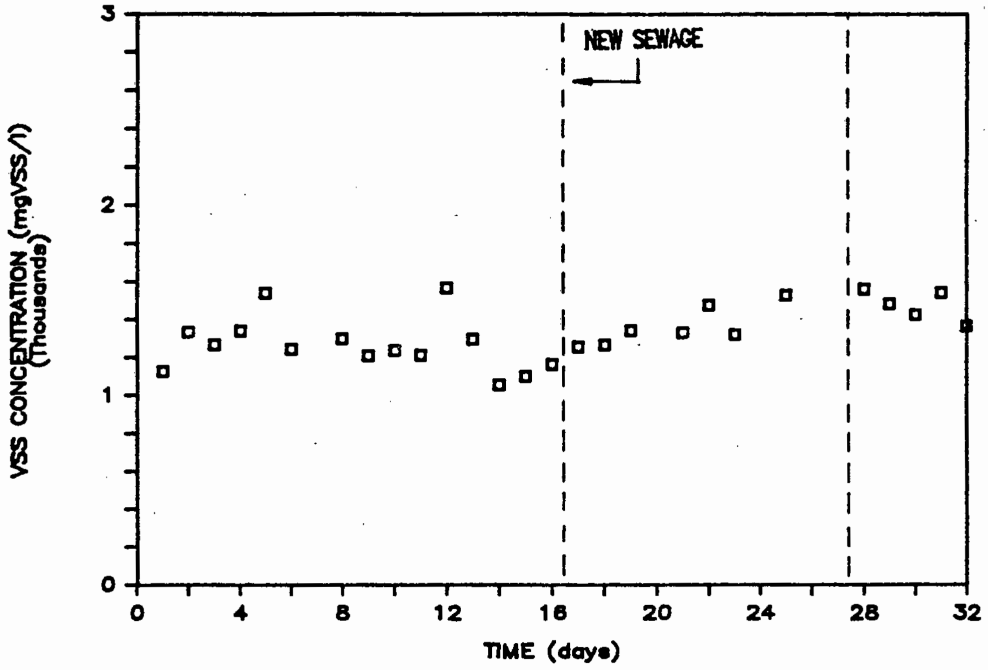


Fig 4.161: Daily performance of the volatile suspended solids in the second reactor of the 3 day sludge age Johannesburg system.

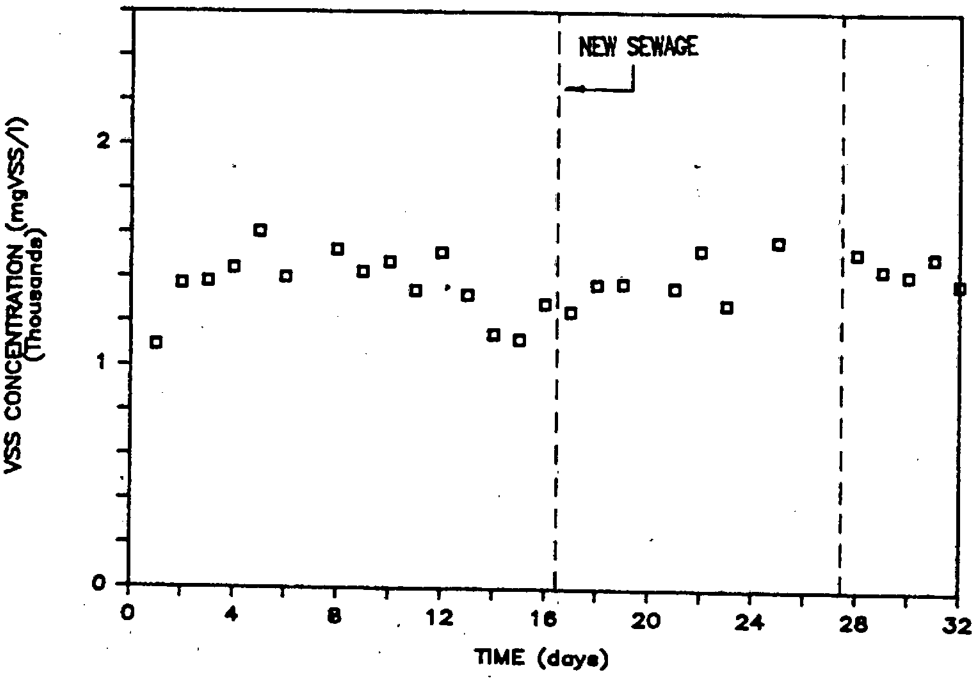


Fig 4.162: Daily performance of the volatile suspended solids in the third reactor of the 3day sludge age Johannesburg system.

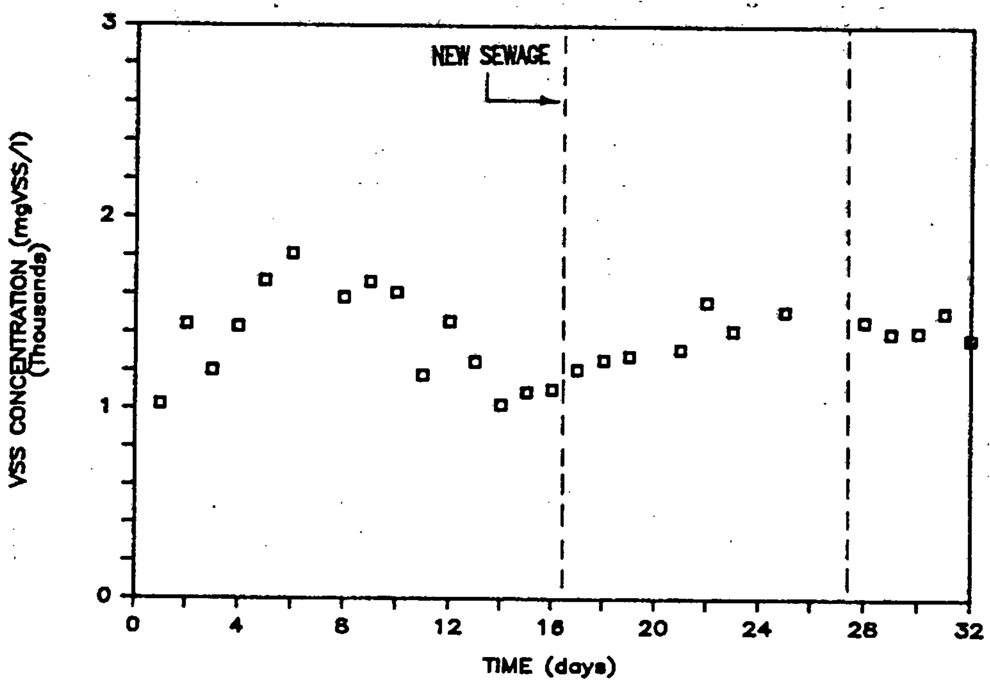


Fig 4.163: Daily performance of the volatile suspended solids in the fourth reactor of the 3 day sludge age Johannesburg system.

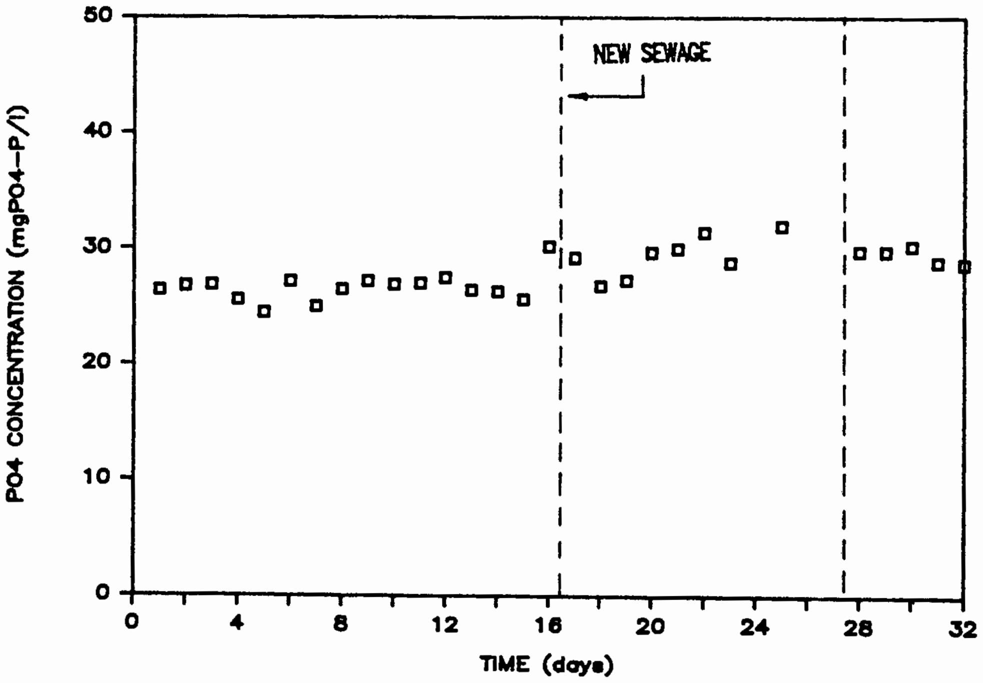


Fig 4.166: Daily performance of the phosphorus concentration in the second reactor of the 3 day sludge age Johannesburg system.

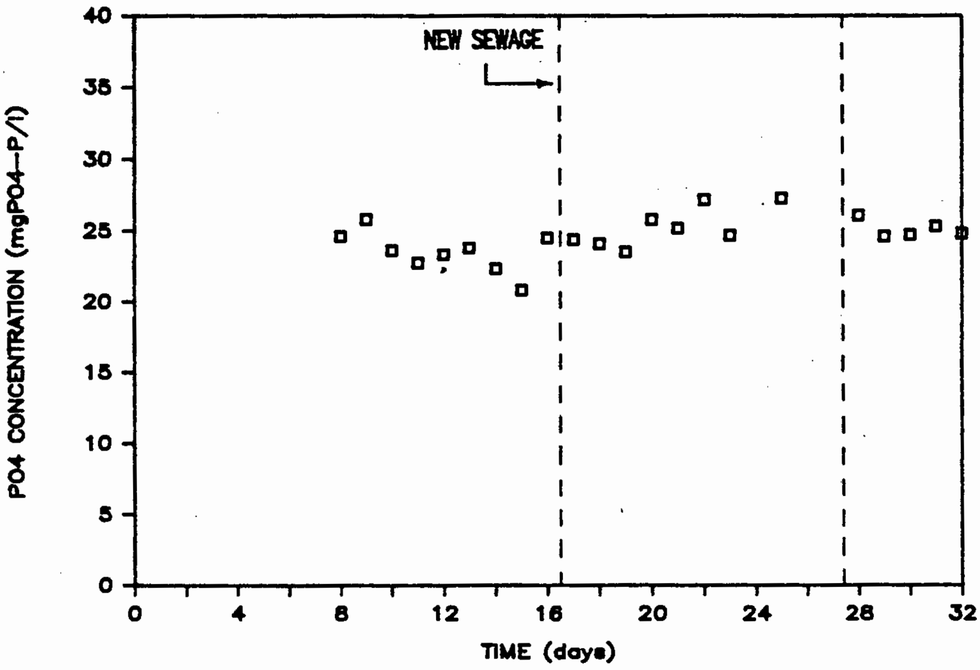


Fig 4.167: Daily performance of the phosphorus concentration in the selector reactor of the 3 day sludge age Johannesburg system.

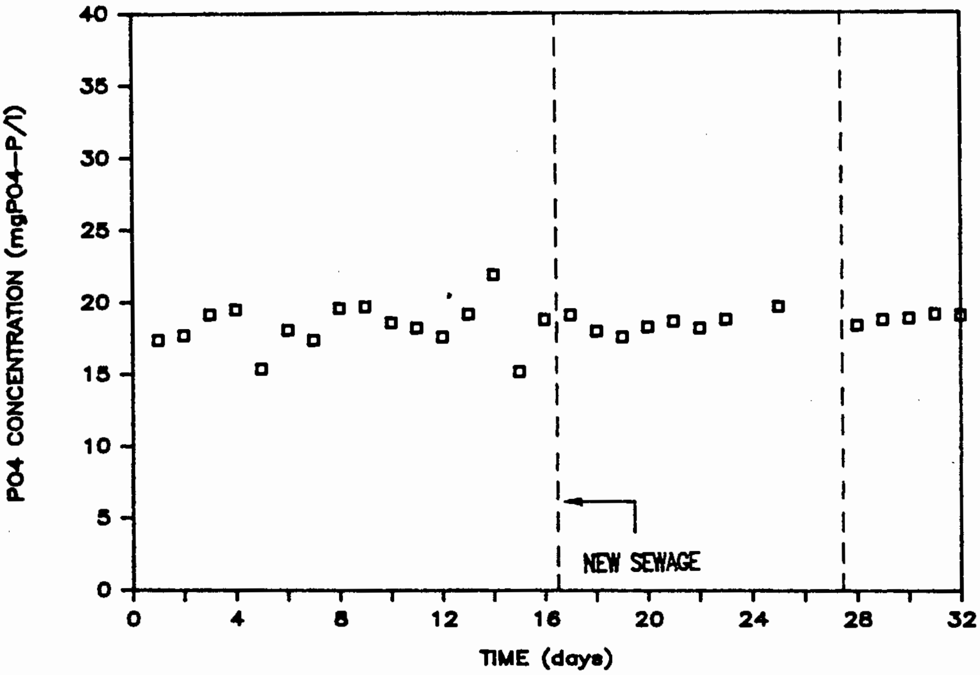


Fig 4.168: Daily performance of the phosphorus concentration in the third reactor of the 3 day sludge age Johannesburg system.

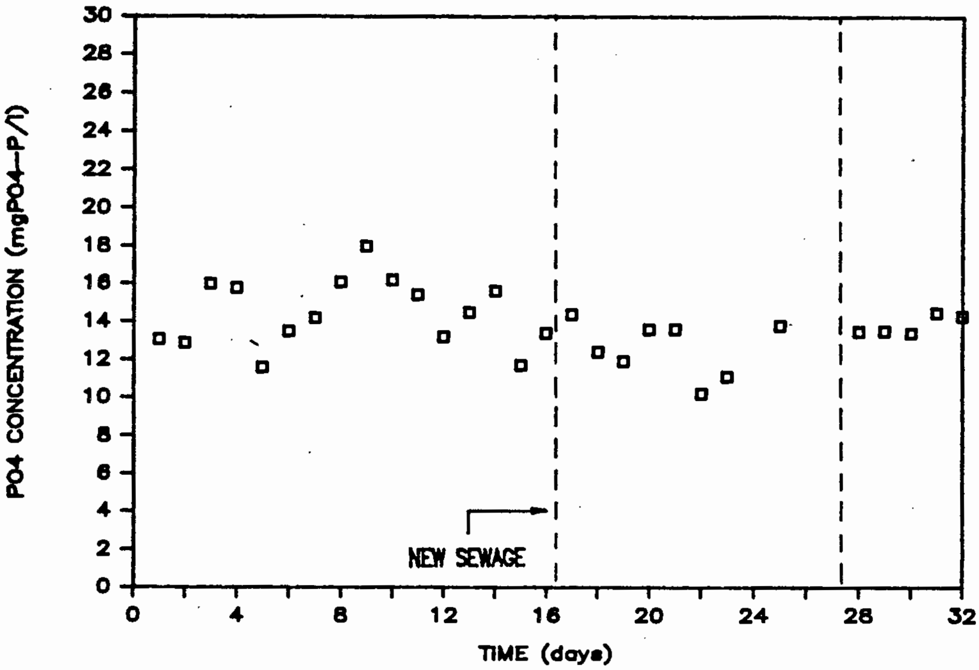


Fig 4.169: Daily performance of the phosphorus concentration in the fourth reactor of the 3 day sludge age Johannesburg system.

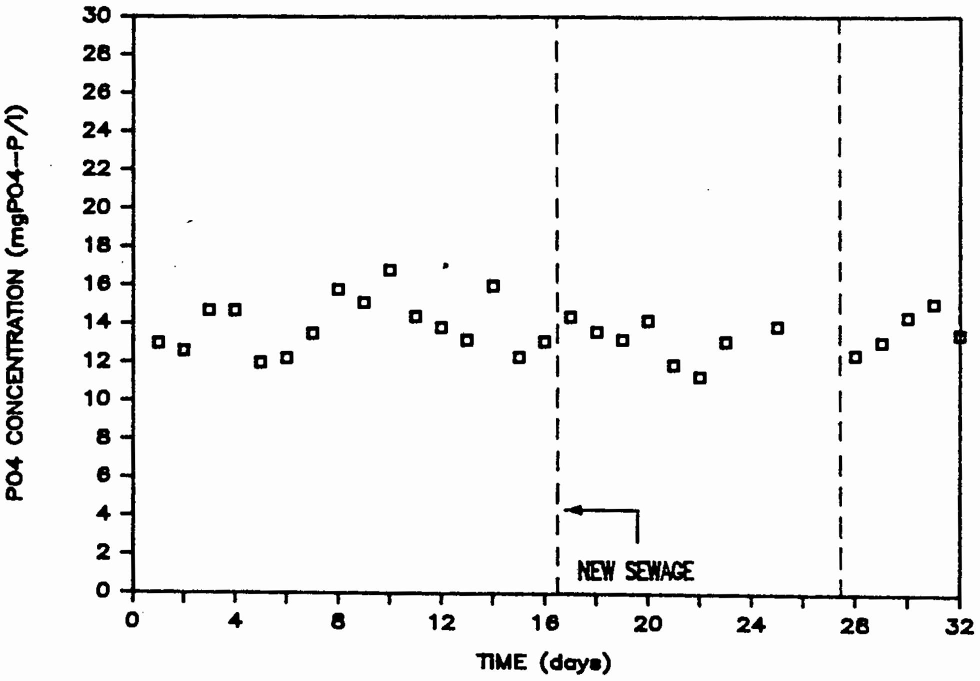


Fig 4.170: Daily performance of the phosphorus concentration in the filtered effluent from the 3 day sludge age Johannesburg system.

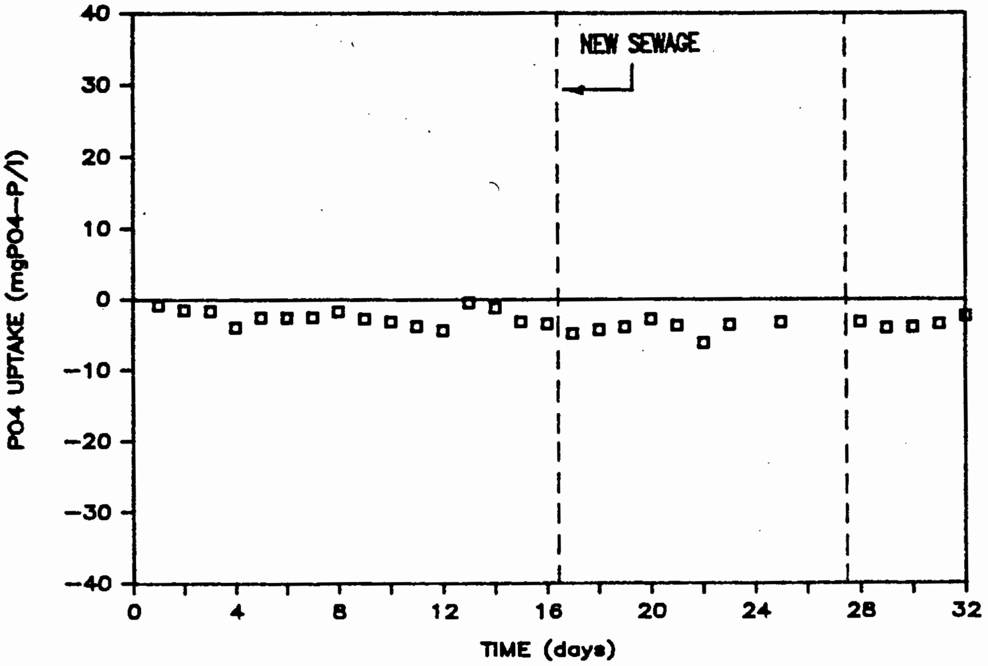


Fig 4.171: Daily performance of the phosphorus uptake in the first reactor of the 3 day sludge age Johannesburg system.

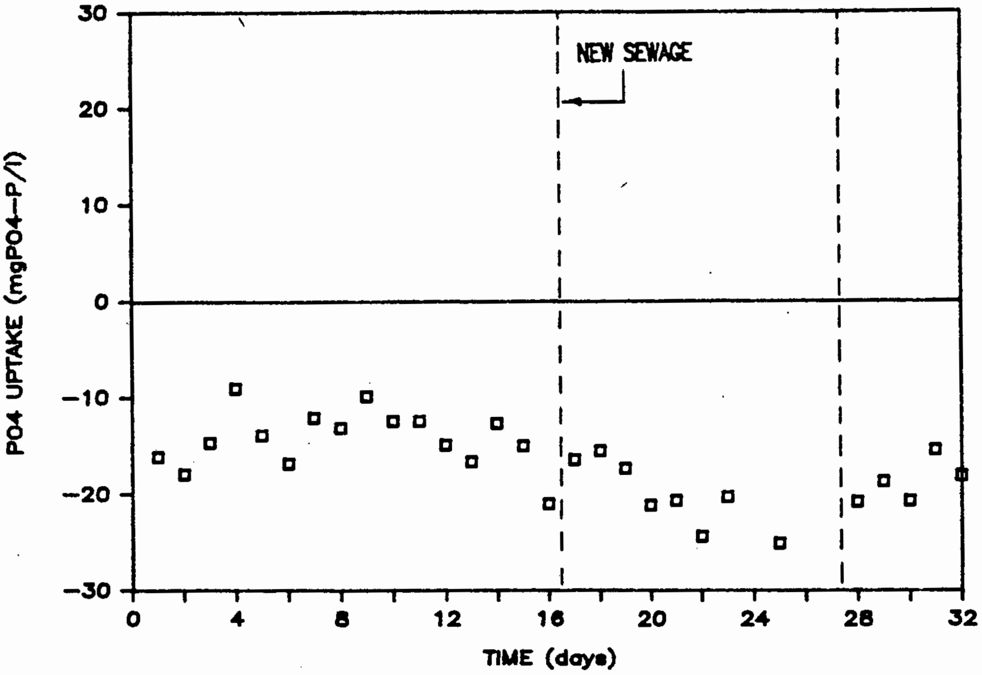


Fig 4.172: Daily performance of the phosphorus uptake in the second reactor of the 3 day sludge age Johannesburg system.

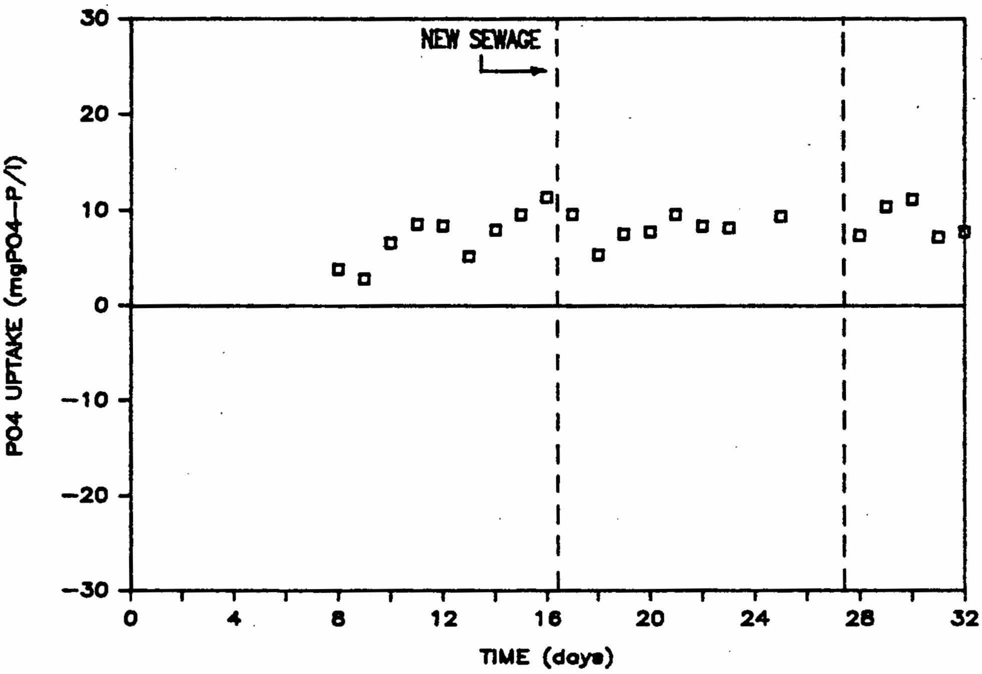


Fig 4.173: Daily performance of the phosphorus uptake in the selector reactor of the 3 day sludge age Johannesburg system.

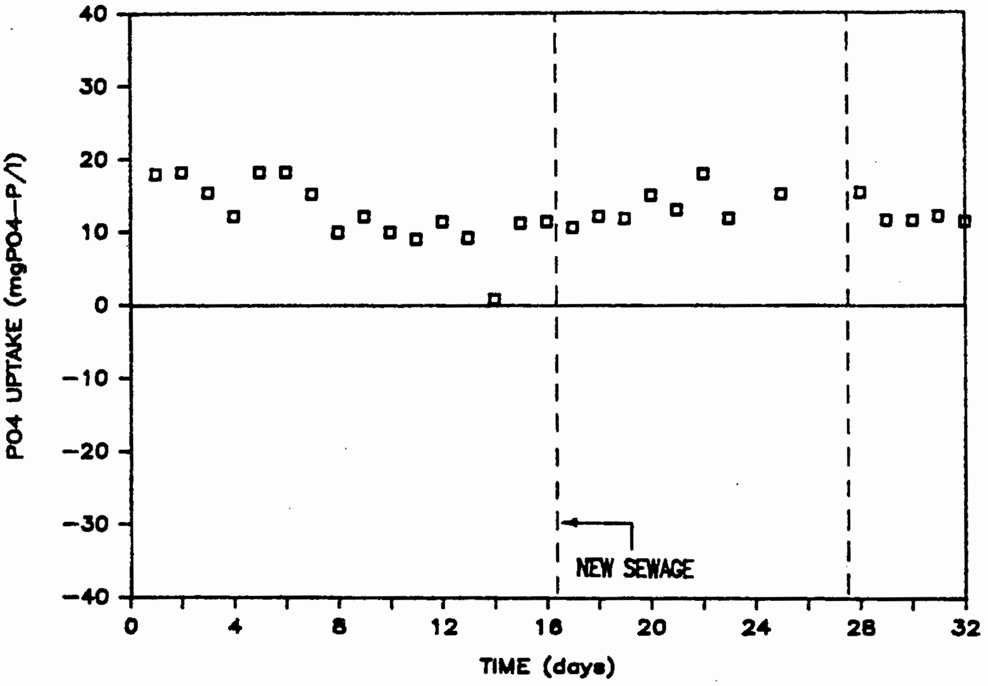


Fig 4.174: Daily performance of the phosphorus uptake in the third reactor of the 3 day sludge age Johannesburg system.

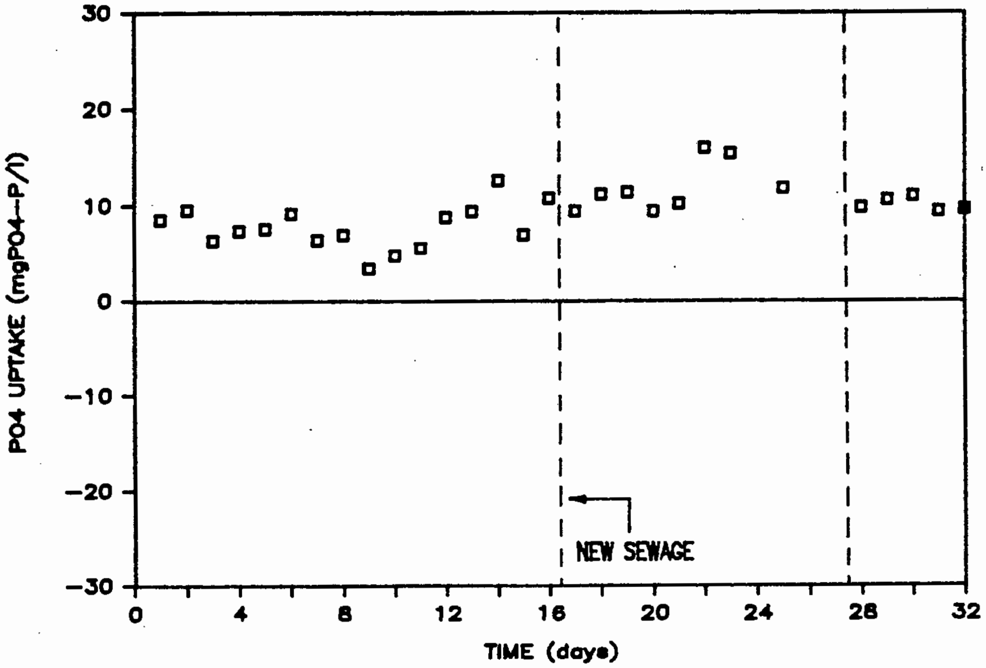


Fig 4.175: Daily performance of the phosphorus uptake in the fourth reactor of the 3 day sludge age Johannesburg system.

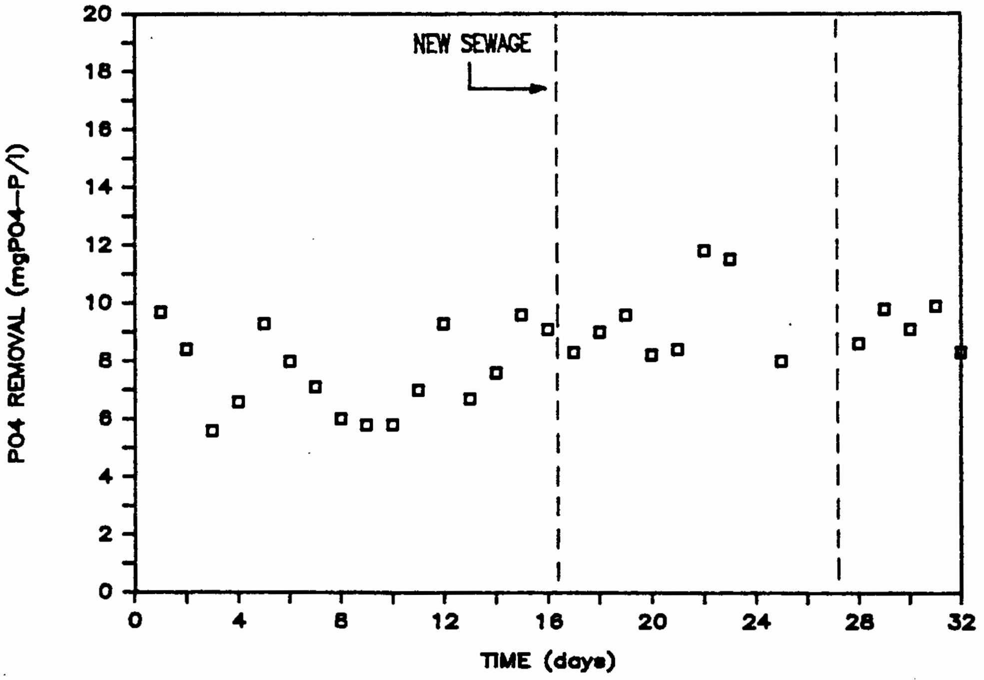


Fig 4.176: Daily performance of the phosphorus removal in the 3 day sludge age Johannesburg system.

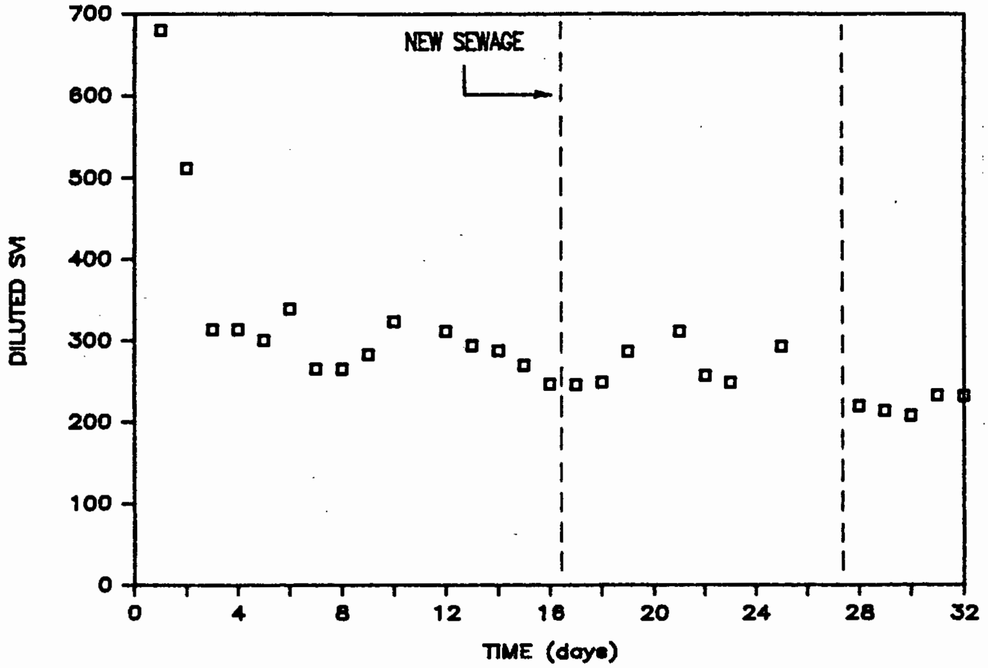


Fig 4.177: Daily performance of the Diluted Sludge Volume Index for the 3 day sludge age Johannesburg system.

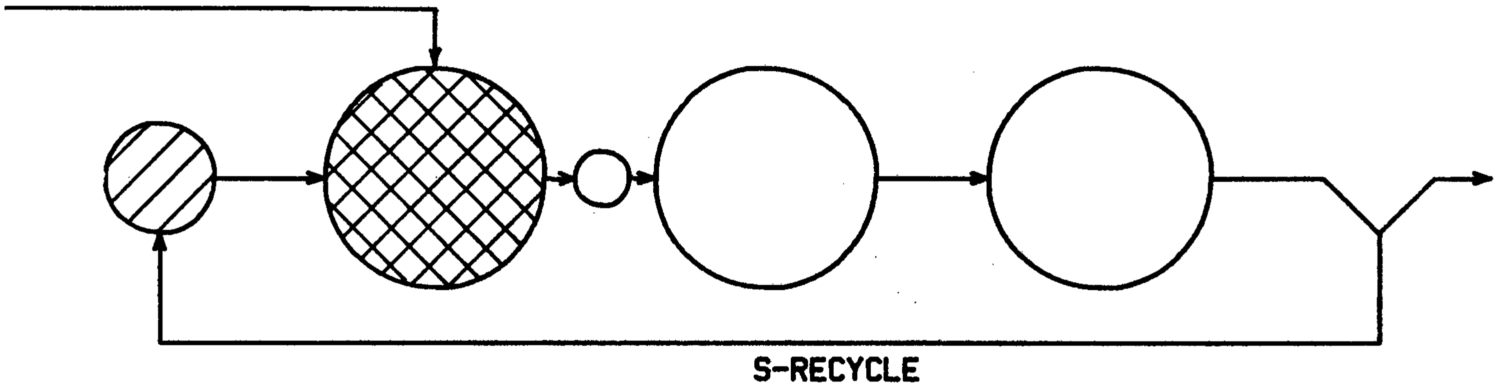


Fig 4.178: Schematic diagram of the Johannesburg configuration.

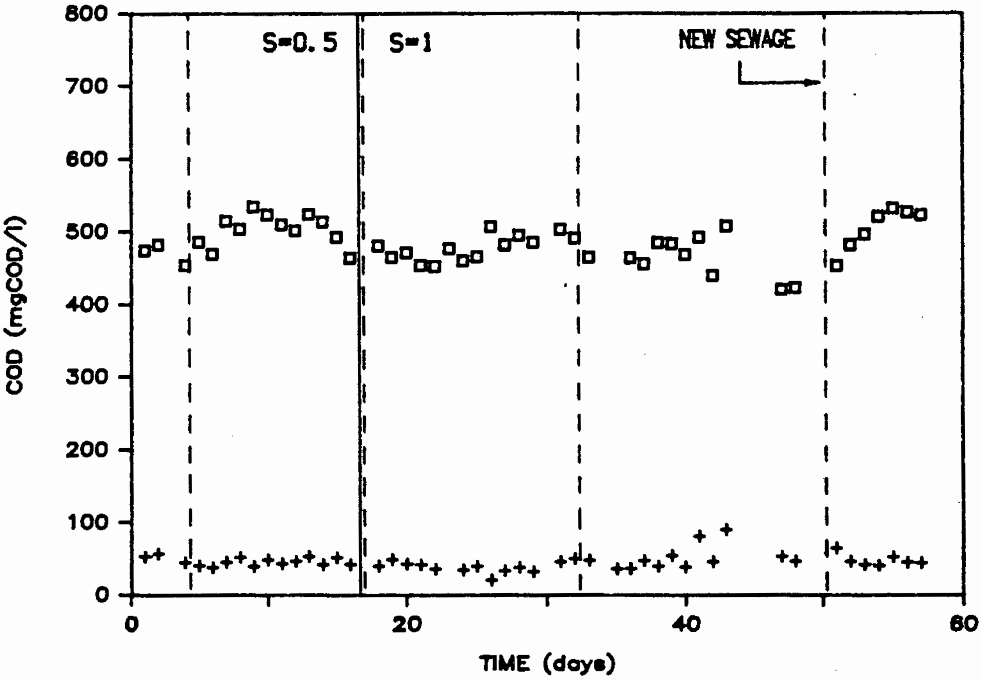


Fig 4.179: Daily performance of the unfiltered influent and filtered effluent COD concentrations for the 5 day sludge age Johannesburg system.

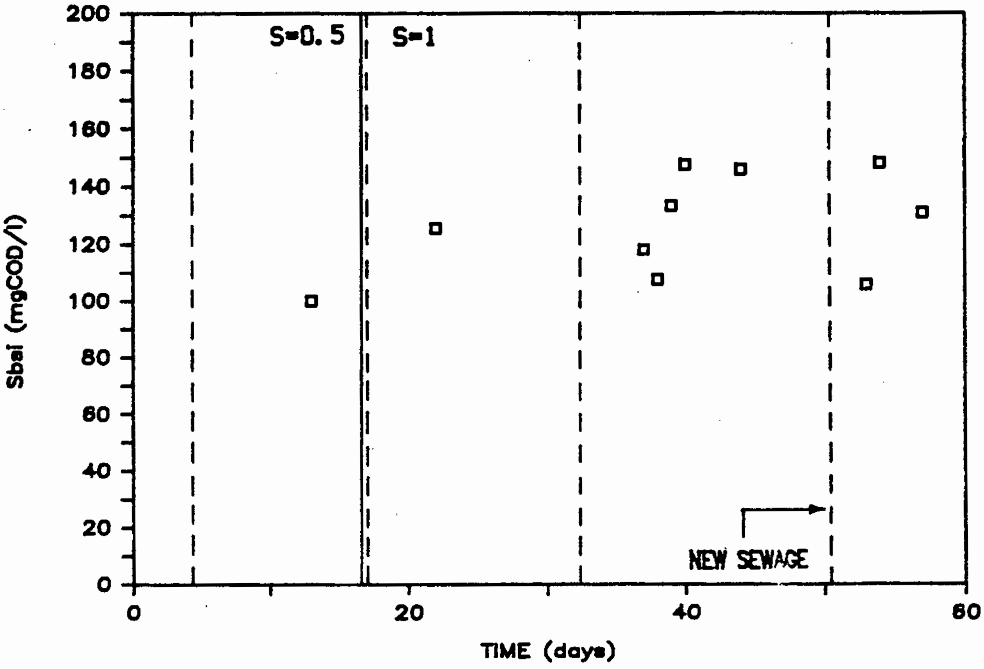


Fig 4.180: Daily performance of the influent readily biodegradable COD concentration for the 5 day sludge age Johannesburg system.

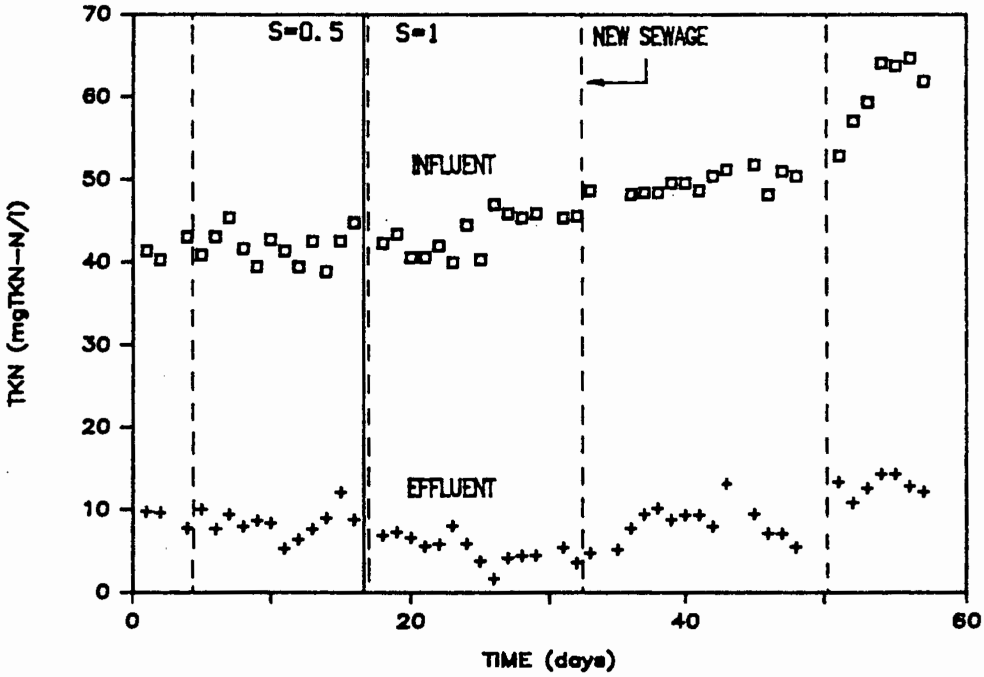


Fig 4.181: Daily performance of the unfiltered influent and filtered effluent TkN concentrations for the 5 day sludge age Johannesburg system.

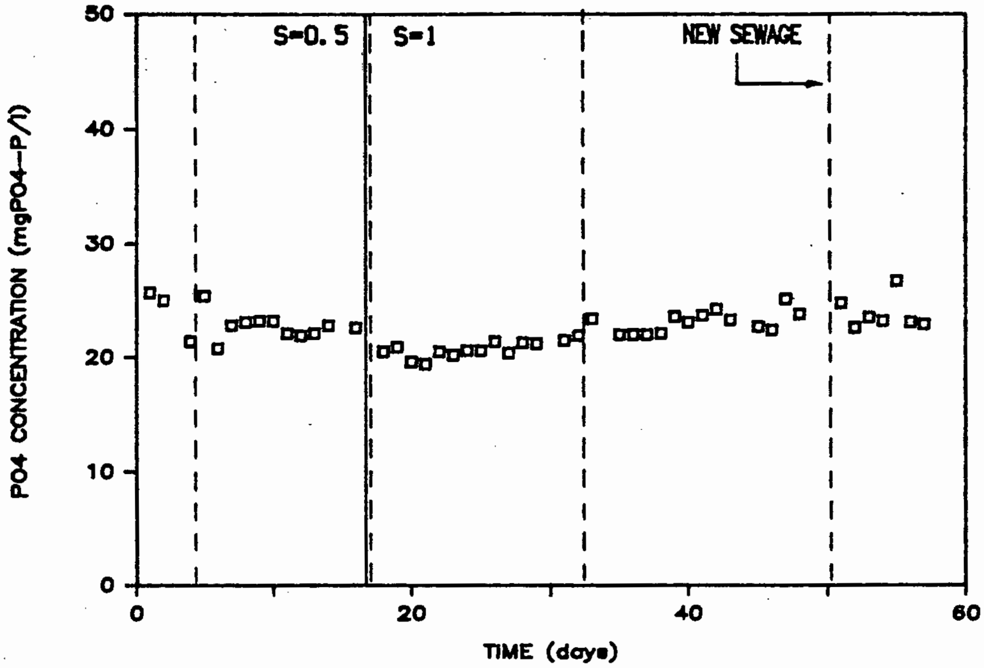


Fig 4.182: Daily performance of the phosphorus concentration in the influent to the 5 day sludge age Johannesburg system.

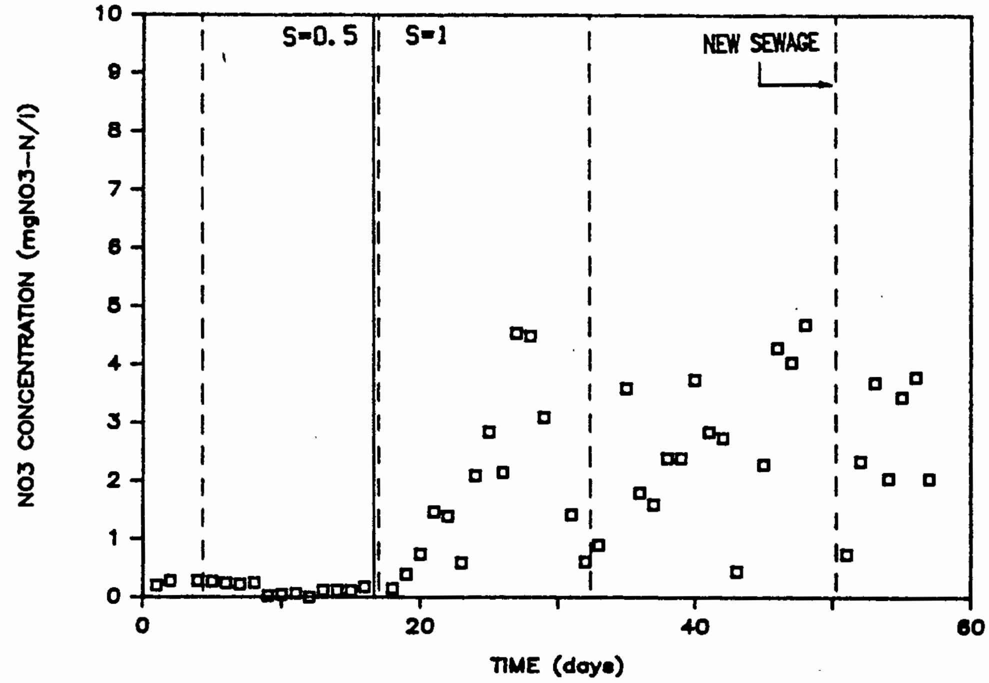


Fig 4.183: Daily performance of the nitrate concentration in the first reactor of the 5 day sludge age Johannesburg system.

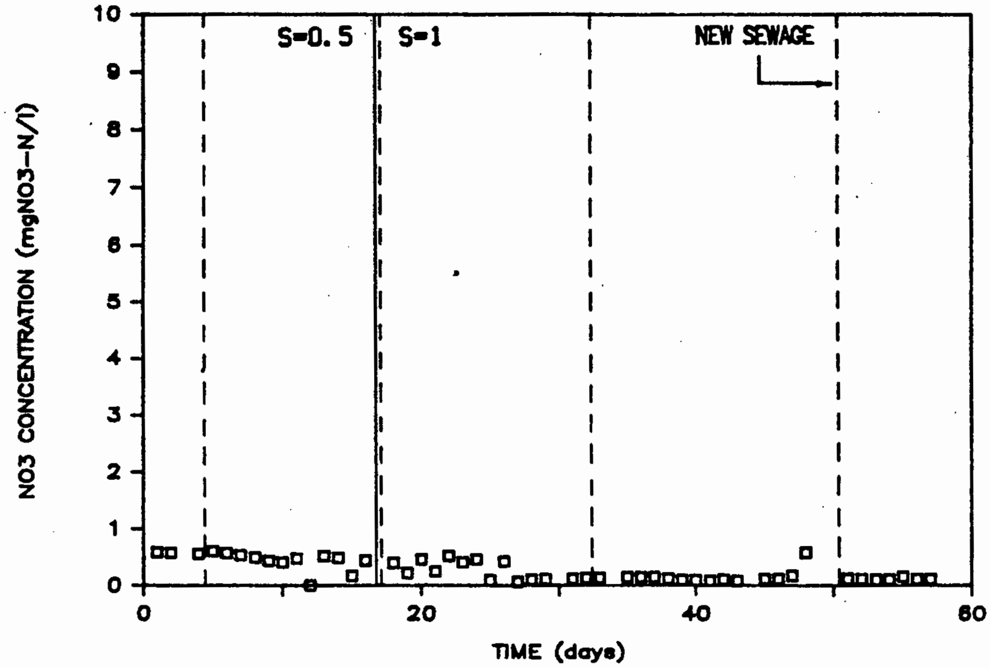


Fig 4.184: Daily performance of the nitrate concentration in the second reactor of the 5 day sludge age Johannesburg system.

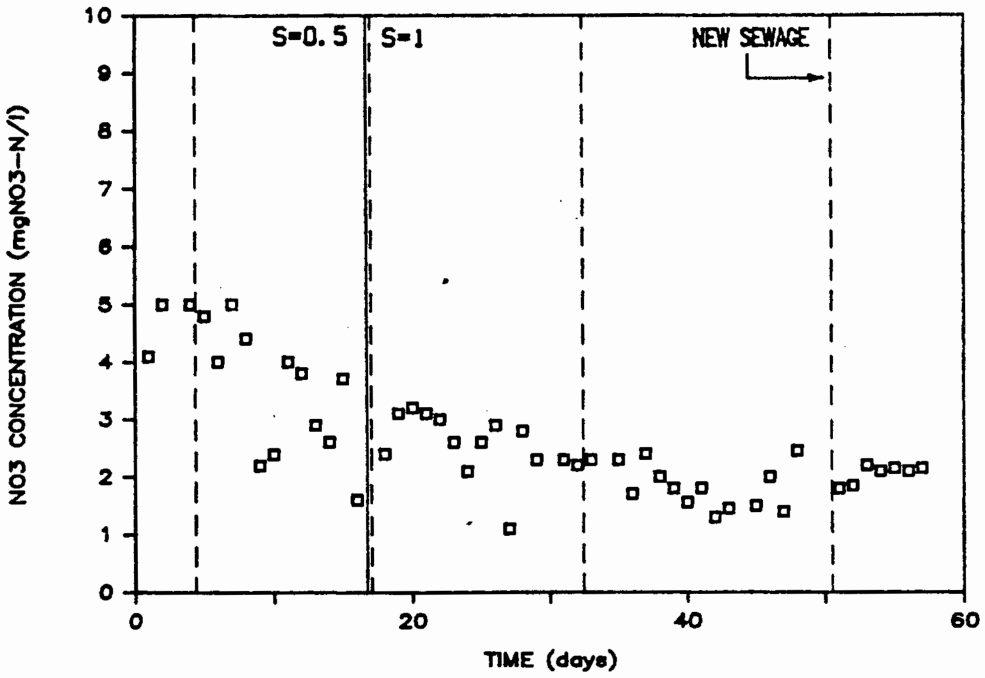


Fig 4.185: Daily performance of the nitrate concentration in the selector reactor of the 5 day sludge age Johannesburg system.

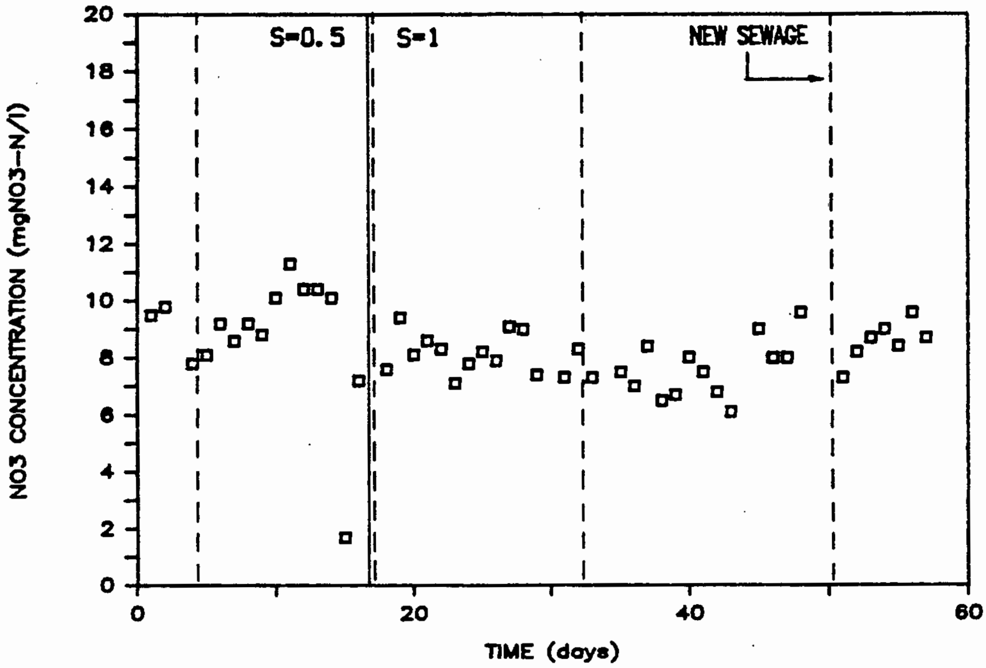


Fig 4.186: Daily performance of the nitrate concentration in the third reactor of the 5 day sludge age Johannesburg system.

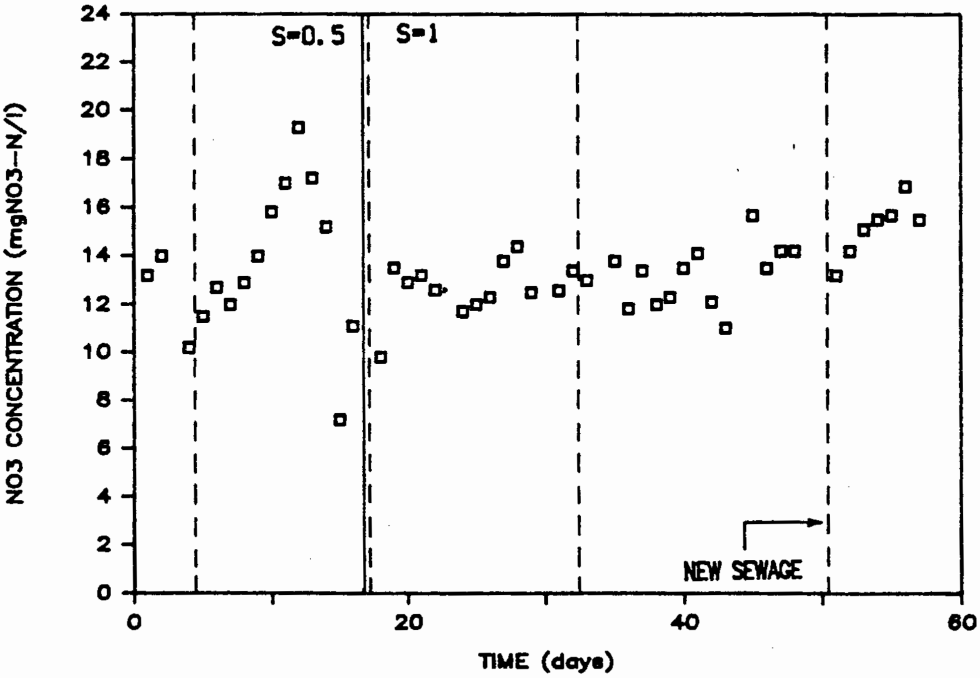


Fig 4.187: Daily performance of the nitrate concentration in the fourth reactor of the 5 day sludge age Johannesburg system.

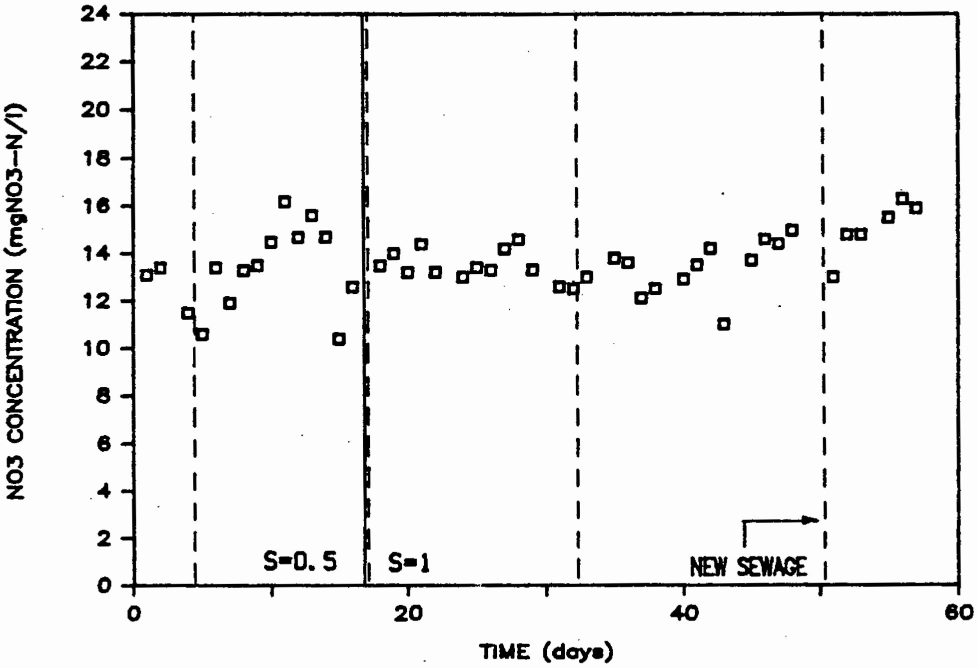


Fig 4.188: Daily performance of the nitrate concentration in the effluent from the 5 day sludge age Johannesburg system.

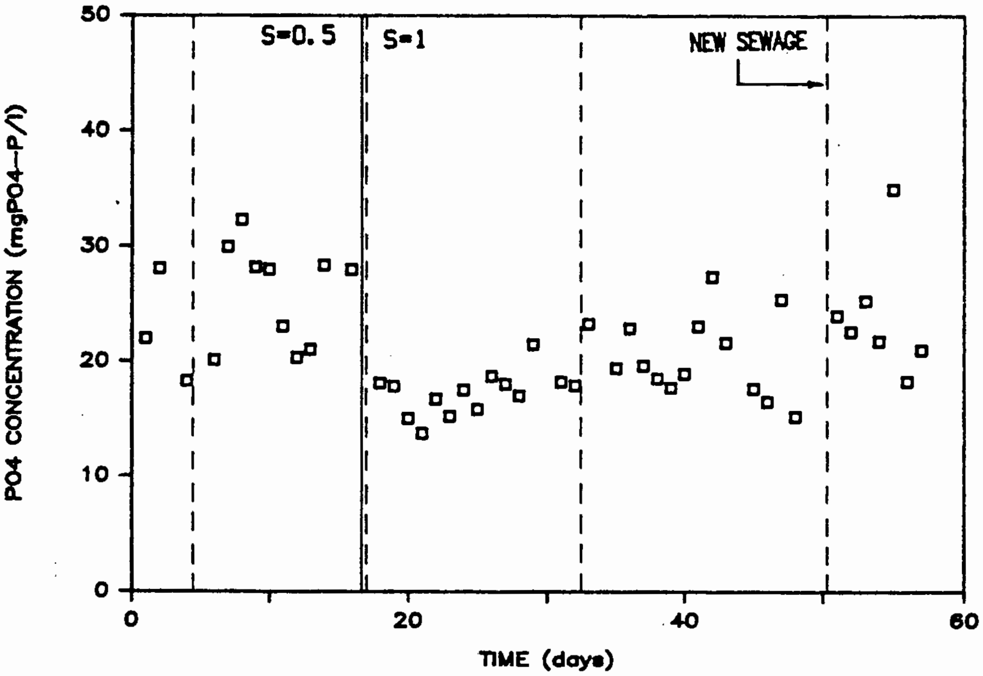


Fig 4.189: Daily performance of the phosphorus concentration in the first reactor of the 5 day sludge age Johannesburg system.

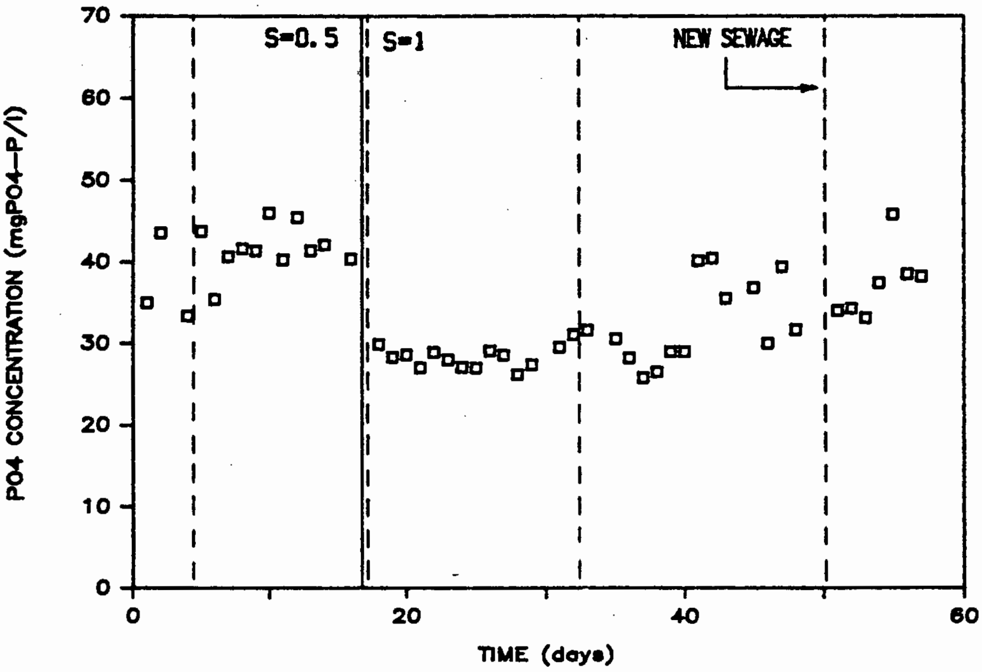


Fig 4.190: Daily performance of the phosphorus concentration in the second reactor of the 5 day sludge age Johannesburg system.

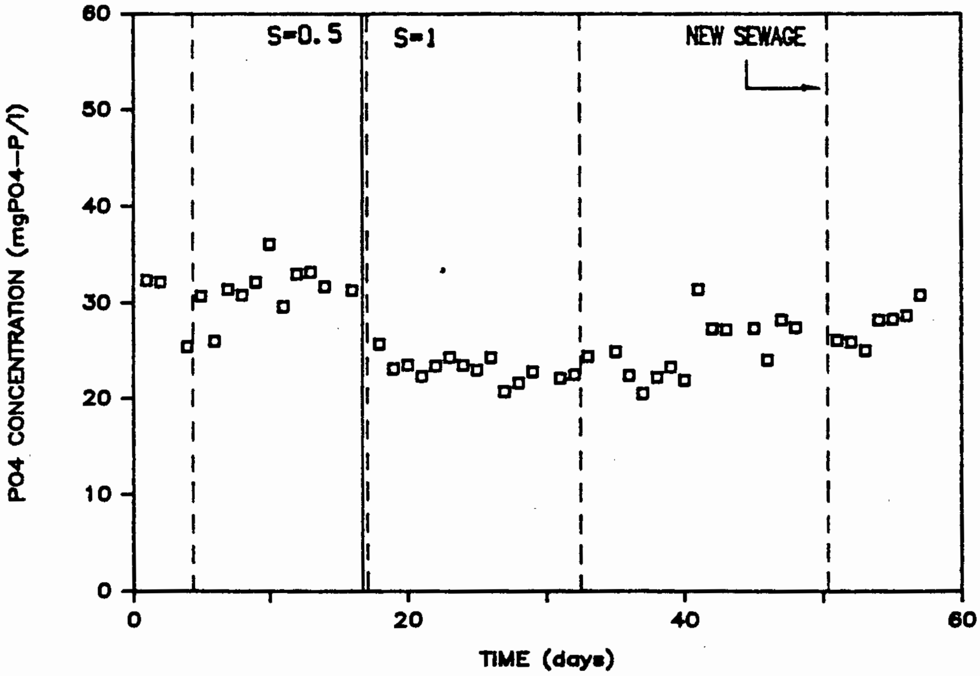


Fig 4.191: Daily performance of the phosphorus concentration in the selector reactor of the 5 day sludge age Johannesburg system.

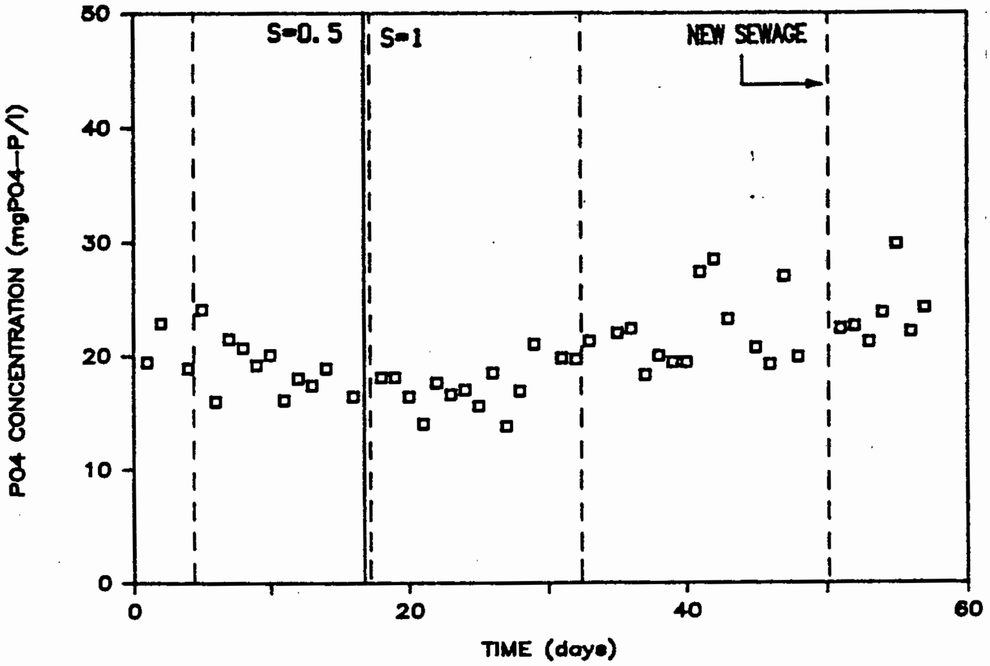


Fig 4.192: Daily performance of the phosphorus concentration in the third reactor of the 5 day sludge age Johannesburg system.

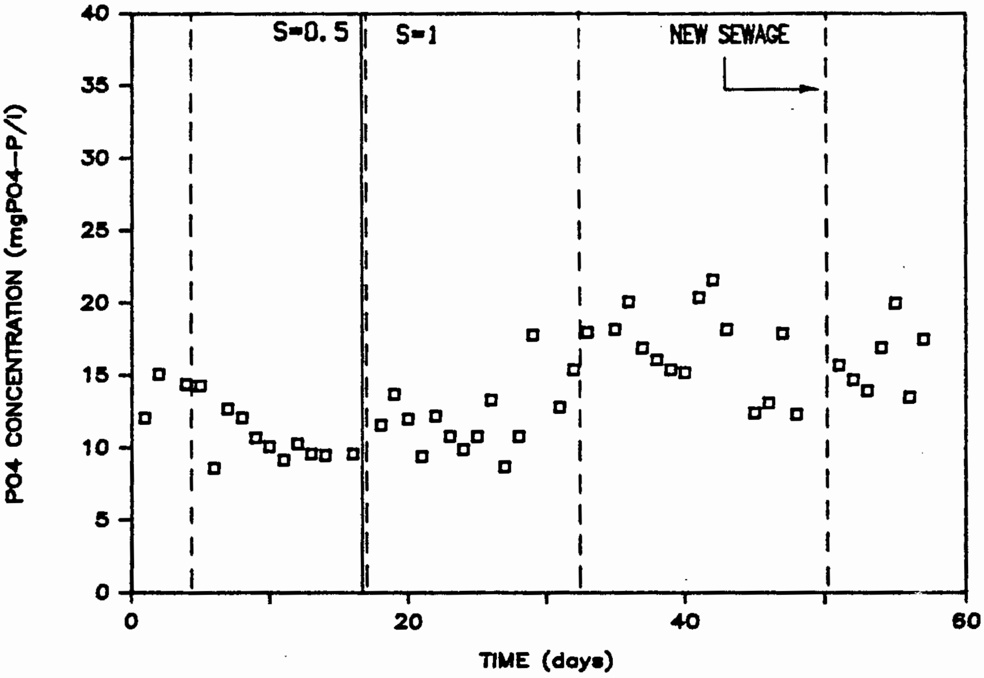


Fig 4.193: Daily performance of the phosphorus concentration in the fourth reactor of the 5 day sludge age Johannesburg system.

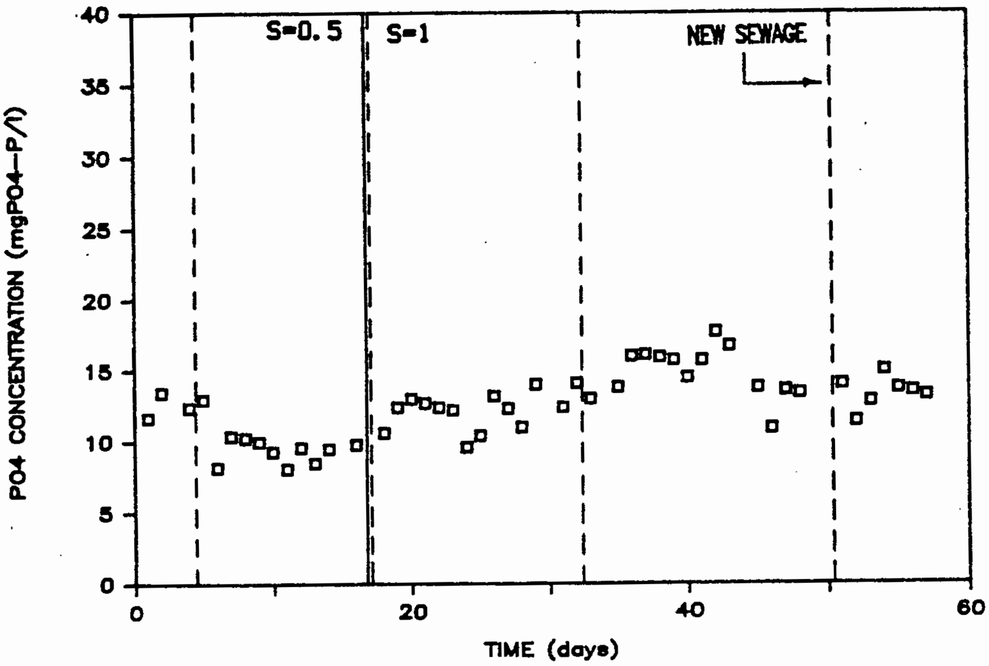


Fig 4.194: Daily performance of the phosphorus concentration in the filtered effluent from the 5 day sludge age Johannesburg system.

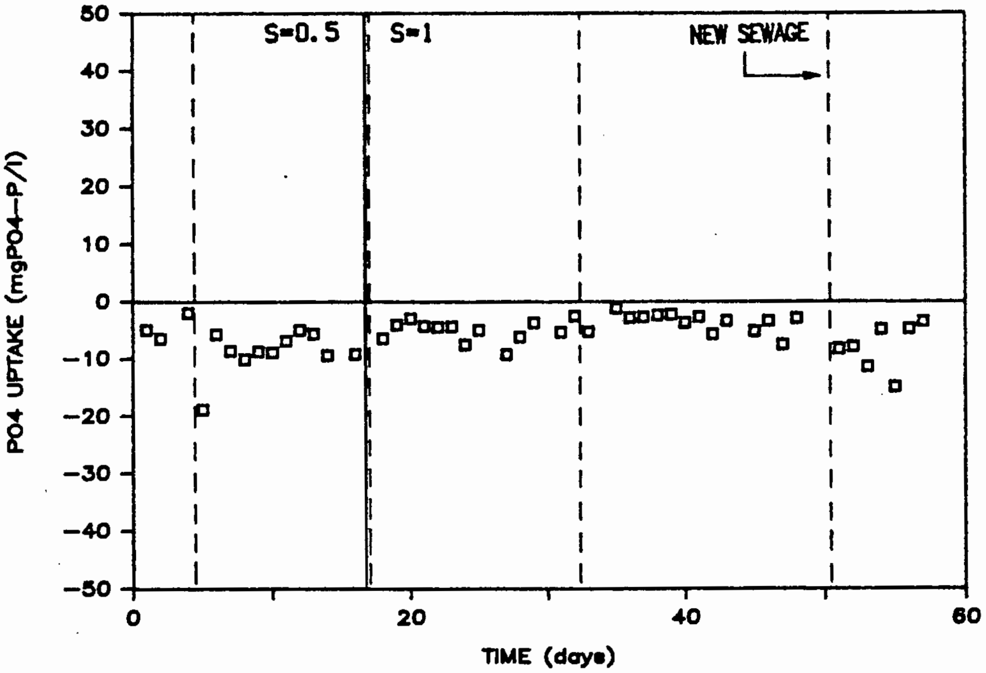


Fig 4.195: Daily performance of the phosphorus uptake in the first reactor of the 5 day sludge age Johannesburg system.

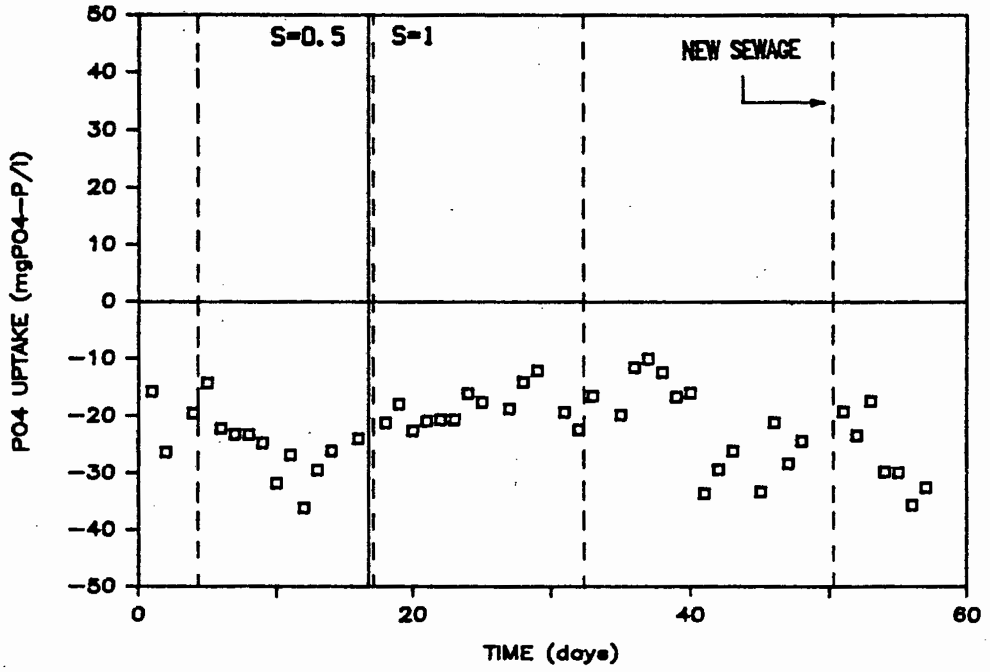


Fig 4.196: Daily performance of the phosphorus uptake in the second reactor of the 5 day sludge age Johannesburg system.

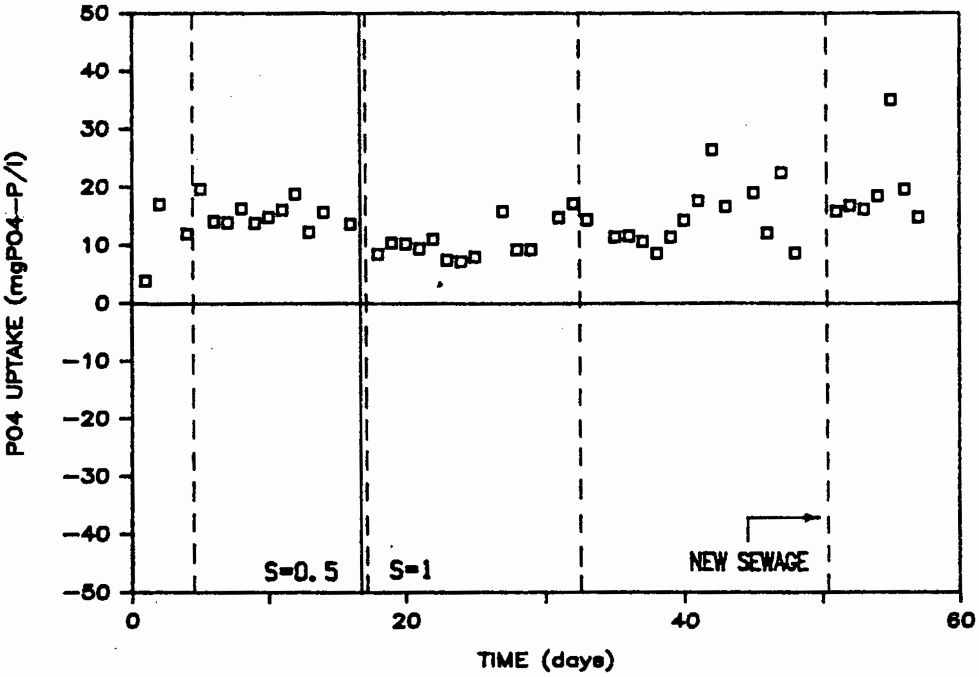


Fig 4.197: Daily performance of the phosphorus uptake in the selector reactor of the 5 day sludge age Johannesburg system.

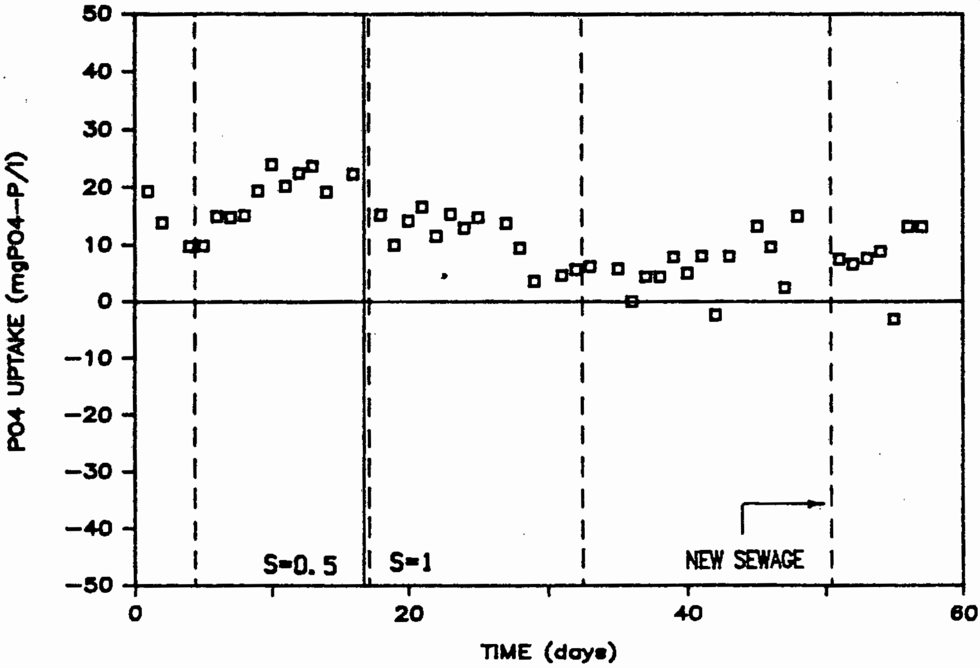
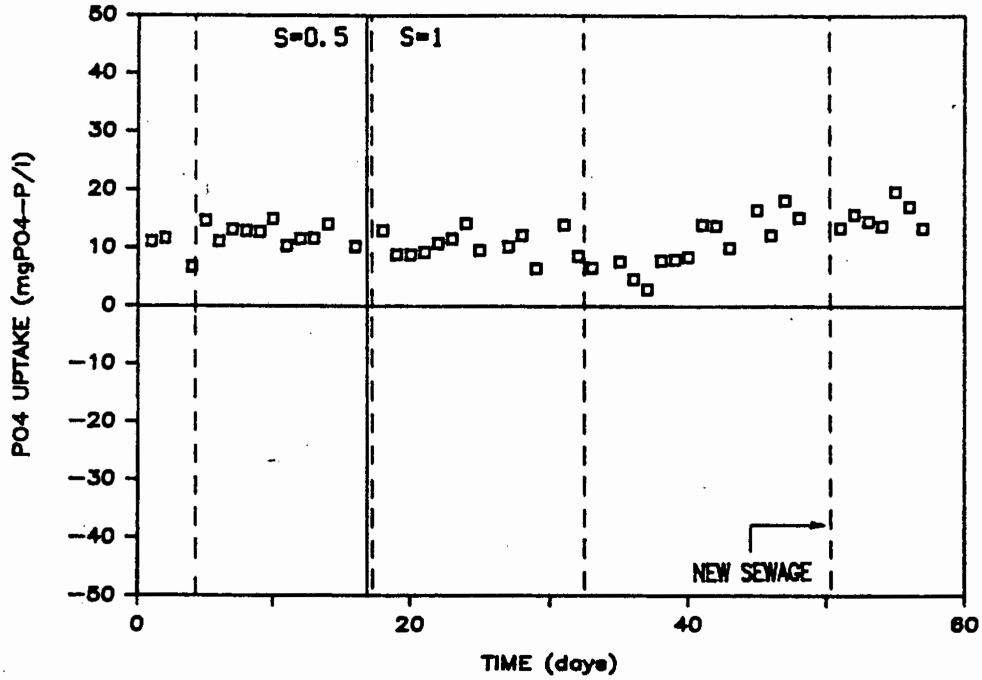
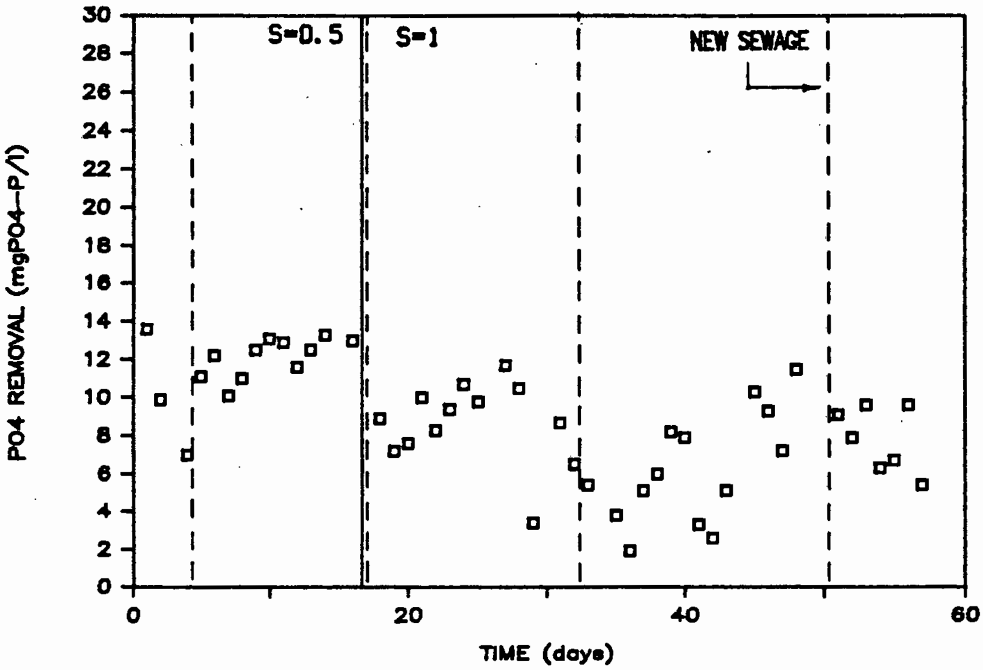


Fig 4.198: Daily performance of the phosphorus uptake in the third reactor of the 5 day sludge age Johannesburg system.



<u>Fig 4.199</u>: Daily performance of the phosphorus uptake in the fourth reactor of the 5 day sludge age Johannesburg system.



<u>Fig 4.200</u>: Daily performance of the phosphorus removal in the 5 day sludge age Johannesburg system.

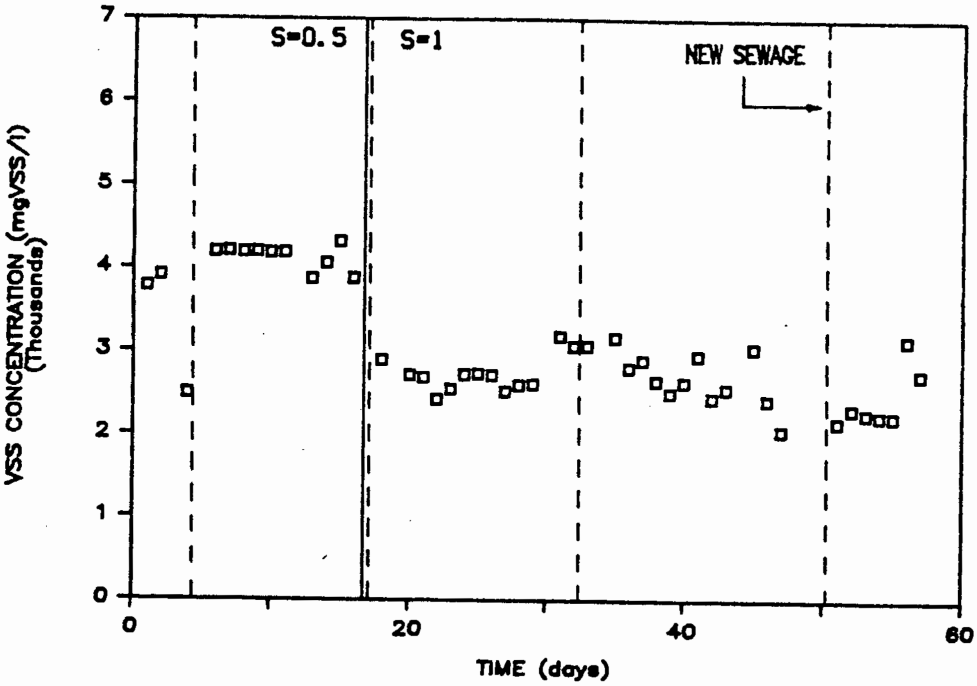


Fig 4.201: Daily performance of the volatile suspended solids in the first reactor of the 5 day sludge age Johannesburg system.

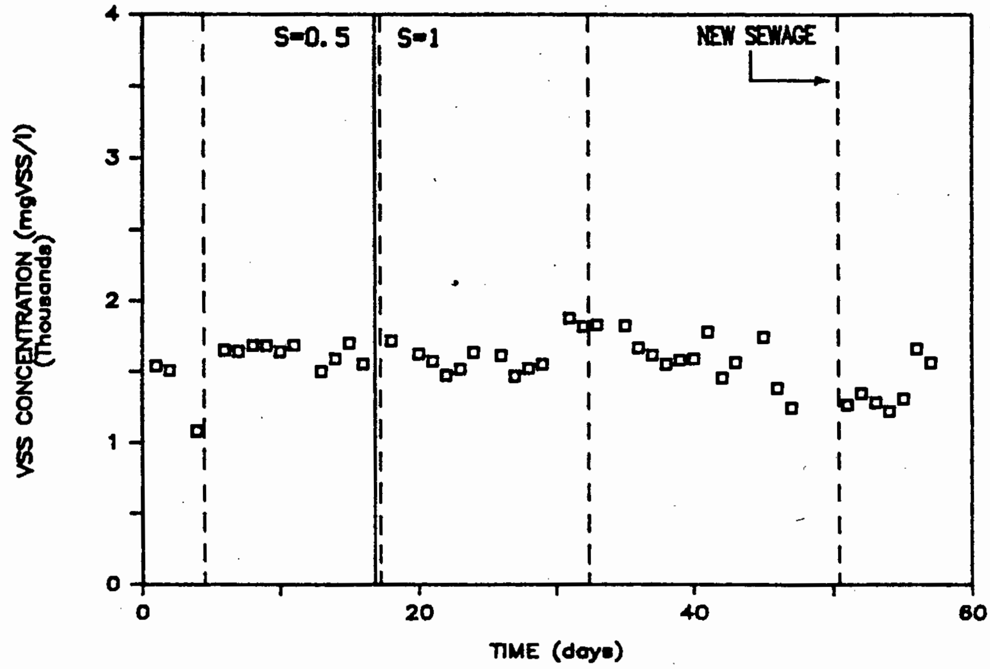
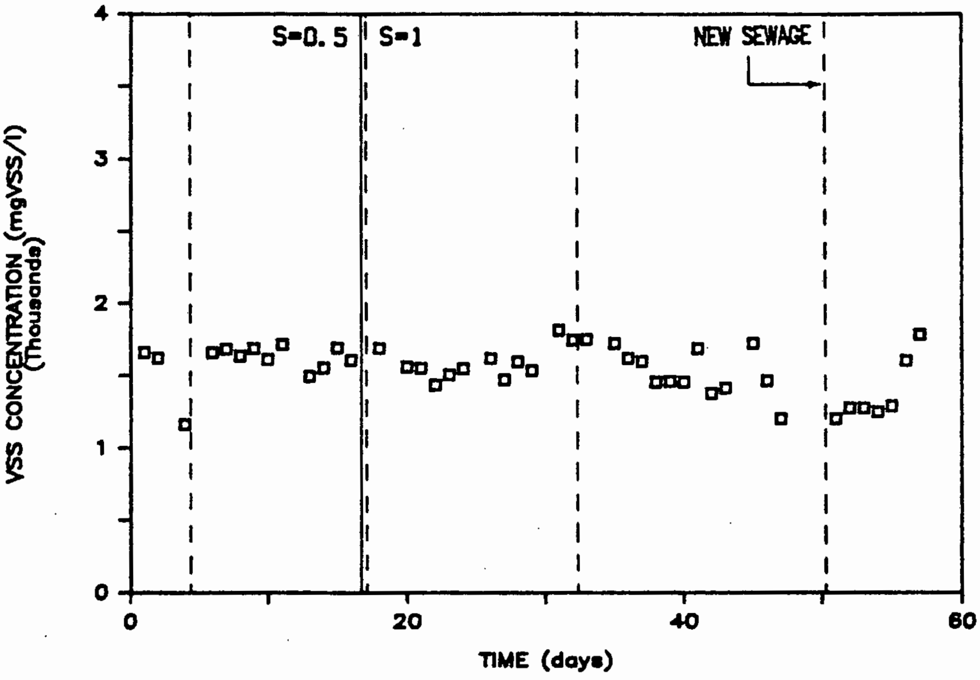
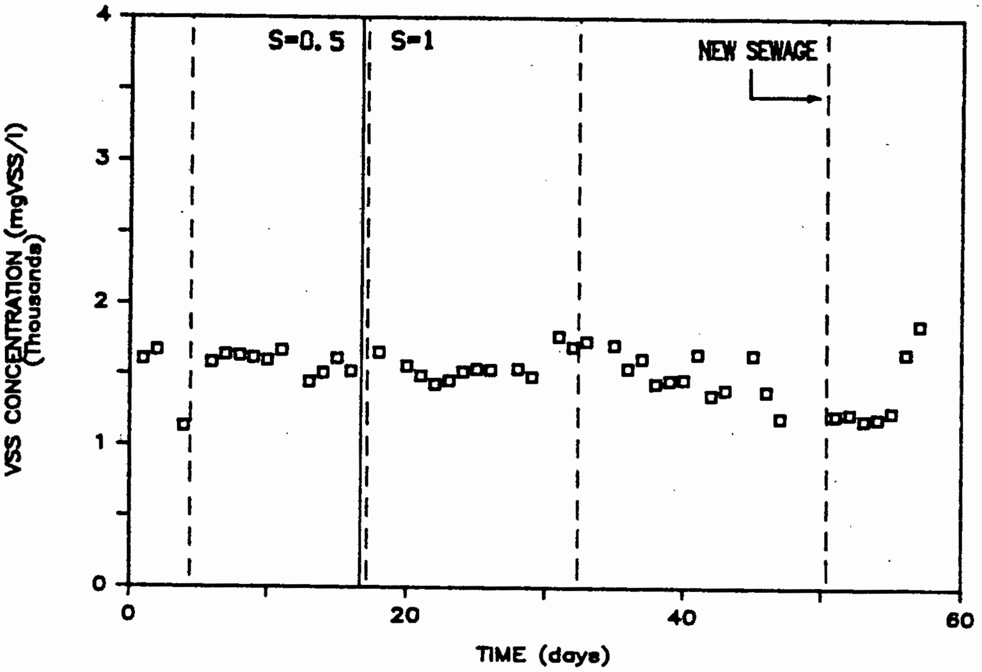


Fig 4.202: Daily performance of the volatile suspended solids in the second reactor of the 5 day sludge age Johannesburg system.



<u>Fig 4.203</u>: Daily performance of the volatile suspended solids in the third reactor of the 5 day sludge age Johannesburg system.



<u>Fig 4.204</u>: Daily performance of the volatile suspended solids in the fourth reactor of the 5 day sludge age Johannesburg system.

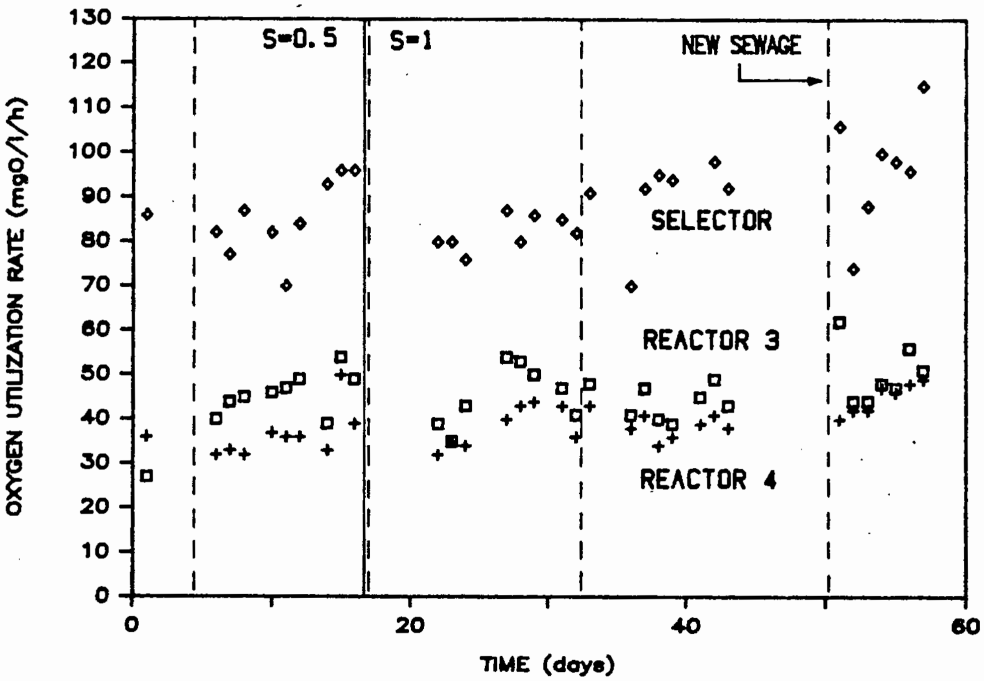


Fig 4.205: Daily performance of the oxygen utilisation rates in the aerobic reactors of the 5 day sludge age Johannesburg system.

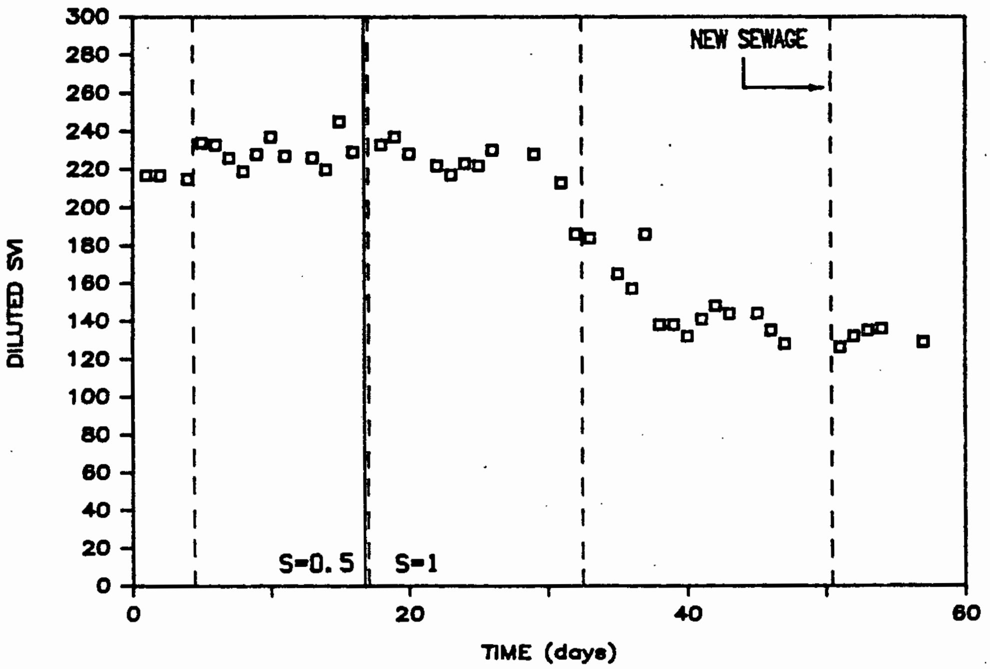


Fig 4.206: Daily performance of the Diluted Sludge Volume Index for the 5 day sludge age Johannesburg system.

CHAPTER FIVE

COMPARISON OF EXPERIMENTAL OBSERVATIONS WITH PREDICTIONS OF THE GENERAL ACTIVATED SLUDGE MODEL AND THE P RELEASE/REMOVAL MODEL

1. INTRODUCTION

This chapter is divided into two sections:

1. Simulation of the experimentally observed data on the General Activated Sludge Model (Dold and Marais, 1985), discussion of deviations between predicted and observed results, and suggestions of possible processes that need to be incorporated in the model to predict short sludge age behaviour.

2. Simulation of the experimentally observed data on the P release-/excess P removal model of Wentzel, Dold, Ekama and Marais (1984) and discussion of any shortcomings in the model.

2. COMPARISON OF OBSERVED AND PREDICTED BEHAVIOUR USING THE GENERAL ACTIVATED SLUDGE MODEL

2.1 Description of model

Research into the behaviour of activated sludge systems at the University of Cape Town culminated in the formulation of a general kinetic model by Dold and Marais (1985). The model describing the system response is highly complex. It incorporates carbonaceous material oxidation, oxygen demand, nitrification, denitrification, sludge generation and other processes under steady state or daily cyclic flow and load conditions, in series reactor systems with inter reactor recycles and with both aerated and unaerated reactors. A brief description of the model is given in Appendix F.

The model has been tested extensively over the past few years and the consensus has been that the model simulates the response behaviour of activated sludge systems satisfactorily over a wide range of process configurations, sludge ages and operating conditions.

Certain parameter constants in the model have been found to be specific to the waste flow or are influenced by the operating conditions. There are 5 of these, viz. (1) the maximum specific growth rate of the nitrifiers, (2) the maximum specific growth rate of the heterotrophs, and the influent (3) readily biodegradable, (4) particulate unbiodegradable and (5) soluble unbiodegradable COD fractions.

(1) The maximum specific growth rate of the nitrifiers can vary from 0,2 to 0,7 per day and there is no substantive criterion whereby one can estimate this constant; each waste flow appears to give rise to its own value. Therefore, for design, either some experimental estimate is found, often by curve fitting to the experimental nitrate response using the simulation model or, in the absence of an experimental estimate, a conservative (low) value is selected to give a high probability that the design will provide an adequate aerobic mass fraction and a long enough sludge age for nitrification.

(2) With regard to the maximum specific growth rate of the heterotrophs, there is conclusive evidence that this rate is influenced by the process configuration (Still, Blackbeard, Ekama and Marais, 1985). Single completely mixed reactors tend to give "low" values of about 2/day, series reactors give higher values, and the highest values of about 4,5/day (Still *et al.*) have been obtained with "aerobic selector reactors" installed ahead of the main aeration reactor and receivingthe influent and underflow recycle. For simulation purposes, the high or low specific growth rate usually does not result in significantly different responses when municipal waste water serves as influent because the solubilization of particulate COD tends to control the rate of growth. However the magnitude of the specific growth rate is important in predicting bulking sludge development: high growth rates appear to be associated with good settling sludges. For our purposes therefore, the default value in the program was adequate.

(3) The readily biodegradable COD fraction of the influent can vary from 0,1 to 0,3 with respect to the total COD of unsettled municipal wastewaters. Experimental estimates therefore are necessary, either from a biological short sludge age plant operated in a specific manner (Ekama, Dold and Marais, 1986) or from a physical separation technique (Bagg, Dold and Marais, 1986). In our experimental studies, this COD fraction was measured daily using the short sludge age procedure.

(4) The particulate unbiodegradable influent COD fraction tends to be less variable than the readily biodegradable COD. Usually, the factor most likely to affect this fraction is whether or not garbage-grinding, with disposal to the sewer, is practised. If garbage-grinding is practised, as is usually the case in the USA, then the fraction with respect to the unsettled municipal waste COD is approximately 0,22; if garbage-grinding is not permitted, the fraction is nearer 0,13 [which is the default value accepted for design in South Africa (WRC, 1984)]. However, for municipal flows from particular regions, this fraction can deviate quite substantially from the general mean value of 0,13. For example, for the satellite town of Mitchell's Plain near Cape Town, the wastewater is virtually 100 percent domestic and the experimental responses repeatedly have indicated that the unbiodegradable particulate COD fraction is approximately 0,08.

(5) Historically the influent soluble unbiodegradable COD has been estimated as equal to the filtered effluent from a system operated under aerobic sludge ages of 10 days or longer (WRC, 1984). This approach has been adopted because experience has shown that, for systems operated on the same sewage, there appears to be no observable difference in this fraction for aerobic sludge ages ranging from about 3 to 30 days.

In assessing the suitability of the general model to the short sludge age systems studied in this investigation, it should be noted that the majority of check simulations done in the past were on systems operated at long sludge ages (10 to 30 days) incorporating anaerobic/anoxic reactors with mass fractions ranging from 30 to 70 percent. A number of check simulations were also carried out on *completely aerobic* systems, with both single and series reactor configurations, for sludge ages ranging from 3 to 30 days. For both sets of simulations the correspondence between predicted and observed responses was so close that it was assumed that the model would also be valid for the systems operated in this investigation, even though strictly the conditions of operation fell outside the experience on which the model was built; that is, short total sludges, as low as 3 days, with unaerated mass fractions of 50 percent.

2.2 Selection of process constants

For simulation, the model requires, *inter alia*, input of (1) wastewater composition, (2) constants defining the kinetic behaviour of the various processes, and (3) constants defining the stoichiometric relationships between the various mass transformations that take place. Taking cognisance of our remarks earlier, on the factors influencing the magnitudes of certain constants, appropriate changes to the default input constant values were made. Information on the unbiodegradable COD fractions of the influent was obtained from experimental observations on activated sludge systems operating at relatively long sludge ages (10 days or more). These gave the following fractions with respect to the total influent COD; unbiodegradable soluble 0,06 and unbiodegradable particulate 0,08. The readily biodegradable COD was measured experimentally according to the procedure proposed by Ekama, Dold and Marais (1986). The maximum specific growth rate of the nitrifiers at 20°C ($\mu_{nm_{20}}$) was selected by trial to fit the nitrate response of the system being investigated. Accordingly, the relevant constants in the model were adjusted from the default values. The other constants were kept unchanged as these had been found, from experience, either not to be affected by the sludge age and system configuration (yield, endogenous mass loss, etc.) or not to be critical in steady state operation (maximum specific growth rate of the heterotrophs).

In simulating the responses of the different systems studied experimentally in this investigation, it soon became apparent that the difficulties encountered were common to all the systems. Consequently, in discussing the various points of interest in the study, it was decided to take one system as an example and to develop these points of interest around it. Application to the other systems then is readily appreciated. The system selected as the reference one was the 4 day sludge age Phoredox system described in Section 2.

The model input data for the first simulation (default constants and other constants modified as discussed above) is listed in Table 5.1 under "SIMULATION ONE". On simulating the response of this system (and the others studied experimentally in this investigation), it was immediately apparent that there were appreciable differences between the simulated and observed responses. For example, Table 5.2, showing the simulated results and the observed results for the 4 day sludge Phoredox system, suggests that, in systems with short sludge ages and large anaerobic mass fractions, the numerical values of some of the constants need to be changed and that the model itself may need to be modified. To assess these changes, the significance of each major deviation is discussed below.

(1) Filtered effluent COD/soluble unbiodegradable COD

The first significant difference observed in Table 5.2 is that the simulated prediction of the filtered effluent quality is very much lower than the value observed (34,1 mgCOD/ℓ predicted versus 61 mgCOD/ℓ observed). In terms of the model, the simulated effluent COD is composed of two fractions; an unbiodegradable fraction derived from the influent, and a biodegradable soluble fraction remaining from incomplete degradation in te process. In practice, a third soluble effluent COD component exists; namely, COD generated through intermediate and end product formation and cell lysis and death, i.e. COD of microbial origin. This fraction is not accounted for in the model because, for the sludge ages generally used in South Africa, the contribution is very small (Dold, Bagg and Marais, 1986). In attempting to account for the observed under-prediction of the effluent soluble COD *by the model*, it should be noted that the simulated soluble biodegradable fraction is small; in no manner, by changing the kinetic constants defining the rate of growth of the heterotrophs and the rate of solubilisation, could the effluent COD be raised to the observed level. Also, the effluent COD could not be increased rationally by increasing the influent unbiodegradable COD fraction because the filtered COD of parallel systems, operating under long sludge age conditions with the same influent, at the same COD concentration, continued to deliver filtered effluents with COD concentrations of approximately 30 mgCOD/ℓ. Therefore, it was concluded that the higher COD in the effluent must be due to undegraded soluble COD from the microbial source. It is worthwhile to consider for a moment the aspect of microbial soluble COD generation within the process in more detail in order to appreciate why this component is excluded from the model:

> Generally data on the microbial generation of effluent COD has been presented in the form of a linear relation between the effluent soluble COD ($0.45\mu_m$ filtrate usually) and the influent COD. For example, experimental work of Chudoba (1985) on both batch and continuous flow laboratory systems utilising completely biodegradable substrates has shown that the effluent COD is approximately 1 percent of the influent COD; that is, for a typical influent COD of 500 mg/ℓ the portion of the effluent COD originating from microbial activity would be approximately 5 mg/ℓ.

A generation of 1 percent would seem surprisingly small considering the attention given to this aspect in the sanitary engineering literature. Perhaps this attention has arisen partially because these observations are based on experimentation using only synthetic substrates such as glucose where all of the influent substrate is biodegradable. In this case all of the effluent COD is derived from the microbial source, and assumes a certain importance in terms of percentages. However, in the case of a typical 500 mgCOD/ℓ municipal wastewater, an amount of 5 mg/ℓ is relatively small in a soluble effluent COD of 25 to 50 mg/ℓ, and is certainly small compared to a typical influent S_{bs} of 120 mg/ℓ of the same influent. In the case of municipal wastewater treatment, an additional factor is likely to minimise the microbial contribution; namely, the diversity of organisms. With the wide range of substrates present in a municipal wastewater the mixed organism population should be extremely diverse; this diversity should increase the possibility of degrading the complex molecules arising from microbial activity compared to either a pure culture or a culture grown on a limited synthetic substrate.

The contribution from microbial sources to the effluent COD has been related principally to the influent concentration. However, limited research has demonstrated that system operating parameters, and in particular the sludge age or solids retention time, also will influence the production. Grady and Williams (1975), on the basis of results from completely-mixed reactor systems (without recycle) receiving a mixed synthetic substrate, proposed that the soluble effluent COD is related *inter alia* inversely to the sludge age and can be modelled by an expression of the form

$$S = K''S_o + K'S_o/SRT$$

where S = effluent soluble COD concentration
S_o = influent COD concentration
SRT = solids retention time (sludge age)
K', K'' = constants

The data of Grady and Williams (1975) was collected over a range of operating conditions very different to those encountered in municipal wastewater treatment practice; namely solids retention times ranging from 0,17 to 0,46 days with average suspended solids concentrations between 148 and 797 mg/ℓ. It is possible that at the low reactor solids concentrations the influence of adsorption and enmeshment of microbially-generated matter would be less evident than in full-scale treatment plants where the solids concentration is in the range 3000 to 5000 mg/ℓ. In this respect the data of Saunders and Dick (1981) is more pertinent to this discussion. In that study laboratory plants were operated over a range of sludge ages from 0,8 to 19,4 days, with a 1:1 mixture of raw sewage and synthetic substrate. The soluble ($<0,45\mu_m$) effluent COD samples were fractionated into 3 divisions defined as follows:

Fraction	Approx. MW range
High molecular weight	> 100 000
Low molecular weight	500 - 100 000
Dissolved	< 500

The effect of sludge age on the 0,45 μ_m COD was marked with the average value decreasing from 57 to 20 mg/ℓ in an inverse manner for sludge ages from 0,8 to 19,4 days with an influent COD of approximately 450 mg/ℓ; in contrast the dissolved fraction (< 500 MW) was near constant. These results show that the contribution of microbial material with molecular weight in excess of 500 increases with decreasing sludge age; an observation in conformity with the interpretation of data by Chudoba (1985) and the data observed in this investigation.

To explain the observed data, Saunders and Dick (1981) have noted that the diversity of organisms in activated sludge systems is lower at short than at long sludge ages; as sludge age decreases, certain organisms will be "washed out" depending on the maximum specific growth rates. Therefore the presence of a high undegraded COD fraction in short sludge age systems would not be unexpected.

It is also likely that, above a certain sludge age, the heterotrophic organism mass has developed a fully diversified organism community, whereupon the unbiodegradable soluble effluent will exhibit a fixed fraction of generated unbiodegradable soluble material. Such a fully developed community indeed is implicitly suggested by the death-regeneration hypothesis of Dold, Ekama and Marais (1980) a hypothesis which forms the basis of the general activated sludge kinetic model. The death-regeneration hypothesis indicates a high interaction between organisms, leading to death and regeneration using the dead material as substrate. The model response indicates that, for aerobic sludge ages greater than 3 days, the interaction effects dominate which can be interpreted to mean that at a 3 day sludge age, a stable climax-type ecosystem has been established by the effluent COD quality obtained in the systems studied. In Fig 5.1, the filtered effluent COD is plotted versus the *aerobic* sludge age for each of the systems. The data clearly shows that, as the sludge age decreases below 3 days, the filtered effluent COD increases sharply whereas the COD remains essentially constant for aerobic sludge ages greater than 3 days.

Because the general activated sludge model does not provide for soluble microbial COD generation, this effect has to be accommodated by empirically raising the fraction of soluble unbiodegradable COD in the influent (f_{us}) to equal the filtered COD value observed experimentally. Accordingly, in the second simulation, the f_{us} in the wastewater was increased to a value that very nearly gives the filtered effluent COD, an approach that was used also with all the other system simulation studies.

(2) Acidogenesis COD loss

A second significant difference observed in Table 5.2 is that the simulated predictions of the VSS concentrations in the reactors are considerably higher than the observed values (3050 mgVSS/ℓ predicted as against 2100 mgVSS/ℓ observed). This behaviour was present in all the systems studied in the investigation. The model is based on a 100 percent COD mass balance but in the experimental systems, only about 80 percent recoveries were obtained. This difference shows itself principally in the higher predicted VSS values. The question now arises as to why there appears to be less COD leaving the experimental system than entering it. One, of a number of options, is the following:

> In the anaerobic reactor, the *Acinetobacter* organisms sequester lower fatty acids (and only lower fatty acids) by releasing stored polyP. Looking at it in another way, the fact that P is released implies

that lower fatty acids have been taken up out of the liquid. Yet, in this wastewater, the fatty acid content was low, that is, the fatty acids must have been generated in the anaerobic zone by acidogenesis, a process that converts carbohydrates to lower fatty acids by hydrolysis and release of hydrogen gas. When a carbohydrate, such as glucose for example, is converted to acetate, approximately a third of the electrons are transferred to the hydrogen ions to form hydrogen gas (see Chapter 4, Section 2.4.2). This implies that in acidogenesis, one third of the COD of the glucose may be lost from the system via hydrogen gas. In biological P removal studies, the hypothesis has been accepted that the readily biodegradable COD in the influent is the only fraction that can be broken down to lower fatty acids. This hypothesis finds considerable support in the release behaviour of phosphorus in the anaerobic zones of long sludge age UCT and Bardenpho systems. In particular, in batch experiments, the implied conversion of readily biodegradable COD to fatty acids presents a reasonably consistent picture (Wentzel *et al.*, 1984). However, in the long sludge age systems, the anaerobic mass fractions are relatively small (10-15 percent) whereas in the short sludge age systems in this investigation these ranged from 14 to 50 percent. It is possible that, in these short sludge age systems, not only is the conversion of readily biodegradable carbohydrates to fatty acids relatively complete, but that solubilization of particulate carbohydrate materials also takes place under anaerobic conditions, i.e. there is break-down of complex carbohydrates like starch to simpler glucose components. To account for the 20 percent loss in COD via acetate formation and hydrogen gas production in acidogenesis, a COD fraction much larger than that indicated by the influent readily biodegradable COD would need to be involved. Thus, if this COD loss arose from acidogenesis, then solubilization of particulate COD must have taken place.

Accepting the behavioural pattern described above, a sample calculation to account for the 20 percent COD loss via acidogenesis is given for the 4 day sludge age Phoredox system.

Total influent COD (S_{ti}) = 515 mgCOD/ℓ
Percentage COD recovery = 87 %
i.e. Hydrogen produced = 515.(1-0,87)
= 67 mgCOD/ℓ

Readily biod. COD in influent (S_{bsi}) = 115 mgCOD/ℓ
i.e. Hydrogen produced from S_{bsi} = 1/3.115
= 38,3 mgCOD/ℓ
i.e. Hydrogen from hydrolysed S_{bs} = 67 - 38,3
= 28,7 mgCOD/ℓ
i.e. S_{bs} hydrolysed = 3.28,7
= 86,1
i.e. Total S_{bs} in system = (115 + 86,1).2/3
= 134,1 mgCOD/ℓ

Effluent COD (S_{te}) = 61,0 mgCOD/ℓ
i.e. $f_{us} \sim S_{te}/S_{ti}$ = 0,13
f_{up} = (0,08.515)/(0,87.515)
= 0,09
i.e. f_u = 0,09 + 0,13
= 0,22
i.e. f_b = 1 - 0,22
= 0,78
i.e. Total biodegradable COD = 0,78.0,87.515
= 349,5 mgCOD/ℓ
i.e. f_{bs} = 134,1/349,5
= 0,38

Accepting the solubilisation with conversion to acetate, the data to be entered into the model was:

S_{ti} = 448,1 mgCOD/ℓ
f_{bs} = 0,38
f_{up} = 0,13
f_{us} = 0,09

(3) COD:VSS ratio

In the experimental systems, a vital requirement is that a COD balance of near unity is obtained. The COD:VSS ratio of the mixed liquor forms an integral part in performing such a balance because the practice has arisen, prompted by convenience, to determine the VSS rather than the COD of the mixed liquor and to convert the VSS to COD by accepting a COD:VSS ratio (f_{cv}). Considerable research has been undertaken to establish a value for f_{cv} and to determine the factors affecting it. Various researchers have calculated different theoretical values for f_{cv} by accepting a single empirical stoichiometric formulation for the biological sludge mass. These theoretical values range from 1,22 to 1,48 mgCOD/mgVSS.

Experimentally, for no assignable cause, the COD:VSS ratios for different influents often can differ appreciably so that it is not a good policy to use the VSS as a surrogate parameter for determining COD for accurate mass balances, the COD of the sludge should be measured directly. However practically, there is difficulty in obtaining precise repeatable results due to the difficulty in obtaining representative samples of the sludge; at best, one must accept a wide dispersion of measured results on the same sludge.

The above discussion indicates that the f_{cv} value for the sludges in this investigation could have differed from the default value of 1,48 mgCOD-/mgVSS. Measurements of f_{cv} were taken on the Johannesburg system operating at a 5 day sludge age and these produced an average value of 1,54 mgCOD/mgVSS. Unfortunately, no measurements of the ratio were taken on the other systems, so there is uncertainty introduced in all the mass balances. Probably f_{cv} lies between 1,48 and 1,54 mgCOD/mgVSS but the ratio may differ for the 3 and 6 day sludge age investigations.

Because of the uncertainty with regard to the COD:VSS ratio, a sensitivity analysis was performed by entering different ratios into the model and noting the system response with respect to volatile suspended solids. For the COD:VSS ratio range of 1,48 to 1,54 mgCOD/mgVSS, the response showed relative insensitivity, at the most approximately 5 percent. Hence it is unlikely that a wrong COD:VSS ratio could have more than a marginal effect on the COD balance.

Taking cognisance of the remarks made above, S_{ti}, f_{bs} and f_{us} were modified to account for the COD loss through acidogenesis, acetate formation and unbiodegradable soluble COD generation respectively and hence f_{up} had to be modified to fit into the model structure (although the concentration of unbiodegradable particulate COD remained the same). The COD:VSS ratio was selected in the range 1,48 to 1,54 mgCOD/mgVSS to provide the greatest "improvement" in the simulation. The set of constants used in the model for the second simulation of the 4 day sludge age Phoredox system are listed in Table 5.1 under "SIMULATION TWO". The system response is listed in Table 5.2.

Evidently there was a considerable improvement in the correspondence between the observed and simulated responses. Although there is little or no experimental evidence supporting the anaerobic solubilisation hypothesis, the improvement in prediction achieved does indicate that the hypothesis merits further study.

Following on the success in simulating the 4 day sludge age Phoredox system, the method of calculating input data for the model as set out above was applied to all the other studies. The revised input data for all the systems is presented in Table 5.3. A comparison between the predicted and the observed data for the systems is given in Tables 5.4 to 5.9. Again the approach was generally successful but, where COD recoveries were excessively poor (approximately 70 percent), the slowly biodegradable COD required for solubilisation was greater than that in the influent to the system, (i.e. $f_{bs} > 1$) and the approach could not be used rationally.

2.3 Discussion of simulation results

In reviewing the results obtained in simulating the various systems, the hypothesis that led to a general improvement in the predicted responses when compared with those observed, was the one proposing firstly, anaerobic solubilization of particulate slowly biodegradable COD to the readily biodegradable form and secondly, accepting that the readily biodegradable material is converted to acetate in which process electrons (COD) are lost from the system by the formation of hydrogen gas. Simulations based on the sewage modifications suggested by this hypothesis gave significantly improved volatile suspended solids concentration and oxygen utilization rate (OUR) values. In particular, with the OUR's, the relative values simulated in the series of aerobic reactors followed reasonably closely the trend observed experimentally. From the fact that P release is observed in the anaerobic reactor, there is support that lower fatty acids are generated in the anaerobic reactor and this reaction must therefore contribute to a loss of COD. However, the magnitude of lower fatty acid production required to account for the low COD recoveries is so high that one tends to doubt if the COD loss can be accounted for completely by this phenomena. In addition, there is difficulty in accepting that solubilisation of the slowly biodegradable material could have taken place to the level required, particularly because this effect had not been evident to any marked degree in the anaerobic zones of long sludge age nutrient removal systems. Perhaps the most important conclusions from the simulation study are that,

1. There is a loss of COD in the anaerobic reactor due to the conversion of COD to lower fatty acids but the magnitude of this loss is not yet clear. It appears to be higher in short sludge age anaerobic/anoxic/aerobic systems than in long sludge age anaerobic/anoxic/aerobic systems.

2. There appears to be a case for the conversion of slowly biodegradable to readily biodegradable COD in the anaerobic zone. Again, this appears to be more pronounced in short than in long sludge age systems.

From the conclusions above, it would appear that research studies into solubilisation and lower fatty acid formation should be undertaken. However, besides these phenomena, there is a further one that complicates the behaviour of the anaerobic zone which, up to the present, has been completely ignored in the general model, i.e. the influence of the polyP organisms. These organisms sequester lower fatty acids in the anaerobic zone and subsequently, in the anoxic and aerobic zones, utilise the stored material for the storage of phosphorus and growth. The consequential removal of COD from the *non*-polyP organisms and the subsequent utilisation of the remaining COD by the non-polyP organisms must affect the oxygen utilisation rates in the aerobic reactors. The influence of the polyP organism mass on the behaviour of the system cannot be incorporated into the model until the characteristics of these organisms in the anaerobic/anoxic-/aerobic environment is understood and quantified.

3. PHOSPHORUS REMOVAL MODEL

3.1 Simulation

At the outset of the investigation, the objective was to obtain experimental data on the P removal behaviour of short sludge age anaerobic/anoxic-/aerobic systems and to check the measure in which the P removal model, proposed by Wentzel, Dold, Ekama and Marais (1984), predicts the removal in short sludge age systems. The model of Wentzel *et al.* was developed to predict P removal at long sludge ages (8 to 30 days) and no check on its predictive quality was available for systems operated with sludge ages of 8 days or less.

The Wentzel model is a semi-empirical one. Briefly, an equation is developed linking the magnitude of the P release in the anaerobic reactor to the concentration of readily biodegradable COD in the influent, the non-polyP heterotrophic mass, the anaerobic mass fraction and the reactor flow regime (see Eq 5.1).

$$\Delta P_n = C_{sp}.S'_{bsi}\left[\frac{1}{1+K\cdot\frac{f_{xa}}{N}\cdot\frac{MX_{ah}}{Q}/(1+r)^{(n-1)}} - \frac{1}{(1+K\cdot\frac{f_{xa}}{N}\cdot\frac{MX_{ah}}{Q}/(1+r))^{n}}\right] \qquad (5.1)$$

where ΔP_n = P release in the n^{th} reactor per litre of influent flow

C_{sp} = stoichiometric ratio ($\Delta P:\Delta S_{bs}$)

= 0,5 mgPO_4-P/mgCOD converted

S'_{bsi} = readily biodegradable COD available for conversion per litre influent

= $S_{bsi} - r.8,6.N_{nr}$

S_{bsi} = readily biodegradable influent COD concentration (mgCOD/ℓ)

r = recycle ratio to anaerobic reactor based on influent flow

N_{nr} = nitrate concentration in recycle to anaerobic reactor (mgN/ℓ)

K = first order rate constant

f_{xa} = anaerobic mass fraction

N = number of anaerobic reactors of equal volume in series

$$\frac{MX_{ah}}{Q} = \frac{[S_{bi}-(S'_{bsi}-(1+r)S_{bsN})]Y_h.R_s}{(1+b_h.R_s)}$$

MX_{ah} = active mass of non polyP organisms in system (mgVASS)

Q = influent flow to system (ℓ/d)

S_{bi} = biodegradable infuent COD (mgCOD/ℓ)
S_{bsN} = readily biodegradable COD concentration leaving the last anaerobic reactor (mgCOD/ℓ)
Y_h = heterotrophic organism yield constant (0,45 mgVASS/mgCOD)
b_h = heterotrophic endogenous mass loss rate constant (0,24/d at 20°C)
R_s = system sludge age (d)
n = reactor number in a series of anaerobic reactors, e.g. reactor 2 in a series of 3 will have n = 2, N = 3

The authors then showed that a linear relationship existed between the biological excess P removal and the P release in the anaerobic reactor (Eq 5.2).

$$P(removal) = (a'-1).P(release) + P(metabolic) \quad (5.2)$$

where P(metabolic) = normal metabolic P requirement wasted daily in the sludge (mgP/ℓ)
= $0,03.MX_v/(Q.R_s)$
MX_v = mass of VSS in the system (mgVSS)
a' = constant ranging from 1,145 at a sludge age of 20 days to 1,198 at a sludge age of 8 days

To estimate the P removal in the short sludge age systems, the experimental mean values of the readily biodegradable COD in the influent and the nitrate concentrations in the recycles to the anaerobic reactors were inserted in Eqs (5.1 and 5.2) to give the P release and excess P removal for each system. The predicted P release and excess P removal, the experimentally observed P release and excess P removal, and the predicted and observed P removals per COD removed are listed in Table 5.10. A plot of the predicted versus observed P removal per COD removal is shown in Fig 5.2. A plot of predicted versus observed P release is shown in Fig 5.3.

3.2 Discussion

At first glance, the correlation between the observed and predicted P removal/COD removed appears to be reasonable although the dispersion is large. The positive correlation probably is more apparent than real as the plot of observed versus predicted release (see Fig 5.3) gives a poor correlation. No proper critical analysis of the P removal kinetics is possible until greater understanding is obtained of the processes and the kinetics involved in biological excess P removal phenomena and, in this respect, there appears to be little merit in further pursuing the matter here.

The short sludge age results highlight our deficiencies in understanding of the processes involved in biological excess p removal and the eventual solution would have to reconcile or modify some apparently conflicting hypotheses that had to be proposed to rationalise the observed system behaviour. An important conflict is apparent between the P removal behaviour and the hypothesis that there is a COD loss due to lower fatty acid formation. The stoichiometric constant C_{sp} in Eq (5.1) is based on observed release per unit of acetate added. If this constant should be related to the readily biodegradable COD (S_{bs}) as is done in Eq 5.1, and the S_{bs} is not in the lower fatty acid form, then clearly, C_{sp} must differ from 0,5 because there will be a loss of COD in the conversion of S_{bs} to lower fatty acids. The present value for C_{sp} could be retained only if in fact a compensating concentration of slowly biodegradable COD is converted to readily biodegradable COD.

There is difficulty also in reconciling the P release, uptake and removal if the hypothesis is accepted that the loss of COD, which caused the poor COD recoveries in the mass balances of the short sludge age plants, was due to solubilisation of slowly biodegradable COD and conversion to lower fatty acids. If this hypothesis should be true, then very high masses of readily biodegradable COD should have been available to the polyP organisms in the anaerobic reactor in which event the P release should have been higher.

Table 5.1: Model input data for simulation of response of 4 day sludge age Phoredox system.

			DEFAULT VALUE	SIMULATION 1	SIMULATION 2
	Wastewater Characteristics				
1	S_{ti}	(mgCOD/ℓ)	-	515	448,1
2	N_{ti}	(mgN/ℓ)	-	40,5	40,5
3	f_{bs}	(mgCOD/mgCOD)	0,2	0,26	0,38
4	f_{us}	(mgCOD/mgCOD)	0,08	0,06	0,13
5	f_{up}	(mgCOD/mgCOD)	0,13	0,08	0,09
6	f_{na}	(mgN/mgN)	0,84	0,84	0,84
7	f_{nox}	(mgN/mgN)	0,5	0,5	0,5
8	f_{nu}	(mgN/mgN)	0	0	0
9	f_{xbh}	(mgX_{bh}COD/mgCOD)	0	0	0
	Heterotrophs				
1	Mue max.	(d^{-1})	3,5	3,5	3,5
2	K_s	($gCOD/m^3$)	5	5	5
3	K_{oh}	(gO_2/m^3)	0,002	0,002	0,002
4	b_h	(d^{-1})	0,62	0,62	0,62
5	η(solubilization)		0,37	0,37	0,37
6	η(growth)		1	1	1
7	K_{no}	(gN/m^3)	1	1	1
8	K_h	(d^{-1})	2,2	2,2	2,2
9	K_x		0,15	0,15	0,15
10	K_r	($m^3/gCOD/d$)	0,016	0,016	0,016
11	K_{na}	(gN/m^3)	0,1	0,1	0,1
	Autotrophs				
1	Mue max.	(d^{-1})	0,45	0,32	0,31
2	K_{nh}	(gN/m^3)	1	1	1
3	K_{oa}	(gO_2/m^3)	0,002	0,002	0,002
2	b_a	(d^{-1})	0,04	0,04	0,04
	Stoichiometry				
1	Y_h	(gCOD/gCOD)	0,666	0,666	0,666
2	f_e	(gCOD/gCOD)	0,08	0,08	0,08
3	i_{xb}	(gN/gCOD)	0,068	0,068	0,068
4	i_{xe}	(gN/gCOD)	0,068	0,068	0,068
5	Y_a	(gCOD/gCOD)	0,15	0,15	0,15
6	COD:VSS	(gCOD/gVSS)	1,48	1,48	1,544

Table 5.2: Comparison between data predicted by the general activated sludge model and mean experimental results from a 4 day sludge age Phoredox system.

		EXPERIMENTAL VALUE	PREDICTED VALUE SIMULATION ONE	PREDICTED VALUE SIMULATION TWO
VSS (mgVSS/ℓ) : Reactor	1	2080 ± 70	3070	2168
	2	1960 ± 70	3069	2167
	3	2220 ± 95	3068	2173
	4	2160 ± 90	3046	2156
EFFLUENT COD (mgCOD/ℓ)		61,0 ± 4,9	34,1	61,3
OUR (mgO/ℓ/h) : Reactor	3	66 ± 3	63,4	62
	4	45,5 ± 3	45,5	40
EFFLUENT TKN (mgN/ℓ)		22,5 ± 1,5	22,6	24,8
NITRATE : (mgN/ℓ) Reactor	1	-	0	0
	2	-	0	0
	3	-	0,6	0,6
	4	1,1 ± 0,2	1,1	1,2

Table 5.3: Model input data for simulation of system responses.

		DEFAULT VALUE	PHOREDOX R_s = 3d	PHOREDOX R_s = 3d Repeat	SPLIT-FEED	U C T	JOHANNESBURG R_s = 3d	JOHANNESBURG R_s 0 5d
	Wastewater Characteristics							
1	S_{ti} (mgCOD/ℓ)	-	396,9	417,1	391,6	367,2	397,6	383,2
2	N_{ti} (mgNH_3/ℓ)	-	43,7	44,1	39,8	41,9	50,1	46,8
3	f_{bs} (mgCOD/mgCOD)	0,2	0,63	0,42	0,75	0,98	0,64	0,63
4	f_{us} (mgCOD/mgCOD)	0,08	0,16	0,14	0,15	0,10	0,12	0,11
5	f_{up} (mgCOD/mgCOD)	0,13	0,10	0,09	0,10	0,11	0,10	0,10
6	f_{na} (mgN/mgN)	0,84	0,84	0,84	0,84	0,84	0,84	0,84
7	f_{nox} (mgN/mgN)	0,5	0,5	0,5	0,5	0,5	0,5	0,5
8	f_{nu} (mgN/mgN)	0	0	0	0	0	0	0
9	f_{xbh} (mgX_{bh}COD/mgCOD)	0	0	0	0	0	0	0
	Heterotrophs							
1	Mue max. (d^{-1})	3,5	3,5	3,5	3,5	3,5	3,5	3,5
2	K_s (gCOD/m^3)	5	5	5	5	5	5	5
3	K_{oh} (gO_2/m^3)	0,002	0,002	0,002	0,002	0,002	0,002	0,002
4	b_h (d^{-1})	0,62	0,62	0,62	0,62	0,62	0,62	0,62
5	η(solubilization)	0,37	0,37	0,37	0,37	0,37	0,37	0,37
6	η(growth)	1	1	1	1	1	1	1
7	K_{no} (gN/m^3)	1	1	1	1	1	1	1
8	K_h (d^{-1})	2,2	2,2	2,2	2,2	2,2	2,2	2,2
9	K_x	0,15	0,15	0,15	0,15	0,15	0,15	0,15
10	K_r (m^3/gCOD/d)	0,016	0,016	0,016	0,016	0,016	0,016	0,016
11	K_{na} (gN/m^3)	0,1	0,1	0,1	0,1	0,1	0,1	0,1
	Autotrophs							
1	Mue max. (d^{-1})	0,45	0,43	0,71	0,65	0,63	0,69	0,63
2	K_{nh}	1	1	1	1	1	1	1
3	K_{oa} (gO_2/m^3)	0,002	0,002	0,002	0,002	0,002	0,002	0,002
2	b_a (d^{-1})	0,04	0,04	0,04	0,04	0,04	0,04	0,04
	Stoichiometry							
1	Y_h (gCOD/gCOD)	0,666	0,666	0,666	0,666	0,666	0,666	0,666
2	f_e (gCOD/gCOD)	0,08	0,08	0,08	0,08	0,08	0,08	0,08
3	i_{xb} (gN/gCOD)	0,068	0,068	0,068	0,068	0,068	0,068	0,068
4	i_{xe} (gN/gCOD)	0,068	0,068	0,068	0,068	0,068	0,068	0,068
5	Y_a (gCOD/gCOD)	0,15	0,15	0,15	0,15	0,15	0,15	0,15
6	COD:VSS (gCOD/gVSS)	1,48	1,544	1,544	1,544	1,48	1,48	1,48

Table 5.4: Comparison between data predicted by the general activated sludge model and mean experimental results from a 3 day sludge age Phoredox system.

		EXPERIMENTAL VALUE	PREDICTED VALUE
VSS (mgVSS/ℓ) :	Reactor 1	1280 ± 18	1365
	2	1210 ± 20	1365
	3	1400 ± 17	1386
	4	1300 ± 28	1377
EFFLUENT COD (mgCOD/ℓ)		67,0 ± 0,8	66,1
OUR (mgO/ℓ/h) :	Reactor 3	60 ± 1	61
	4	42 ± 1	33
EFFLUENT TKN (mgN/ℓ)		26,2 ± 0,6	28,0
NITRATE (mgN/ℓ)	Reactor 1	-	0
	2	-	0
	3	-	0,8
	4	1,9 ± 0,1	1,7

Table 5.5: Comparison between data predicted by the general activated sludge model and mean experimental results from a 3 day sludge age Phoredox system (repeat investigation).

		EXPERIMENTAL VALUE	PREDICTED VALUE
VSS (mgVSS/ℓ) :	Reactor 1	1275 ± 53	1360
	2	1240 ± 47	1361
	3	1200 ± 59	1363
	4	1200 ± 62	1350
EFFLUENT COD (mgCOD/ℓ)		62,0 ± 3,3	61,3
OUR (mgO/ℓ/h) :	Reactor 3	52,0 ± 4	52
	4	40,0 ± 2	41
EFFLUENT TKN (mgN/ℓ)		18,5 ± 1,3	17,0
NITRATE (mgN/ℓ)	Reactor 1	0,3 ± 0,1	0,2
	2	0,5 ± 0,1	0
	3	6,7 ± 0,4	3,5
	4	8,4 ± 1,2	7,1

Table 5.6: Comparison between data predicted by the general activated sludge model and mean experimental results from the Split-feed system.

		EXPERIMENTAL VALUE	PREDICTED VALUE
VSS (mgVSS/ℓ) :	Reactor 1	1320 ± 63	1408
	2	1280 ± 63	1409
	3	1225 ± 69	1209
	4	1170 ± 67	1200
EFFLUENT COD (mgCOD/ℓ)		61,0 ± 5,1	60,9
OUR (mgO/ℓ/h) :	Reactor 3	53,5 ± 3,0	62,2
	4	39,5 ± 2,0	37,8
EFFLUENT TKN (mgN/ℓ)		12,1 ± 0,7	14,3
NITRATE (mgN/ℓ)	Reactor 1	0,08 ± 0,01	0,1
	2	0,22 ± 0,04	0
	3	4,0 ± 0,5	3,3
	4	6,4 ± 0,8	6,7

Table 5.7: Comparison between data predicted by the general activated sludge model and mean experimental results from a UCT system.

		EXPERIMENTAL VALUE	PREDICTED VALUE
VSS (mgVSS/ℓ) :	Reactor 1	1300 ± 37	1071
	2	2350 ± 78	2110
	3	2380 ± 74	2121
	4	2370 ± 78	2113
EFFLUENT COD (mgCOD/ℓ)		40,0 ± 1,6	37,8
OUR (mgO/ℓ/h) :	Reactor 3	78,5 ± 4,0	87,8
	4	43,0 ± 4,5	42,5
EFFLUENT TKN (mgN/ℓ)		3,8 ± 0,3	4,0
NITRATE (mgN/ℓ)	Reactor 1	1,1 ± 0,8	0
	2	3,4 ± 0,4	0,3
	3	9,3 ± 0,4	6,5
	4	10,6 ± 0,4	9,4

Table 5.8: Comparison between data predicted by the general activated sludge model and mean experimental results from a 3 day sludge age Johannesburg system.

		EXPERIMENTAL VALUE	PREDICTED VALUE
VSS (mgVSS/ℓ) : Reactor	1	2280 ± 104	2252
	2	1315 ± 44	1185
	sel.	-	1193
	3	1400 ± 50	1205
	4	1390 ± 75	1195
EFFLUENT COD (mgCOD/ℓ)		51,0 ± 3,3	49,5
OUR (mgO/ℓ/h) : Reactor	sel.	98 ± 6	83
	3	36 ± 1	56
	4	31,5 ± 2	39
EFFLUENT TKN (mgN/ℓ)		14,2 ± 1,8	19,3
NITRATE (mgN/ℓ) Reactor	1	1,3 ± 0,1	5,3
	2	0,5 ± 0,1	0,1
	sel	2,4 ± 0,1	0,8
	3	6,3 ± 0,9	4,9
	4	8,9 ± 0,6	9,1

Table 5.9: Comparison between data predicted by the general activated sludge model and mean experimental results from a 5 day sludge age Johannesburg system.

		EXPERIMENTAL VALUE	PREDICTED VALUE
VSS (mgVSS/ℓ) : Reactor	1	2660 ± 104	2366
	2	1560 ± 71	1242
	sel.	-	1251
	3	1530 ± 60	1258
	4	1510 ± 57	1248
EFFLUENT COD (mgCOD/ℓ)		44,0 ± 2,8	44,2
OUR (mgO/ℓ/h) : Reactor	sel.	89 ± 4	85
	3	46 ± 3	61
	4	41 ± 2	44
EFFLUENT TKN (mgN/ℓ)		7,0 ± 0,9	8,1
NITRATE (mgN/ℓ)	Reactor 1	2,2 ± 0,3	5,9
	2	0,13 ± 0,01	0,1
	sel	2,3 ± 0,2	1,6
	3	7,9 ± 0,3	7,9
	4	13,0 ± 0,4	13,6

Table 5.10: Comparison of observed and predicted P removal behaviour.

SYSTEM	PREDICTED		OBSERVED		P REMOVAL / COD REMOVAL	
	P RELEASE (mgP/ℓ)	P REMOVAL (mgP/ℓ)	P RELEASE (mgP/ℓ)	P REMOVAL (mgP/ℓ)	PREDICTED (mgP/mgCOD)	OBSERVED (mgP/mgCOD)
Phoredox (R_s=4d)	48,5	13,8	57,1	15,7	0,030	0,035
Phoredox (R_s=3d)	32,9	10,0	40,9	14,5	0,024	0,034
Phoredox (R_s=3d)-repeat	18,5	7,6	2,8	4,8	0,018	0,011
Split-feed	8,2	5,0	15,5	6,6	0,013	0,017
3-stage Bardenpho	0	3,7	4,5	7,7	0,008	0,017
UCT (a=2)	19,8	7,3	1,6	8,1	0,016	0,017
UCT (a=1)	40,3	11,3	25,0	12,0	0,024	0,026
Johannesburg (R_s=3d)	40,4	12,4	16,4	8,4	0,028	0,019
Johannesburg (R_s=5d, a=0,5)	45,5	13,3	25,2	12,5	0,031	0,029
Johannesburg (R_s=5d, a=1)	39,0	11,8	21,4	7,4	0,026	0,017

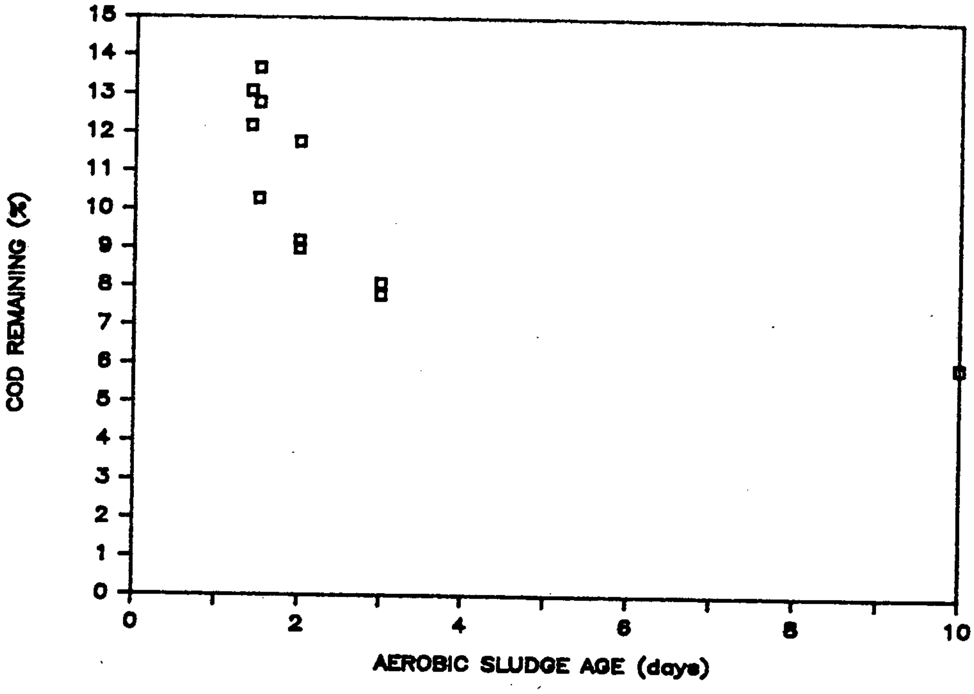


Fig 5.1: The effect of aerobic sludge age on the filtered effluent COD.

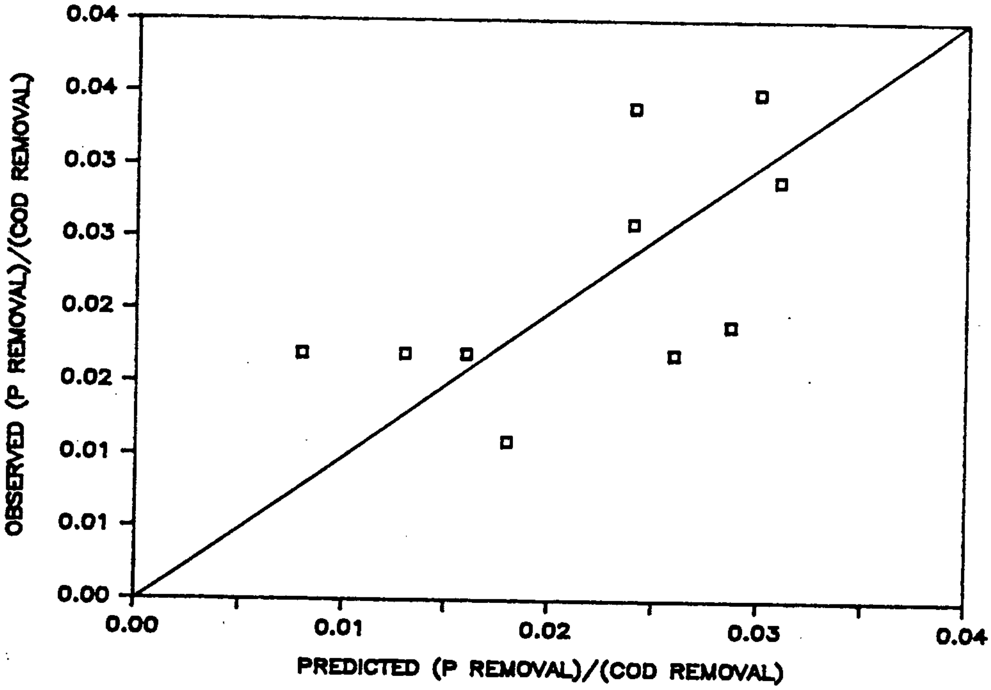


Fig 5.2: Predicted P removal per COD removal versus observed P removal per COD removal.

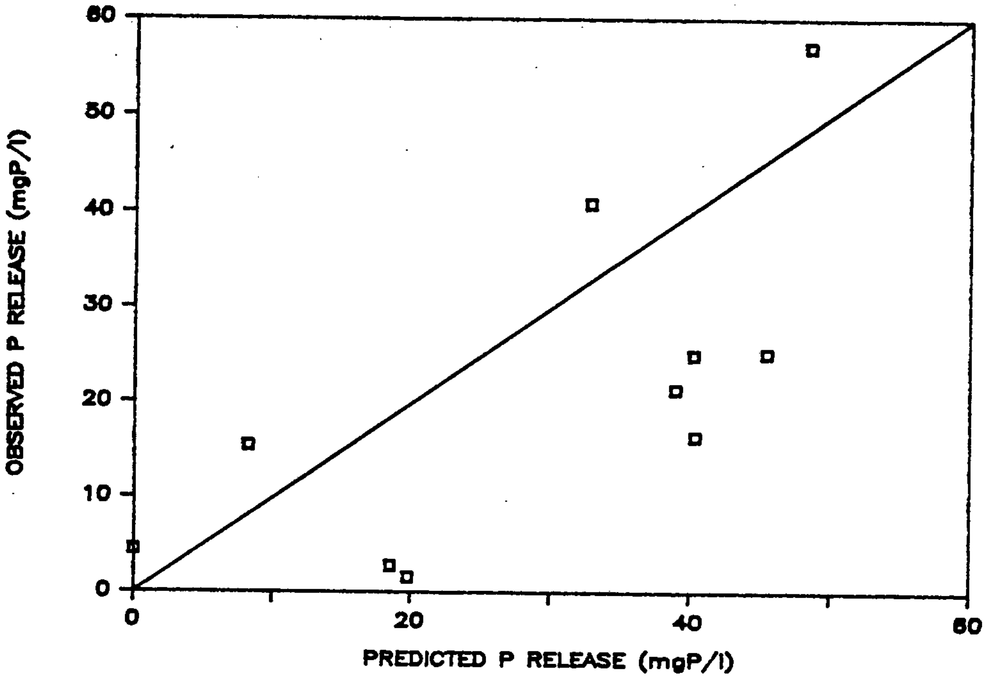


Fig 5.3: Predicted versus observed P release.

CHAPTER SIX

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

The study of short sludge age biological excess P removal activated sludge systems was motivated by the need to:

(i) check the extremely favourable findings obtained on this system by the commercial firm that developed it in the United States of America,

(ii) develop a viable pre-treatment P removal facility for existing trickling filter systems.

The system tested by the Americans essentially reduced to

(i) a non-nitrifying Phoredox system, which they designated the A/0 system, and

(ii) a nitrification/denitrification system identical to the Modified 3-stage Bardenpho system.

The major part of their study was focussed on the non-nitrifying system. In their system configuration, each reactor, anaerobic and aerobic, was specifically subdivided to approach plug-flow conditions. An important feature in the operational design was the very low underflow recycle ratios employed, ranging from as little as 0,15 to 0,42 with respect to the influent flow rate. These low recycle ratios were possible because the systems developed very good settling sludges with SVI's of less than 100 mℓ/g. The American researchers found that these good settling properties were obtained with system sludge ages as short as 2 days and with anaerobic mass fract ions ranging from about 30 to 40 percent; this implied aerobic sludges of about 1,2 to 1,4 days. At these short sludge ages the effluent was clear with low COD and low suspended solids concentrations. The phosphorus removals, achieved in the majority of the laboratory and pilot scale plants, did not provide information on the full potential of these systems as the P/COD ratios in the influent were apparently less than the removal potentials; as a consequence, their effluent phosphorus concentrations were always very low. This viewpoint is supported by the one pilot-scale plant which treated a wasteflow with an unusually high P/COD ratio - the ΔP/COD ratio achieved in this plant was excellent (0,028 mgP removed/mg influent COD).

In order to specifically check the findings above, a non-nitrifying Phoredox-A/0 system was set up using unsettled municipal waste water from a largely residential suburb (Mitchell's Plain). The system sludge age was selected at 3 days with an anaerobic mass fraction of 0,5, giving an aerobic sludge age of 1,5 days. Each of the aerobic and anaerobic zones was subdivided into two reactors in series in order to approach plug flow conditions. The magnitude of underflow recycle ratio could be varied but initially was selected at 1:1. This system gave results varying significantly in some aspects from those reported in the USA. The effluent quality was poor, the filtered COD being almost twice as high as those obtained on systems with larger sludge ages (6 days and more), and the effluent was very turbid. Furthermore the system gave rise to growth of the filamentous organism *S.natans* in the sludge mass and hence DSVI's of up to 200 m*ℓ*/g were recorded. The system was tested in two separate experiments and, on both occasions, gave the same response as that noted above. With regard to the P removal, in the first experiment the system did not nitrify and a very high mean ΔP/influent COD was obtained (0,03 mgP/mgCOD). In the second experiment, partial and rather variable nitrification was obtained; this influenced the P removal giving rise to variable ΔP/influent COD with ΔP/COD's ranging from 0,01 to 0,02 mgP/mg influent COD. It was not possible to reduce the nitrate feedback by lowering the underflow recycle ratio because of the poor settling properties of the mixed liquor.

Comparing the results obtained on American and South African Phoredox-A/0 systems, there are some significant differences:

(i) Effluent COD quality - In the USA at a 2 day sludge age and with anaerobic mass fractions of about 30 percent, the A/0 system produced a clear effluent with a high percentage COD reduction (± 92 percent). In South Africa at a 3 day sludge age and with a 50 percent anaerobic mass fraction, the A/0 system produced a turbid effluent with a relatively low COD reduction (± 86 percent). During the investigation, two other systems were operated at a 3 day sludge age and, on each occasion, poor quality, turbid effluents were obtained.

(ii) Sludge settleability - The American experience indicates exceptionally good settleability whereas the South African experience indicates poor settleability. The poor settleability in South Africa was caused by the proliferation of *S.natans*, a high F/M, low D.O. filament whose growth is promoted by high surface area/volume ratios. The South African systems were operated at D.O. concentrations and F/M ratios which should not have favoured the growth of *S.natans*. However, while the South African studies were conducted on laboratory-scale units with high surface area/volume ratios most of the American investigations were performed on pilot-scale plants. In order to minimise the surface area/volume effect, the reactor surfaces were thoroughly scrubbed at least twice a day to remove attached growths, the feed bucket was washed with hot water daily and the inter-reactor tubing was cleared periodically. Despite these precautions, the surface area effect cannot be eliminated and therefore it is not possible to come to a definite conclusion with regard to the bulking potential of this system at 3 days sludge age.

(iii) Nitrification - At aerobic sludge ages of 1,5 days and at 20°C, it would appear that nitrification is still a possibility. When nitrification does occur, it has a significant adverse effect on P removal. The nitrification effect could have been reduced by lowering the underflow recycle ratio but this could not be tested because of the poor settleability of the sludge.

The factors discussed above (poor quality effluent, susceptibility to bulking sludges and the possibility of nitrification) raise doubts as to the viability of the Phoredox-A/0 system in South Africa.

As a consequence of the difficulties encountered in the Phoredox-A/0 system discussed above, it was decided to study the response of short sludge age *nitrifying* systems. From an earlier study on a 4 day sludge age Phoredox system with a 50 percent anaerobic mass fraction, it was found that the system nitrified significantly, the filtered effluent COD was near the quality expected from a long sludge age plant, the effluent was clear and the sludge settleability was excellent (DSVI ~ 70 mℓ/g). Taking cognisance of these results, it was decided to accept a sludge age of about 6 days and an anaerobic mass fraction of about 50 percent for testing nitrifying, P removal systems. Three systems were investigated; a Modified 3-stage Bardenpho, a UCT and a Johannesburg system.

The 3-stage Bardenpho system was selected in preference to the 5-stage version because of the high TKN/COD ratio of the wastewater to be treated (TKN/COD ~ 0,1 mgN/mgCOD). Research on long sludge age systems indicated that, at this ratio, maximum denitrification is achieved by removing the secondary anoxic zone and adding its mass to the primary anoxic zone (WRC, 1984). The underflow recycle ratio was selected at 1:1 because there was no guarantee that the sludge settleability would be good.

Despite the consolidation of the 2 anoxic zones into a single primary anoxic reactor, it was still not possible to obtain a near nitrate-free effluent. Consequently, appreciable nitrate concentrations (± 13 mgN/ℓ) were recycled to the anaerobic reactor, thereby reducing the P removal significantly. The settleability of the sludge was excellent (DSVI ~ 90 mℓ/g) and therefore the underflow recycle ratio could have been lowered to reduce the nitrate returned to the anaerobic reactor. However, such an action would not have resolved the basic fault of the Modified 3-stage Bardenpho system that, above a certain TKN/COD ratio, there will always be nitrate in the effluent and hence in the underflow recycle. The P removal will therefore always be diminished to some degree.

The UCT system provides positive and selective removal of the nitrate in the flow recycled to the anaerobic reactor. By discharging the underflow and other denitrification recycle flows to the primary anoxic reactor, it is possible to reduce the nitrate in the primary zone to zero and completely free the anaerobic zone from its dependency on the nitrate in the effluent/underflow recycle. As soon as the UCT system was operated with zero nitrate in the recycle to the anaerobic zone, there was a gradual increase in P removal and by the time the experiment was terminated (unfortunately rather prematurely), the removal had climbed to 14 mgP/ℓ giving a ΔP/influent COD of 0,028 mgP/mg influent COD. This ratio would very likely have improved even further if the test was continued. The settleability of the mixed liquor was not as good as that of the Modified

3-stage Bardenpho system (DSVI of ± 110 mℓ/g for UCT and ± 90 mℓ/g for the 3-stage Bardenpho system). From the South African experience on settleability in long sludge age P removal plants the settleability in both these systems is relatively speaking very good. In any event, no limitation is placed on the magnitude of the underflow recycle in the UCT system because this recycle does not affect the P removal potential.

In the Johannesburg system, the primary and secondary anoxic zones are removed from their original locations, combined and placed in the underflow recycle. The denitrification capacity of the anoxic zone per unit mass of sludge is well below that of a primary anoxic zone, and approximately the same as that in the secondary anoxic zone. Despite the reduced denitrification potential, the mass of nitrate that needs to be denitrified is also reduced; for example, with a 1:1 underflow recycle ratio, half of the mass of nitrate passes out with the effluent and the other half is recycled via the anoxic zone in the underflow recycle to the anaerobic reactor. Thus, this system selectively removes the nitrate from the recycle to the anaerobic zone. With an anoxic mass fraction of 0,36, a TKN/COD ratio of about 0,1 mgN/mgCOD and an underflow recycle ratio of 1:1, the effluent from the anoxic zone ranged between 1 and 5 mgN/ℓ and the average P removal was between 7 and 8 mgP/ℓ. When the recycle ratio was reduced to 0,5:1, the effluent nitrate from the anoxic zone became zero and the P removal increased to an average of 12,5 mgP/ℓ. An analysis of the system showed that the recycle ratio could have been increased to about 0,7:1 and still maintained a zero nitrate flow to the anaerobic reactor. The settleability of the sludge was reasonably good - from the previous 3 day sludge age Split-feed experiment with a DSVI of 688 mℓ/g, the DSVI of the Johannesburg experiment decreased to a final value of 130mℓ/g.

One aspect repeatedly highlighted is that nitrate entering an anaerobic reactor always has an adverse effect on the P removal. In this study, the possibility of nitrification was very high for sludge ages longer than 3 days, even for unaerated mass fractions of 50 percent. In the Phoredox system when nitrate was not generated, P removal was always higher than when nitrate was generated and recycled to the anaerobic reactors. The use of shorter sludge ages to positively prevent nitrification does not seem to be the answer as the effluent COD and effluent volatile suspended solids concentrations increase very sharply at 3 days sludge age and the settleability deteriorates due to the growth of *S.natans*. At sludge ages of 4 days and longer, the settleability and effluent quality improve markedly. Where a selected sludge age could give rise to nitrification, it would seem that the Phoredox system is not to be recommended. It would further seem that the design should always allow for nitrification, in which event the Modified 3-stage Bardenpho system is likely to present the same problems as the Phoredox system, i.e. nitrate entering the anaerobic zone. The UCT system can positively control nitrate entering the anaerobic reactor; this system however requires 3 recycle streams and an enlarged volume for the anaerobic reactor to preserve the same anaerobic mass fraction as that in the 3-stage Bardenpho and Phoredox systems. A solution, which in a sense is a compromise one between the simplicity of the Phoredox system and the complexity of the UCT system, is the Johannesburg system. Essentially, this system has a denitrification reactor built into the underflow recycle line which conveys the settled mixed liquor to the anaerobic reactor. Even at a high underflow recycle ratio of 1:1, this denitrification reactor has to deal with only half the nitrate generated and correspondingly less if the recycle ratio is reduced below 1. If the TKN:COD ratio is not above 0,09 mgN/mgCOD and if the recycle ratio is not allowed to go above 1:1, the underflow anoxic reactor usually has the capability to reduce the nitrate to zero and thereby allow optimal P removal opportunity. At high TKN/COD ratios, the nitrate can still be controlled by reducing the underflow recycle ratio.

From the P removal aspect discussed above, this study gives rise to the recommendations that:

1. Short sludge age biological excess P removal systems should be designed to take account of the possibility of nitrate generation.

2. Sludge ages should not be as low as 3 days, probably 6 days is an acceptable value.

3. The Phoredox and the 3-stage Bardenpho systems cannot effectively prevent the nitrate generated from entering the anaerobic zone.

4. The UCT and Johannesburg systems can effectively prevent nitrate entering the anaerobic reactor and therefore are the recommended systems.

5. Provided the TKN:COD ratio and the readily biodegradable COD concentration are within the normal range for raw municipal wastewaters (0,08 to 0,09 mgN/mgCOD), and provided the settleability of the sludge is not so poor that the underflow recycle ratio needs to be higher than 1:1, the Johannesburg system should function adequately. It is a less complex system than the UCT system and hence would seem to be a viable alternative system for P removal plants at short sludge ages. However, this system should be investigated further to determine the ranges within which it can be practically utilised.

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APPENDIX A

TABULATION OF EXPERIMENTAL DATA

LIST OF TABLES

A.1a to A.1b	Daily results for 4 day sludge age laboratory-scale Phoredox system with system specifications listed in Table 4.1.
A.2a to A.2b	Daily results for 3 day sludge age laboratory-scale Phoredox system with system specifications listed in Table 4.4.
A.3a to A.3c	Daily results for repeat investigation of 3 day sludge age laboratory-scale Phoredox system with system specifications listed in Table 4.7.
A.4a to A.4c	Daily results for laboratory-scale Split-feed system with specifications listed in Table 4.10.
A.5a to A.5c	Daily results for 6 day sludge age laboratory-scale 3-stage Bardenpho system with system specifications listed in Table 4.15.
A.6a to A.6c	Daily results for 6 day sludge age laboratory-scale UCT system with system specifications listed in Table 4.18.
A.7a to A.7c	Daily results for 3 day sludge age laboratory-scale Johannesburg system with system specifications listed in Table 4.21.
A.8a to A.8c	Daily results for 5 day sludge age laboratory-scale Johannesburg system with system specifications listed in Table 4.25.

ABBREVIATIONS

1. COD = chemical oxygen demand (mgCOD/ℓ)
2. TKN = total Kjeldahl nitrogen (mgN/ℓ)
3. PO_4 = total phosphorus concentration (mgP/ℓ)
4. VSS = volatile suspended solids (mgVSS/ℓ)
5. OUR = oxygen utilization rate (mgO/ℓ/h)
6. NO_3 = filtered nitrate concentration (mgN/ℓ)
7. DSVI = diluted sludge volume index (mg/ℓ)
8. S_{bsi} = influent readily biodegradable COD (mgCOD/ℓ)
9. Pupt = phosphorus uptake (mgP/ℓ)
10. Prem = phosphorus removal (mgP/ℓ)

Subscript in refers to influent concentration
" out " " effluent "
" 1 " " reactor number 1
" 2 " " reactor number 2
" 3 " " reactor number 3
" 4 " " reactor number 4
" sel. " " selector reactor

Table A.1a : Experimental results from Phoredox system (Rs=4d)

Day No.	CODin	CODout	Sbsi	OUR,3	OUR,4	VSS,1	VSS,2	VSS,3	VSS,4	TKNin	TKNout	NO3out
	(mgCOD/l)	(mgCOD/l)	(mgCOD/l)	(mgO/l/h)	(mgO/l/h)	(mgVSS/l)	(mgVSS/l)	(mgVSS/l)	(mgVSS/l)	(mgN/l)	(mgN/l)	(mgN/l)
1	498.5	55.6	97	93	61	1399	1269	1466	1374	30.0	20.3	NA
2	487.2	38.1	70	104	69	1431	1259	1422	1378	40.3	23.1	0.0
3	493.4	36.1	NA	112	70	1500	1364	1530	1484	38.4	18.8	0.0
4	483.1	42.2	67	116	104	1549	1431	1756	1509	41.4	23.7	0.0
5	458.4	39.1	NA	78	46	1382	1310	1383	1285	38.9	20.7	0.0
6	476.9	34.0	64	95	60	1699	1640	1661	1617	38.6	19.9	0.0
7	554.1	NA	81	84	52	1225	1225	1238	1180	38.9	20.3	1.3
8	527.3	56.1	111	54	38	1304	1165	1323	1261	48.7	28.4	1.2
9	466.1	55.0	90	62	43	1345	1245	1331	1348	28.6	19.6	0.5
10	485.8	48.8	69	55	41	1591	1587	1514	1406	45.9	11.3	1.3
11	NA	26.0	153	65	47	1998	1433	1427	1462	53.5	22.7	1.1
12	540.8	52.9	105	70	49	1827	1480	1961	1762	44.5	26.7	0.9
13	551.2	59.2	NA	NA	NA	1347	1339	1483	1305	47.9	26.6	0.7
14	541.8	66.4	NA	NA	NA	1431	1293	1952	1902	44.2	24.4	1.7
15	532.5	70.6	NA	NA	NA	2052	1952	2065	1925	45.1	26.0	0.6
16	572.9	52.9	137	74	54	1974	1862	2669	2025	42.6	25.8	0.6
17	521.1	61.2	142	70	46	1878	1833	2153	2108	42.0	26.3	0.8
18	516.9	56.1	148	57	38	2025	1422	2048	2234	40.0	27.4	0.7
19	511.7	61.2	163	63	44	2024	1962	2332	2548	36.4	23.2	0.8
20	520.0	57.1	139	57	36	1797	1820	2521	2251	40.9	NA	0.8
21	481.6	70.6	NA	72	48	2304	1859	1894	2184	42.3	21.6	1.3
22	496.0	57.3	147	51	35	1995	2047	NA	2234	34.7	22.3	1.4
23	505.4	63.6	NA	74	50	2172	1900	2289	2302	39.8	21.6	1.5
24	531.4	57.3	70	70	53	2193	2270	2775	2396	36.4	20.2	0.9
25	488.6	41.8	108	53	42	2273	1894	2349	2114	32.5	11.2	1.3
26	489.6	32.6	108	59	44	2263	1975	2054	2182	35.0	17.5	2.1
27	504.2	51.2	107	NA	NA	1936	1838	2318	2409	34.4	21.0	2.1
28	537.7	66.8	111	77	57	2358	2176	2109	2125	33.6	14.8	1.7
29	588.8	65.8	110	67	44	2111	1962	2579	2446	36.1	17.6	0.0
30	559.6	62.6	NA	73	50	2156	2521	2143	2536	32.2	12.2	1.8
31	566.9	56.4	80	75	53	2242	1908	2304	2379	37.5	16.4	0.8
32	513.6	60.6	112	68	46	2058	1982	2360	2394	30.8	14.7	1.6
33	439.5	31.3	106	63	43	2235	2937	2333	2193	28.6	13.9	2.8
34	519.9	85.6	NA	60	41	1610	1691	1699	1917	32.5	16.2	2.3
35	533.5	61.6	109	51	36	NA	1608	2000	1968	35.6	14.7	2.7
36	486.0	65.0	138	74	53	1731	1659	2045	1991	37.5	17.4	2.2
37	NA	NA	149	53	35	1577	1563	1889	1691	38.2	16.8	2.1
38	507.7	52.7	169	79	63	1974	2064	2155	1871	37.8	15.3	2.9
39	450.3	89.4	135	64	42	2262	2058	2062	1932	32.5	15.4	2.3
40	550.1	76.5	NA	75	52	2302	2162	2176	2057	29.7	12.6	0.8
41	596.2	69.9	74	NA	NA	2572	2298	2178	2210	30.4	10.4	4.1
42	619.5	89.1	96	72	50	2099	1961	1973	1976	33.3	10.9	5.9

Day No.	CODin (mgCOD/l)	CODout (mgCOD/l)	Sbsi (mgCOD/l)	OUR,3 (mgO/l/h)	OUR,4 (mgO/l/h)	VSS,1 (mgVSS/l)	VSS,2 (mgVSS/l)	VSS,3 (mgVSS/l)	VSS,4 (mgVSS/l)	TKNin (mgN/l)	TKNout (mgN/l)	NO3out (mgN/l)
43	NA	78.1	96	81	57	2379	2192	2673	2546	40.9	10.2	5.1
44	588.4	75.6	130	78	52	2623	2287	2556	2431	NA	NA	NA
45	450.7	82.3	125	65	46	2026	2043	2593	2602	30.5	9.8	NA
46	505.3	98.4	NA	NA	NA	1937	1944	2346	2283	25.2	7.8	5.1
47	477.6	55.9	130	NA	NA	1647	1664	2562	2044	25.8	8.5	5.4
48	524.3	106.9	102	NA	NA	2001	2007	2199	1900	25.5	8.4	3.9
49	462.6	66.8	118	62	40	1888	1636	2074	2165	22.2	7.3	4.8
50	505.6	76.6	157	58	39	1969	1973	2066	2010	26.0	7.6	NA
51	465.7	65.8	NA	62	41	1949	1917	1779	1719	24.9	7.6	5.4

Table A.1b : Experimental results from Phoredox system (Rs=4d)

Day No.	PO4in	PO4,1	PO4,2	PO4,3	PO4,4	PO4eff	Prel,1	Prel,2	Pupt,3	Pupt,4	Prem
	(mgP/l)	(mgP/l)	(mgP/l)	(mgP/l)	(mgP/l)	(mgP/l)	(mgP/l)	(mgP/l)	(mgP/l)	(mgP/l)	(mgP/l)
1	16.5	26.1	34.6	11.9	2.5	3.6	-33.2	-17.0	45.4	18.8	14.0
2	20.3	29.8	35.8	15.9	4.3	3.5	-35.0	-12.0	39.8	23.2	16.0
3	21.4	34.0	38.1	17.6	6.0	4.5	-40.6	-8.2	41.0	23.2	15.4
4	20.5	36.8	40.3	17.3	14.2	10.6	-38.9	-7.0	46.0	6.2	6.3
5	21.5	31.5	36.5	15.6	4.3	3.2	-37.2	-10.0	41.8	22.6	17.2
6	23.2	25.7	37.4	12.8	7.2	10.8	-21.0	-23.4	49.2	11.2	16.0
7	22.0	31.9	39.8	19.7	6.5	8.8	-35.3	-15.8	40.2	26.4	15.5
8	17.2	32.1	37.9	16.8	4.5	4.5	-42.5	-11.6	42.2	24.6	12.7
9	21.2	36.5	42.5	34.1	NA	18.1	NA	-12.0	16.8	NA	NA
10	18.5	23.8	30.0	11.8	9.0	7.4	-20.1	-12.4	36.4	5.6	9.5
11	19.0	25.7	28.4	16.1	6.7	8.4	-25.7	-5.4	24.6	18.8	12.3
12	23.1	35.1	41.6	20.6	8.0	10.6	-39.1	-13.0	42.0	25.2	15.1
13	23.4	NA	NA	38.8	17.4	11.4	NA	NA	NA	42.8	6.0
14	22.5	29.6	38.9	20.4	8.6	8.8	-28.1	-18.6	37.0	23.6	13.9
15	22.9	31.2	42.2	26.3	11.7	5.2	-27.8	-22.0	31.8	29.2	11.2
16	26.0	42.0	52.2	24.9	9.0	5.8	-49.0	-20.4	54.6	31.8	17.0
17	24.3	39.0	48.0	19.6	8.5	4.3	-45.2	-18.0	56.8	22.2	15.8
18	21.8	38.0	43.4	19.0	8.5	4.3	-45.7	-10.8	48.8	21.0	13.3
19	21.3	40.0	47.3	19.0	5.1	5.1	-53.6	-14.6	56.6	27.8	16.2
20	24.7	41.5	47.8	23.9	8.5	6.3	-49.8	-12.6	47.8	30.8	16.2
21	22.2	40.2	45.9	17.3	8.7	7.4	-49.5	-11.4	57.2	17.2	13.5
22	23.5	37.8	50.0	23.0	6.7	5.6	-45.4	-24.4	54.0	32.6	16.8
23	22.8	35.3	45.1	19.9	7.9	4.7	-39.9	-19.6	50.4	24.0	14.9
24	20.0	35.9	45.8	24.3	6.6	2.6	-45.2	-19.8	43.0	35.4	13.4
25	21.8	31.7	38.6	15.7	4.3	2.6	-37.3	-13.8	45.8	22.8	17.5
26	23.3	39.7	46.7	18.3	8.0	6.3	-48.1	-14.0	56.8	20.6	15.3
27	28.5	39.6	46.2	25.8	8.5	8.5	-42.2	-13.2	40.8	34.6	20.0
28	22.6	41.2	47.9	20.8	6.6	6.6	-53.2	-13.4	54.2	28.4	16.0
29	25.7	37.8	48.7	23.2	6.1	5.5	-43.8	-21.8	51.0	34.2	19.6
30	23.5	39.8	47.1	21.1	6.6	5.0	-49.5	-14.6	52.0	29.0	16.9
31	23.7	36.6	47.2	18.7	4.6	5.8	-44.9	-21.2	57.0	28.2	19.1
32	21.6	37.7	39.0	17.4	5.2	5.1	-48.6	-2.6	43.2	24.4	16.4
33	22.6	34.3	40.0	14.0	2.7	11.5	-43.3	-11.4	52.0	22.6	19.9
34	23.3	37.1	45.3	24.9	13.2	11.5	-37.7	-16.4	40.8	23.4	10.1
35	17.1	29.3	38.8	19.0	7.0	7.1	-34.5	-19.0	39.6	24.0	10.1
36	24.5	37.8	42.8	25.9	12.4	7.7	-38.7	-10.0	33.8	27.0	12.1
37	22.9	34.9	41.5	10.2	7.9	6.3	-39.0	-13.2	62.6	4.6	15.0
38	24.1	36.0	43.5	21.0	7.0	4.8	-40.9	-15.0	45.0	28.0	17.1
39	21.8	35.9	43.4	21.6	7.1	4.7	-42.9	-15.0	43.6	29.0	14.7
40	23.0	38.5	43.9	20.4	7.2	8.4	-46.8	-10.8	47.0	26.4	15.8
41	25.8	38.4	48.1	22.0	8.6	8.0	-42.4	-19.4	52.2	26.8	17.2
42	22.8	41.2	49.0	22.0	8.6	5.6	-51.0	-15.6	54.0	26.8	14.2

Day No.	PO4in (mgP/l)	PO4,1 (mgP/l)	PO4,2 (mgP/l)	PO4,3 (mgP/l)	PO4,4 (mgP/l)	PO4eff (mgP/l)	Prel,1 (mgP/l)	Prel,2 (mgP/l)	Pupt,3 (mgP/l)	Pupt,4 (mgP/l)	Prem (mgP/l)
43	25.6	37.3	49.6	24.5	10.0	7.5	-39.0	-24.6	50.2	29.0	15.6
44	24.5	43.2	48.2	17.9	7.4	11.4	-54.5	-10.0	60.6	21.0	17.1
45	23.5	34.7	42.1	20.6	8.5	7.0	-37.4	-14.8	43.0	24.2	15.0
46	24.6	32.7	37.8	19.0	10.0	6.5	-30.8	-10.2	37.6	18.0	14.6
47	24.9	37.0	40.7	24.9	9.3	8.0	-39.8	-7.4	31.6	31.2	15.6
48	23.9	34.2	41.0	19.8	7.4	5.6	-37.1	-13.6	42.4	24.8	16.5
49	24.5	34.8	40.0	19.8	10.0	6.0	-35.1	-10.4	40.4	19.6	14.5
50	23.1	30.0	35.5	17.2	7.4	6.3	-29.5	-11.0	36.6	19.6	15.7
51	24.1	33.8	40.3	19.2	7.6	7.0	-35.9	-13.0	42.2	23.2	16.5

Table A.2a : Experimental results from Phoredox system (Rs=3d)

Day No.	CODin (mgCOD/l)	CODout (mgCOD/l)	Sbsi (mgCOD/l)	OUR,3 (mgO/l/h)	OUR,4 (mgO/l/h)	VSS,1 (mgVSS/l)	VSS,2 (mgVSS/l)	VSS,3 (mgVSS/l)	VSS,4 (mgVSS/l)	DSVI (ml/g)	TKNin (mgN/l)	TKNout (mgN/l)	NO3out (mgN/l)
1	535.6	67.6	98	72	55	NA	NA	NA	NA		38.1	22.7	5.0
2	524.3	59.7	138	59	45	NA	NA	NA	NA		42.3	21.4	5.0
3	522.2	68.0	114	61	44	1440	1336	1891	1697	76	42.0	22.7	4.5
4	626.2	76.2	137	70	49	1628	1546	1992	2015		52.6	22.0	6.5
5	499.6	45.2	90	73	48	1340	1033	2398	1932		41.2	22.1	5.3
6	570.5	52.4	99	68	49	1321	1209	1698	1736		47.0	19.5	6.5
7	484.2	61.7	111	69	48	1508	1379	1867	2019		43.0	24.0	5.0
8	450.3	67.8	101	54	35	1498	1192	1458	1784	NA	37.8	21.1	5.3
9	525.3	59.6	117	57	42	1592	1385	1616	1694	118	42.0	21.0	5.8
10	499.6	70.0	103	59	41	1523	1764	1847	1944		41.7	20.2	2.8
11	494.4	60.8	141	55	40	2091	1372	1681	1831		35.8	22.3	3.6
12	485.2	44.3	114	57	42	NA	NA	NA	NA		38.4	22.5	3.2
13	430.5	57.7	NA	51	39	1900	1556	1591	1679		37.8	21.4	3.2
14	452.2	48.4	NA	62	43	1611	1462	1563	1449		34.2	19.5	3.6
15	462.6	58.7	98	51	40	1842	1281	1790	1914		44.2	20.3	3.0
16	494.4	52.5	120	42	26	1853	1083	1094	970		43.7	22.3	4.4
17	486.2	65.9	125	57	32	961	924	1043	981		41.4	23.7	4.7
18	507.8	61.7	68	68	45	1475	1186	1677	2192		41.7	17.1	2.8
19	517.1	80.3	NA	58	40	1091	1027	2267	2115		41.2	30.7	4.2
20	497.5	73.1	NA	56	43	1725	1473	1544	1727	72	39.2	23.9	1.5
21	502.6	69.0	109	52	42	1594	1409	1863	2042		49.3	21.1	1.6
22	460.4	67.0	111	55	38	1459	1391	1709	1842		36.4	24.4	2.3
23	471.2	68.3	104	NA	NA	1628	1281	1660	1799		40.6	24.6	1.7
24	451.9	75.5	105	52	40	1442	1261	1894	NA		37.5	24.8	1.6
25	467.2	56.7	104	55	40	230	1043	1750	913		39.4	26.5	2.5
26	507.9	94.9	76	58	41	1112	761	1495	1877		42.8	30.5	1.6
27	466.1	80.6	94	50	39	1372	1145	1220	1445		38.1	25.8	2.3
28	447.2	70.9	NA	50	40	1422	1264	1326	1443		38.6	23.7	1.6
29	556.1	67.8	144	60	41	1315	1119	1439	1321		46.2	25.6	1.5
30	515.0	61.7	90	51	46	1127	1153	1127	1064		44.2	29.5	1.6
31	491.4	67.8	NA	55	46	1432	1434	1472	1427		46.5	31.1	1.8
32	495.5	67.9	95	57	47	1386	1349	1407	1423		47.3	29.3	1.4
33	473.9	73.0	83	56	42	1350	1350	1360	1353		47.3	29.7	1.4
34	478.0	77.1	NA	59	42	1359	1280	1340	1440		44.5	27.7	1.4
35	481.1	76.1	NA	67	40	1384	1361	1406	1414		45.1	28.8	2.0
36	469.7	61.8	NA	60	42	1260	1249	1276	1234	155	45.6	29.4	1.6
37	475.9	60.8	NA	55	39	1385	1407	1439	1436		48.2	29.7	1.5
38	486.2	57.7	NA	59	39	1298	1252	1378	1293		48.2	31.5	2.8
39	477.9	65.9	NA	60	41	1178	1158	1208	1197		46.5	29.4	2.9
40	496.5	68.0	NA	61	45	1174	1160	1241	1174		48.7	30.4	1.6
41	445.4	76.8	NA	53	37	1169	1123	1170	1145			27.3	2.5
42	523.3	62.5	78	62	43	1260	1249	1343	1306		38.1	22.7	2.4

Day No.	CODin (mgCOD/l)	CODout (mgCOD/l)	Sbsi (mgCOD/l)	OUR,3 (mgO/l/h)	OUR,4 (mgO/l/h)	VSS,1 (mgVSS/l)	VSS,2 (mgVSS/l)	VSS,3 (mgVSS/l)	VSS,4 (mgVSS/l)	DSVI (ml/g)	TKNin (mgN/l)	TKNout (mgN/l)	NO3out (mgN/l)
43	549.9	75.8	114	65	45	1236	1215	1303	1317		40.3	17.5	1.8
44	550.9	64.5	100	66	44	1424	NA	1507	1456		43.7	18.5	2.3
45	545.8	65.7	101	75	47	1517	1562	1511	1590		42.6	20.3	2.6
46	518.1	71.8	98	74	47	1386	1382	1408	1431		39.5	18.2	2.5
47	525.3	72.8	100	73	49	1328	1349	1343	1369		35.3	18.6	2.2
48	477.1	64.6	74	88	33	453	1094	1590	1115		39.2	18.6	1.8
49	475.0	68.7	85	62	29	714	679	647	757	139	38.6	20.7	2.2
50	477.1	65.7	NA	76	41	1340	961	1028	968		40.6	20.2	1.8
51	457.0	64.3	79	72	44	992	926	967	1024		43.7	18.1	1.4
52	497.6	80.0	59	66	43	851	792	830	850		41.0	20.0	1.3
53	482.5	72.4	51	70	45	945	881	926	970		38.9	23.9	1.7
54	474.3	68.3	67	73	44	1465	1462	1373	1398		40.3	22.5	0.8
55	356.0	70.6	63	NA	NA	NA	NA	NA	NA		NA	NA	0.9
56	257.5	69.5	84	NA	NA	NA	NA	NA	NA		NA	NA	
57	481.4	66.4	83	51	30	673	635	640	696		50.4	35.6	
58	496.7	57.2	96	49	41	1127	882	772	683	113	47.3	32.3	
59	497.7	56.2	77	54	44	1407	1098	1018	1228		57.7	34.7	
60	528.4	57.2	83	52	34	1621	1529	1533	1439		55.4	36.1	
61	497.7	56.3	70	66	49	1550	1239	1494	1420	127	53.8	35.4	
62	504.8	65.5		49	31	1378	1432	1277	1174		52.9	34.7	
63	NA	NA		63	43	1184	1148	1195	1135		52.9	35.0	
64	495.6	55.3		61	35						53.8	37.2	

Table A.2b : Experimental results from Phoredox system (Rs=3d)

Day No.	PO4in (mgP/l)	PO4,1 (mgP/l)	PO4,2 (mgP/l)	PO4,3 (mgP/l)	PO4,4 (mgP/l)	PO4out (mgP/l)	Pupt,1 (mgP/l)	Pupt,2 (mgP/l)	Pupt,3 (mgP/l)	Pupt,4 (mgP/l)	Prem (mgP/l)
1	22.7	33.1	39.0	19.4	6.9	11.7	-36.6	-11.8	39.2	25.0	15.8
2	26.8	31.5	41.3	23.0	8.9	8.9	-27.3	-19.6	36.6	28.2	17.9
3	25.0	31.6	40.9	20.0	7.7	6.8	-30.5	-18.6	41.8	24.6	17.3
4	25.6	28.3	38.8	25.2	9.5	7.5	-21.5	-21.0	27.2	31.4	16.1
5	23.7	42.2	49.6	16.2	10.0	10.0	-50.7	-14.8	66.8	12.4	13.7
6	22.9	25.8	34.1	21.8	10.6	7.2	-18.1	-16.6	24.6	22.4	12.3
7	22.8	27.4	36.6	16.9	6.0	5.1	-26.0	-18.4	39.4	21.8	16.8
8	23.5	31.8	38.9	15.6	4.8	7.3	-35.3	-14.2	46.6	21.6	18.7
9	24.8	31.0	40.2	19.6	6.3	6.3	-30.9	-18.4	41.2	26.6	18.5
10	22.4	29.9	38.5	16.3	4.6	4.6	-32.8	-17.2	44.4	23.4	17.8
11	22.6	31.8	38.4	16.5	7.8	6.3	-33.2	-13.2	43.8	17.4	14.8
12	19.0	29.4	35.3	18.7	10.1	10.1	-29.7	-11.8	33.2	17.2	8.9
13	26.5	44.0	49.7	29.8	12.9	12.9	-48.6	-11.4	39.8	33.8	13.6
14	22.1	26.0	34.4	23.0	11.5	7.4	-18.4	-16.8	22.8	23.0	10.6
15	17.4	29.7	37.7	18.2	6.8	6.7	-35.2	-16.0	39.0	22.8	10.6
16	23.3	20.9	17.5	14.2	12.0	7.5	-6.5	6.8	6.6	4.4	11.3
17	23.8	28.5	35.9	21.9	12.1	11.3	-21.1	-14.8	28.0	19.6	11.7
18	24.4	28.9	37.1	24.0	11.5	9.2	-21.9	-16.4	26.2	25.0	12.9
19	24.8	30.4	40.0	24.2	11.5	9.8	-24.5	-19.2	31.6	25.4	13.3
20	24.8	33.2	41.8	21.9	9.6	9.2	-32.0	-17.2	39.8	24.6	15.2
21	25.0	32.9	42.8	22.8	8.9	8.9	-31.9	-19.8	40.0	27.8	16.1
22	24.8	30.6	40.8	22.1	9.2	8.0	-27.2	-20.4	37.4	25.8	15.6
23	24.8	29.2	38.0	23.0	10.0	8.9	-23.6	-17.6	30.0	26.0	14.8
24	27.0	34.1	39.9	24.0	11.7	9.5	-29.5	-11.6	31.8	24.6	15.3
25	27.0	35.4	42.4	27.6	12.5	12.0	-31.3	-14.0	29.6	30.2	14.5
26	25.8	30.4	36.2	24.7	10.2	15.2	-24.8	-11.6	23.0	29.0	15.6
27	24.8	27.9	35.0	21.5	9.8	10.8	-21.2	-14.2	27.0	23.4	15.0
28	24.7	26.0	34.0	23.9	10.4	10.8	-16.9	-16.0	20.2	27.0	14.3
29	26.4	32.2	37.4	19.8	13.4	12.5	-24.6	-10.4	35.2	12.8	13.0
30	26.8	30.9	39.7	24.2	13.4	11.8	-21.6	-17.6	31.0	21.6	13.4
31	25.9	31.2	40.0	21.6	12.0	11.9	-24.5	-17.6	36.8	19.2	13.9
32	26.0	29.8	38.7	23.7	9.9	9.6	-23.7	-17.8	30.0	27.6	16.1
33	26.3	33.1	42.2	24.2	9.1	10.0	-30.8	-18.2	36.0	30.2	17.2
34	26.0	31.8	41.0	23.8	9.8	9.5	-27.8	-18.4	34.4	28.0	16.2
35	26.0	33.4	42.9	25.0	10.0	8.8	-30.8	-19.0	35.8	30.0	16.0
36	25.6	31.3	38.7	23.6	9.6	9.2	-27.4	-14.8	30.2	28.0	16.0
37	25.3	32.8	41.7	22.8	8.9	11.4	-31.4	-17.8	37.8	27.8	16.4
38	23.8	32.0	43.0	25.3	8.0	10.6	-32.2	-22.0	35.4	34.6	15.8
39	23.0	31.2	40.4	27.7	8.0	10.6	-31.4	-18.4	25.4	39.4	15.0
40	23.9	31.3	42.7	25.8	7.6	9.0	-31.1	-22.8	33.8	36.4	16.3
41	22.4	33.4	NA	26.1	8.6	9.0	-35.8	NA	NA	35.0	13.8
42	26.9	32.1	41.7	25.0	10.2	10.0	-27.1	-19.2	33.4	29.6	16.7

Day No.	PO4in (mgP/l)	PO4,1 (mgP/l)	PO4,2 (mgP/l)	PO4,3 (mgP/l)	PO4,4 (mgP/l)	PO4out (mgP/l)	Pupt,1 (mgP/l)	Pupt,2 (mgP/l)	Pupt,3 (mgP/l)	Pupt,4 (mgP/l)	Prem (mgP/l)
43	26.3	33.0	44.7	25.6	10.4	10.0	-29.3	-23.4	38.2	30.4	15.9
44	25.6	34.7	44.0	24.0	8.5	6.7	-35.3	-18.6	40.0	31.0	17.1
45	25.5	35.0	46.8	24.5	10.7	8.2	-33.8	-23.6	44.6	27.6	14.8
46	26.4	34.0	50.8	28.8	10.9	8.3	-30.7	-33.6	44.0	35.8	15.5
47	25.9	35.7	44.8	26.8	11.1	7.8	-34.4	-18.2	36.0	31.4	14.8
48	26.4	30.2	60.4	61.2	43.2	24.2	9.2	-60.4	-1.6	36.0	-16.8
49	26.5	23.7	28.5	27.2	15.5	9.8	-5.4	-9.6	2.6	23.4	11.0
50	26.4	30.9	36.0	23.7	13.0	9.8	-22.4	-10.2	24.6	21.4	13.4
51	26.2	30.0	36.0	24.1	13.2	10.0	-20.6	-12.0	23.8	21.8	13.0
52	25.2	33.0	35.9	25.4	13.3	10.9	-27.5	-5.8	21.0	24.2	11.9
53	26.4	29.5	36.8	24.3	13.0	12.0	-19.6	-14.6	25.0	22.6	13.4
54	25.5	34.0	41.1	20.0	11.7	11.3	-30.8	-14.2	42.2	16.6	13.8
55	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
56	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
57	25.7	22.7	28.3	21.7	15.3	14.7	-4.4	-11.2	13.2	12.8	10.4
58	25.3	25.6	30.1	21.4	13.9	13.2	-12.0	-9.0	17.4	15.0	11.4
59	25.5	23.6	27.9	19.7	12.4	12.9	-9.3	-8.6	16.4	14.6	13.1
60	20.1	26.5	34.9	24.2	22.5	20.3	-10.4	-16.8	21.4	3.4	-2.4
61	20.1	25.9	32.9	22.4	11.1	11.9	-20.6	-14.0	21.0	22.6	9.0
62	26.3	28.2	36.3	27.6	14.5	13.4	-15.6	-16.2	17.4	26.2	11.8
63	23.5	28.0	36.7	22.7	12.6	12.4	-19.9	-17.4	28.0	20.2	10.9
64	NA	NA	NA	NA	NA	NA		NA	NA	NA	NA

Table A.3a : Experimental results from Phoredox system (Rs=3d) - repeat

Day No.	CODin (mgCOD/l)	CODout (mgCOD/l)	Sbsi (mgCOD/l)	OUR,3 (mgO/l/h)	OUR,4 (mgO/l/h)	VSS,1 (mgVSS/l)	VSS,2 (mgVSS/l)	VSS,3 (mgVSS/l)	VSS,4 (mgVSS/l)	DSVI (ml/g)
1	505.4	66.7	NA	NA	NA	1752	1654	1716	1583	
2	488.7	55.2	NA	NA	NA	1663	1508	1510	1458	
3	498.8	68.3	NA	71	46	1553	1553	1588	1434	136
4	477.4	62.2	NA	76	60	1516	1516	1412	1369	
5	495.7	61.2	NA	NA	NA	1300	1388	1332	1243	202
6	499.8	NA	NA	NA	NA	1556	1201	1247	1125	
7	481.4	65.1	NA	NA	NA	1431	1170	1268	1191	
8	481.4	NA	NA	NA	NA	1211	1232	1255	1105	
9	479.4	71.4	NA	NA	NA	1223	1295	1224	1097	117
10	NA	NA	NA	NA	NA	NA	NA	NA	NA	
11	475.3	79.6	NA	NA	NA	1245	1197	1247	1093	119
12	478.4	77.5	NA	NA	NA	1219	1164	1131	1085	
13	467.3	60.1	NA	NA	NA	1175	1223	1212	1114	
14	529.4	75.3	NA	NA	NA	1127	1075	1135	976	
15	480.5	64.1	NA	NA	NA	1284	1219	1112	1017	135
16	470.3	63.1	NA	NA	NA	1304	1298	1291	1161	
17	467.3	77.4	NA	NA	NA	1192	1135	1133	1064	
18	372.6	69.2	NA	NA	NA	1011	985	972	896	
19	492.7	57.0	NA	NA	NA	1391	1249	1178	1122	249
20	504.9	52.9	NA	NA	NA	1306	1298	1293	1272	
21	511.0	81.4	NA	NA	NA	1259	1236	1229	1171	
22	477.4	70.4	NA	NA	NA	1115	1063	1088	1042	
23	539.6	70.4	NA	NA	NA	NA	NA	NA	NA	
24	484.5	59.2	NA	NA	NA	1409	1382	1362	1356	70
25	472.0	50.3	NA	NA	NA	1470	1433	1394	1388	
26	496.6	62.6	NA	NA	NA	1422	1430	1435	1418	98
27	NA	NA	NA	NA	NA	NA	NA	NA	NA	
28	509.9	59.5	NA	NA	NA	1242	1289	1298	2698	
29	486.3	45.1	NA	NA	NA	1201	1192	1186	1235	141
30	482.5	41.8	NA	49	39	1335	1300	1334	1292	
31	462.7	51.3	71	71	49	1291	1277	1274	1242	
32	474.0	51.3	81	NA	NA	1347	1316	1312	1300	136
33	520.2	62.6	121	59	44	1352	1343	1353	1310	
34	489.3	61.7	111	60	42	1318	1293	1349	1297	
35	NA	NA	143	NA	NA	NA	NA	NA	NA	
36	543.8	67.8	143	57	31	1327	1331	1280	1254	
37	463.6	51.4	NA	54	39	1165	1152	1139	1150	
38	489.3	41.1	117	54	40	1244	1266	1216	1200	116
39	NA	NA	NA	NA	NA	NA	NA	NA	NA	
40	494.5	65.8	121	58	40	1656	1611	1570	1574	143
41	471.2	56.1	118	NA	NA	1406	1354	1374	1332	
42	NA	NA	119	NA	NA	NA	NA	NA	NA	

Day No.	CODin (mgCOD/l)	CODout (mgCOD/l)	Sbsi (mgCOD/l)	OUR,3 (mgO/l/h)	OUR,4 (mgO/l/h)	VSS,1 (mgVSS/l)	VSS,2 (mgVSS/l)	VSS,3 (mgVSS/l)	VSS,4 (mgVSS/l)	DSVI (ml/g)
43	477.3	49.1	119	56	42	1169	1174	1195	1145	
44	490.6	56.1	132	55	41	1147	1080	1085	1036	86
45	390.7	53.0	121	60	36	1028	1020	1006	994	
46	463.1	63.2	165	45	35	846	808	808	733	
47	NA	NA	116	NA	NA	NA	NA	NA	NA	
48	NA	NA	NA	NA	NA	NA	NA	NA	NA	
49	NA	NA	113	NA	NA	NA	NA	NA	NA	
50	NA	NA	NA	NA	NA	NA	NA	NA	NA	
51	NA	NA	121	NA	NA	NA	NA	NA	NA	
52	426.4	59.2	123	41	28	621	395	812	656	120
53	430.4	49.0	125	56	45	686	627	650	558	
54	494.7	50.0	111	42	25	836	848	1703	1500	107
55	471.4	65.0	125	NA	NA	762	796	811	766	
56	499.9	71.1	121	44	41	988	868	808	829	
57	NA	NA	124	50	46	823	830	844	NA	150
58	NA	NA	116	NA	NA	NA	NA	NA	NA	
59	475.0	77.0	NA	43	34	1601	1578	1577	1483	
60	494.5	80.0	114	42	41	NA	NA	NA	NA	143

Table A.3b : Experimental results from Phoredox system (Rs=3d) - repeat

Day No.	TKNin (mgN/l)	TKNout (mgN/l)	NO3,1 (mgN/l)	NO3,2 (mgN/l)	NO3,3 (mgN/l)	NO3,4 (mgN/l)	NO3out (mgN/l)
1	54.3	23.7	0.4	0.8	4.3	8.4	6.7
2	57.4	24.9	0.3	0.4	3.7	7.4	6.3
3	NA	NA	0.4	0.1	NA	NA	NA
4	57.1	28.6	0.2	0.1	NA	NA	NA
5	59.4	26.5	0.1	0.2	4.1	6.1	4.3
6	37.2	13.0	0.2	0.1	2.7	3.8	3.0
7	35.3	11.6	0.1	0.1	1.5	2.7	2.7
8	36.1	15.3	0.1	0.1	1.2	2.5	2.0
9	39.5	20.0	0.1	0.1	1.0	1.6	1.5
10	NA	NA	NA	NA	NA	NA	NA
11	38.1	NA	0.2	0.1	1.2	1.3	1.6
12	40.0	NA	0.3	0.2	1.5	1.9	1.4
13	40.9	21.6	0.6	0.3	1.9	1.7	2.9
14	38.9	23.0	0.5	0.3	1.7	1.5	1.2
15	39.8	23.0	0.2	0.2	1.3	1.3	1.4
16	38.9	22.1	0.3	0.2	2.1	2.1	1.7
17	38.1	21.0	0.2	0.2	1.5	1.5	1.9
18	35.8	23.8	0.3	0.2	1.6	1.9	1.5
19	38.6	24.9	0.2	0.1	1.5	1.2	1.9
20	40.9	21.3	NA	NA	NA	NA	NA
21	40.9	22.4	NA	NA	NA	NA	NA
22	41.7	23.5	NA	NA	NA	NA	NA
23	42.6	19.6	NA	NA	NA	NA	NA
24	38.6	19.9	0.4	0.2	3.0	5.5	5.2
25	40.9	17.9	0.6	0.3	3.2	5.0	4.8
26	44.5	15.9	0.9	0.3	5.0	7.6	6.5
27	NA	NA	NA	NA	NA	NA	NA
28	44.5	24.6	0.3	0.4	4.6	2.5	5.0
29	45.9	24.6	0.3	0.5	4.6	5.8	5.2
30	46.5	26.0	0.5	0.3	4.4	6.0	7.2
31	43.4	26.3	0.4	0.5	5.7	7.1	6.8
32	44.0	24.9	0.4	0.5	5.7	8.1	6.0
33	43.1	19.9	0.3	0.5	6.9	6.9	8.8
34	44.2	33.9	0.3	0.5	6.2	7.1	7.2
35	NA	NA	NA	NA	NA	NA	NA
36	45.4	20.2	0.4	0.5	6.1	8.1	8.5
37	43.4	18.2	0.3	0.5	5.3	7.5	9.0
38	43.1	19.3	0.3	0.6	6.7	9.5	10.6
39	NA	NA	NA	NA	NA	NA	NA
40	34.7	16.2	0.3	0.6	9.0	13.0	10.1
41	45.4	17.6	0.3	0.6	9.3	10.1	10.3
42	NA	NA	NA	NA	NA	NA	NA

Day No.	TKNin (mgN/l)	TKNout (mgN/l)	NO3,1 (mgN/l)	NO3,2 (mgN/l)	NO3,3 (mgN/l)	NO3,4 (mgN/l)	NO3out (mgN/l)
43	45.1	16.0	0.3	0.5	6.9	9.4	8.0
44	44.5	17.6	0.3	0.5	6.9	9.7	9.5
45	28.6	3.1	0.3	0.5	7.5	10.9	10.1
46	35.3	6.7	0.2	0.4	5.3	6.2	5.5
47	NA	NA	NA	NA	NA	NA	NA
48	NA	NA	NA	NA	NA	NA	NA
49	NA	NA	NA	NA	NA	NA	NA
50	NA	NA	NA	NA	NA	NA	NA
51	NA	NA	NA	NA	NA	NA	NA
52	48.4	23.5	0.3	0.4	5.1	7.2	7.0
53	47.0	21.0	0.2	0.3	4.4	5.9	6.6
54	53.8	21.8	0.2	NA	NA	5.9	5.1
55	51.2	21.0	0.2	0.3	3.7	5.5	5.9
56	51.0	23.2	0.2	0.4	5.0	7.6	5.9
57	50.1	23.0	0.2	0.3	3.7	6.4	6.2
58	NA	NA	NA	NA	NA	NA	NA
59	50.4	24.1	0.3	0.5	9.5	14.1	10.8
60	52.6	21.3	0.4	0.3	9.2	15.0	12.9

Table A.3c Experimental results from Phoredox system (Rs=3d) - repeat

Day No.	PO4in (mgP/l)	PO4,1 (mgP/l)	PO4,2 (mgP/l)	PO4,3 (mgP/l)	PO4,4 (mgP/l)	PO4out (mgP/l)	Pupt,1 (mgP/l)	Pupt,2 (mgP/l)	Pupt,3 (mgP/l)	Pupt,4 (mgP/l)	Prem (mgP/l)
1	22.4	21.0	20.6	19.3	18.5	24.3	-1.1	0.8	2.6	1.6	3.9
2	22.4	20.8	20.4	19.2	18.7	23.7	-0.5	0.8	2.4	1.0	3.7
3	22.8	21.4	20.7	19.5	19.4	24.3	-0.6	1.4	2.4	0.2	3.4
4	22.5	21.1	19.4	18.1	17.0	17.7	-2.7	3.4	2.6	2.2	5.5
5	22.7	21.9	21.5	19.8	18.2	23.7	-2.9	0.8	3.4	3.2	4.5
6	20.8	21.1	19.7	18.5	17.5	NA	-3.9	2.8	2.4	2.0	3.3
7	22.3	20.4	19.2	18.0	17.8	24.8	-0.7	2.4	2.4	0.4	4.5
8	21.6	19.2	19.3	17.1	16.7	16.7	-0.1	-0.2	4.4	0.8	4.9
9	20.5	19.2	19.0	16.7	16.0	21.5	-1.9	0.4	4.6	1.4	4.5
10	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11	17.0	15.6	16.2	13.5	12.3	17.8	-1.9	-1.2	5.4	2.4	4.7
12	19.0	18.2	19.0	17.9	15.0	15.6	-2.4	-1.6	2.2	5.8	4.0
13	21.7	17.4	19.8	15.9	14.4	15.2	1.3	-4.8	7.8	3.0	7.3
14	22.6	17.3	19.8	16.2	15.1	16.2	3.1	-5.0	7.2	2.2	7.5
15	22.2	20.4	19.4	16.4	14.4	15.2	-4.2	2.0	6.0	4.0	7.8
16	22.2	18.1	20.4	18.3	14.8	15.1	0.8	-4.6	4.2	7.0	7.4
17	20.7	22.1	22.0	18.4	16.4	22.3	-7.1	0.2	7.2	4.0	4.3
18	21.0	20.8	22.2	18.6	16.5	20.3	-4.1	-2.8	7.2	4.2	4.5
19	20.2	20.4	22.5	18.1	15.4	20.4	-5.2	-4.2	8.8	5.4	4.8
20	24.0	23.4	25.7	19.9	16.7	21.6	-6.1	-4.6	11.6	6.4	7.3
21	24.1	24.1	24.9	19.9	16.7	17.5	-7.4	-1.6	10.0	6.4	7.4
22	23.6	22.9	25.1	19.9	16.9	17.2	-5.3	-4.4	10.4	6.0	6.7
23	24.2	22.1	25.0	20.8	17.0	16.9	-3.0	-5.8	8.4	7.6	7.2
24	22.1	25.0	26.9	19.7	14.8	14.2	-13.1	-3.8	14.4	9.8	7.3
25	22.0	24.2	26.0	18.8	13.8	14.2	-12.6	-3.6	14.4	10.0	8.2
26	23.0	25.9	27.4	19.5	14.1	14.1	-14.7	-3.0	15.8	10.8	8.9
27	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
28	23.8	30.4	31.9	22.4	24.3	22.6	-12.7	-3.0	19.0	-3.8	-0.5
29	23.6	25.5	27.7	17.4	13.0	14.2	-14.4	-4.4	20.6	8.8	10.6
30	23.4	26.2	29.2	19.9	13.5	NA	-15.5	-6.0	18.6	12.8	9.9
31	23.7	27.0	28.9	19.4	13.8	19.2	-16.5	-3.8	19.0	11.2	9.9
32	23.8	27.6	29.7	20.2	14.1	19.5	-17.3	-4.2	19.0	12.2	9.7
33	24.2	31.4	33.5	20.5	13.5	19.0	-25.1	-4.2	26.0	14.0	10.7
34	23.7	28.0	30.3	19.6	12.4	14.5	-19.9	-4.6	21.4	14.4	11.3
35	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
36	24.0	29.8	33.1	19.6	11.8	12.6	-23.8	-6.6	27.0	15.6	12.2
37	23.9	30.4	32.7	21.3	14.3	18.2	-22.6	-4.6	22.8	14.0	9.6
38	23.3	29.7	33.0	19.0	11.3	15.6	-24.8	-6.6	28.0	15.4	12.0
39	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
40	24.3	32.2	34.3	18.9	10.2	16.7	-29.9	-4.2	30.8	17.4	14.1
41	24.2	32.4	34.4	19.9	11.8	18.2	-28.8	-4.0	29.0	16.2	12.4
42	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Day No.	PO4in (mgP/l)	PO4,1 (mgP/l)	PO4,2 (mgP/l)	PO4,3 (mgP/l)	PO4,4 (mgP/l)	PO4out (mgP/l)	Pupt,1 (mgP/l)	Pupt,2 (mgP/l)	Pupt,3 (mgP/l)	Pupt,4 (mgP/l)	Prem (mgP/l)
43	24.2	31.2	33.6	21.2	12.3	16.6	-25.9	-4.8	24.8	17.8	11.9
44	25.3	32.2	36.1	23.4	13.8	20.5	-25.3	-7.8	25.4	19.2	11.5
45	24.6	30.4	33.0	21.1	15.9	21.8	-20.3	-5.2	23.8	10.4	8.7
46	23.5	27.7	30.6	21.6	15.4	19.4	-16.5	-5.8	18.0	12.4	8.1
47	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
48	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
49	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
50	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
51	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
52	23.7	24.7	26.5	21.6	15.9	20.0	-9.8	-3.6	9.8	11.4	7.8
53	22.3	24.2	26.1	19.5	15.2	19.4	-10.9	-3.8	13.2	8.6	7.1
54	23.0	NA	NA	24.1	16.7	19.9	NA	NA	NA	14.8	6.3
55	23.0	30.2	32.0	24.0	18.1	19.7	-19.3	-3.6	16.0	11.8	4.9
56	22.6	24.8	27.1	19.6	14.5	19.0	-12.5	-4.6	15.0	10.2	8.1
57	22.7	29.7	30.0	20.2	14.4	21.0	-22.3	-0.6	19.6	11.6	8.3
58	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
59	23.8	28.1	30.7	18.4	10.5	13.3	-21.9	-5.2	24.6	15.8	13.3
60	24.6	30.0	31.3	19.1	12.1	16.4	-23.3	-2.6	24.4	14.0	12.5

Table A.4b : Experimental results from Split-feed system

Day No.	TKNin (mgN/l)	TKNout (mgN/l)	NO3,1 (mgN/l)	NO3,2 (mgN/l)	NO3,3 (mgN/l)	NO3,4 (mgN/l)	NO3out (mgN/l)
1	39.5	11.8	0.1	0.3	3.8	5.5	NA
2	41.4	11.8	0.1	0.3	3.6	4.2	NA
3	39.5	12.3	0.1	0.2	3.2	6.4	NA
4	41.7	11.5	0.1	0.3	4.9	6.0	2.6
5	40.3	12.9	0.1	0.3	4.4	6.8	2.6
6	37.5	10.9	0.1	0.2	5.0	10.7	3.7
7	36.7	11.5	0.1	0.3	5.1	10.5	4.2
8	NA	13.2	0.1	0.2	2.9	5.3	1.3
9	40.0	12.6	0.1	0.2	3.9	7.0	1.4
10	40.9	17.1	0.1	0.2	4.1	7.3	1.4
11	38.9	10.1	0.1	0.1	0.9	3.0	1.2
12	32.2	8.1	0.3	0.5	6.6	7.7	5.1
13	32.5	4.5	0.2	0.5	7.7	8.3	7.9
14	34.2	6.9	0.3	0.5	6.6	7.6	7.1
15	35.6	6.9	0.3	0.5	5.7	7.5	5.3
16	36.1	6.3	0.3	0.5	7.5	11.7	6.8
17	33.9	4.6	0.3	0.6	8.0	9.3	8.4
18	31.1	4.8	0.2	0.6	7.9	9.6	5.9
19	46.2	11.1	0.3	0.6	6.9	6.5	5.6
20	43.4	10.1	0.2	0.5	5.9	6.9	5.9

Table A.4c : Experimental results from Split-feed system

Day No.	PO4in (mgP/l)	PO4,1 (mgP/l)	PO4,2 (mgP/l)	PO4,3 (mgP/l)	PO4,4 (mgP/l)	PO4out (mgP/l)	Pupt,1 (mgP/l)	Pupt,2 (mgP/l)	Pupt,3 (mgP/l)	Pupt,4 (mgP/l)	Prem (mgP/l)
1	24.4	31.0	31.9	21.0	14.1	18.9	-21.3	-1.5	19.3	13.8	10.3
2	24.3	28.0	30.2	20.1	14.7	20.8	-15.8	-3.7	18.2	10.8	9.6
3	23.6	31.6	31.6	21.3	16.7	19.1	-20.2	0.0	17.9	9.2	6.9
4	24.6	30.1	31.5	20.6	15.3	19.4	-18.5	-2.3	19.5	10.6	9.3
5	24.2	29.6	30.3	20.0	13.3	19.7	-19.9	-1.2	18.6	13.4	10.9
6	24.1	31.5	32.7	22.5	16.3	21.0	-20.1	-2.0	17.5	12.4	7.8
7	24.0	32.2	33.1	21.0	15.9	20.7	-21.8	-1.5	21.2	10.2	8.1
8	23.5	29.4	31.5	21.0	17.3	21.4	-16.0	-3.5	18.3	7.4	6.2
9	24.8	27.7	28.4	18.9	14.2	18.2	-15.4	-1.2	17.8	9.4	10.6
10	23.2	29.0	30.6	21.0	15.4	21.0	-17.5	-2.7	16.7	11.2	7.8
11	24.4	33.1	33.2	21.2	14.2	20.5	-24.7	-0.2	21.1	14.0	10.2
12	22.4	23.2	24.5	15.2	11.6	16.8	-12.1	-2.2	17.9	7.2	10.8
13	21.8	24.9	26.8	17.2	12.9	17.6	-14.1	-3.2	17.5	8.6	8.9
14	22.3	28.8	31.7	19.7	16.1	19.7	-17.0	-4.8	20.9	7.2	6.2
15	22.8	27.7	28.4	19.9	16.2	18.4	-14.8	-1.2	15.1	7.4	6.6
16	22.8	29.0	27.6	18.4	16.2	17.3	-16.9	2.3	16.8	4.4	6.6
17	23.4	25.6	27.2	18.4	15.4	18.1	-11.7	-2.7	16.3	6.0	8.0
18	21.6	23.2	27.2	19.5	16.6	15.4	-7.7	-6.7	13.5	5.8	5.0
19	23.2	29.0	31.3	22.4	17.6	19.5	-15.3	-3.8	15.1	9.6	5.6
20	22.4	27.2	28.6	26.4	16.5	17.1	-13.9	-2.3	2.3	19.8	5.9

Table A.5a : Experimental results from Modified Bardenpho system

Day No.	CODin (mgCOD/l)	CODout (mgCOD/l)	Sbsi (mgCOD/l)	OUR,3 (mgO/l/h)	OUR,4 (mgO/l/h)	VSS,1 (mgVSS/l)	VSS,2 (mgVSS/l)	VSS,3 (mgVSS/l)	VSS,4 (mgVSS/l)	DSVI (ml/g)
1	496.7	36.8	75	63	45	2049	1894	1921	1876	160
2	495.7	40.9	75	64	40	2709	1636	1563	1598	
3	489.9	40.4	80	71	39	1829	1790	2191	2172	
4	494.9	36.4	93	116	41	1926	1804	1825	1784	
5	487.8	45.5	72	65	35	2148	2143	2192	2348	122
6	476.7	46.5	66	69	43	2200	2078	2014	2024	
7	471.7	52.5	63	67	45	2086	1860	1772	1759	
8	479.8	43.4	77	65	41	1934	1789	1770	1815	
9	492.8	55.7	51	62	34	2253	2080	2026	2060	
10	462.5	64.8	107	72	45	2377	2187	2135	2055	
11	492.8	59.7	102	77	57	2055	1930	1944	1901	
12	469.6	58.7	102	73	50	2363	2119	2161	2262	125
13	495.9	45.6	NA						NA	
14	479.7	52.6	105	60	42	1575	1553	1507	1574	
15	504.9	41.5	113	73	55	1503	1416	1383	1480	
16	461.0	42.0	100	67	47	1831	1710	1704	1720	
17	456.0	44.0	110	61	41	1890	1699	1623	1701	
18	458.0	65.0	97	65	45	2149	1807	1771	1739	
19	561.0	57.0	102	68	50	1990	1889	1788	1798	201
20	495.6	49.2	83	81	72	1882	1798	1744	1758	
21	501.8	50.2	94	87	82	2020	1939	1839	1930	
22	505.9	42.0	NA	86	60	2041	2182	2095	2251	
23	513.0	42.0	NA	82	62				NA	
24										
25										239
26	476.2	37.9	106	64	44	2368	2414	2338	2357	174
27	483.3	34.8	87	69	43	2403	2359	2291	2240	185
28	493.6	34.8	66	73	54	2234	2169	2083	2144	177
29	496.6	42.0	78	72	40	2203	2168	2045	2116	
30	524.3	38.9	66						NA	180
31	503.8	42.0	59	88	78	2185	2159	2176	2057	
32	497.7	41.0	72			2298	2206	2034	2096	168
33	492.5	39.9	74	84	74	2119	2014	1940	1923	
34	533.5	42.0	101	83	38	2218	2161	1980	2098	166
35	480.3	41.0	67	64	42	2189	2230	2308	2532	
36	477.9	38.1	80	78	53	2240	2149	2047	2099	183
37	496.5	36.1	70	78	31	2347	2288	2251	2218	
38	480.0	49.4	86	70	45	2515	2220	2172	2164	
39	457.3	39.1	63	60	43	2356	2214	2187	2167	157
40	480.0	48.4	NA	57	42	2198	2249	2205	2225	

Day No.	CODin (mgCOD/l)	CODout (mgCOD/l)	Sbsi (mgCOD/l)	OUR,3 (mgO/l/h)	OUR,4 (mgO/l/h)	VSS,1 (mgVSS/l)	VSS,2 (mgVSS/l)	VSS,3 (mgVSS/l)	VSS,4 (mgVSS/l)	DSVI (ml/g)
41	499.7	46.1	89	79	32	2151	2046	2107	2203	162
42	584.7	25.6	99	74	50	2164	2099	2024	2046	
43	626.7	32.8	139	77	37	2310	2247	2192	2252	126
44	480.3	37.9	66	71	36	2155	2158	2086	2132	
45	471.0	29.7	85	71	31	2384	2376	2367	2261	
46	498.7	28.7	97			2155	2260	2244	2313	104
47	470.0	24.6	78	67	40	2639	2510	2497	2509	
48	466.9	31.7	93	69	39	2438	2346	2330	2312	106
49	451.4	27.7	70	73	41	2454	2178	2370	2306	
50	468.9	27.7	64	73	41	2298	2183	2305	2136	96
51	506.8	34.9	85	66	43	2588	2160	2300	2200	
52	533.5	30.8				2594	2552	2562	2554	
53	553.0	35.9		80	48	2497	2307	2400	2435	101
54	491.5	38.0		82	52	2776	2083	2597	2501	
55	538.6	41.0	93	80	48	2348	2012	2105	2104	100
56	534.5	34.8	95	79	46	2805	2598	2536	2551	
				79	59					105
57				83	60	2300	2059	2026	2026	
58	518.2	35.8	119	82	61	2699	2616	2653	2497	97
59	511.0	22.5	111	84	55	2409	2591	2506	2541	
60	480.3	41.8	94	73	32	2769	2685	2689	2718	120
61	524.3	40.9	101	69	39	2594	2488	2487	2497	
62	499.8	34.7	72	80	49	2649	2455	2578	2497	
63	500.8	38.8	95	74	47	2639	2593	2606	2581	100
64	476.0	45.2	126	82	48	2673	2560	2506	2533	
65	520.2	34.6	50	81	48	2593	2488	2464	2509	80
66	504.7	42.1	72	90	61					
67	500.6	39.1	70	83	52	2492	2439	2422	2460	101
68	508.9	21.8	69	80	50	2733	2385	2400	2488	
69	491.4	37.0	99	82	44	2320	2302	2363	2288	
70	491.4	29.8	95	83	52	2180	1985	2113	2035	
71	496.6	30.7	106	87	76					

Table A.5b : Experimental results from Modified Bardenpho system

Day No.	TKNin (mgN/l)	TKNout (mgN/l)	NO3,1 (mgN/l)	NO3,2 (mgN/l)	NO3,3 (mgN/l)	NO3,4 (mgN/l)	NO3out (mgN/l)
1	34.2	1.7	.0	0.3	2.0	2.1	1.8
2	33.3	2.0	.0	0.4	2.0	3.2	2.6
3	32.2	2.2	0.3	0.3	8.6	7.0	6.0
4	32.8	2.4	0.2	0.3	7.8	8.6	5.9
5	32.8	2.2	0.2	0.2	8.5	6.3	7.6
6	32.5	3.1	0.2	0.2	6.5	7.0	6.9
7	32.8	2.0	0.0	0.1	5.2	4.7	6.7
8	NA	2.9					
9	32.8	2.9	0.1	0.3	5.9	6.8	5.9
10	48.2	4.9	0.1	5.7	13.3	14.9	11.3
11	49.0	5.3	0.2	5.2	14.6	16.3	14.3
12	48.7	5.7	0.1	5.7	12.7	15.0	14.3
13							
14	50.1	10.1	0.1	6.7	15.6	17.7	17.9
15	51.0	2.7	1.9	9.7	12.4	12.6	13.1
16	50.7	4.3	0.1	7.2	13.1	12.5	13.8
17	50.7	3.5	0.1	10.0	13.4	14.4	14.5
18	49.3	5.5	0.1	6.2	14.6	18.5	12.8
19	54.3	4.9	0.1	10.5	12.0	12.7	14.0
20	50.1	5.2	0.1	9.3	14.9	15.9	14.0
21	52.1	3.4					
22	52.1	2.1					
23	48.2	3.0					
24							
25							
26	47.6	2.7	0.2	8.7	11.6	13.9	9.9
27	47.3	1.7	0.1	9.0	10.3	13.4	11.2
28	51.0	2.0	0.1	8.8	13.4	13.9	13.9
29	50.4	2.7	0.2	9.5	14.8	16.9	14.1
30							
31	52.9	3.5	0.3	8.6	12.4	13.7	12.9
32	52.1	3.8	0.1	7.4	10.3	12.1	10.4
33	52.9	5.7	0.1	7.1	11.5	12.4	12.1
34	53.2	3.4	0.1	7.3	11.7	12.9	12.3
35	53.2	4.5	0.1	9.6	13.3	13.3	13.6
36	53.5	0.7	0.1	8.3	11.2	12.5	12.6
37	52.9	2.9	0.1	9.6	13.3	13.6	12.5
38	53.5	4.5	0.1	8.9	12.5	13.5	13.6
39	52.6	4.8	0.1	9.9	12.7	14.7	15.2
40	53.2	4.2	0.1	7.9	11.6	12.3	11.8

Day No.	TKNin (mgN/l)	TKNout (mgN/l)	NO3,1 (mgN/l)	NO3,2 (mgN/l)	NO3,3 (mgN/l)	NO3,4 (mgN/l)	NO3out (mgN/l)
41	45.1	5.3	1.2	13.6	18.3	19.4	16.3
42	50.1		0.1	7.2	10.4	10.3	10.4
43	49.8	4.1	0.1	7.6	12.5	14.1	18.5
44	49.0	2.7	0.1	9.4	11.7	12.4	15.8
45	45.1	3.9	0.1	8.3	11.7	12.3	12.3
46	44.2	2.7	0.1	10.0	9.3	11.7	15.9
47	43.7	2.9	0.1	9.8	12.3	13.6	16.5
48	37.8	3.4	0.1	4.4	6.9	5.4	5.7
49	37.5	3.6	0.1	5.3	5.4	5.8	6.1
50	37.5	1.5	0.1	4.0	5.4	5.7	5.4
51	37.8	2.0	0.1	4.0	5.4	5.1	5.4
52	42.0	2.2	0.1	1.7	4.1	4.5	5.6
53	42.6	3.2	0.1	2.9	4.1	5.0	4.9
54	26.6	2.7	0.1	3.0	3.9	4.4	4.7
55	45.9	3.1	0.1	3.7	5.0	5.8	5.9
56	44.2	3.2	0.1	2.6	5.0	4.0	5.0
57	44.5	4.1	0.1	10.2	11.8	16.9	16.4
58	45.1	3.4	0.1	8.7	12.4	16.0	16.2
59	44.5	3.5	.0	10.5	14.4	15.2	16.0
60	43.1	6.3	.0	12.4	13.5	17.3	16.2
61	42.6	2.8	.0	8.5	16.2	16.7	17.1
62	45.4	3.2	.0	7.9	12.0	14.0	12.0
63		2.9	.0	2.7	6.3	7.8	8.3
64	44.0	4.1	.0	3.9	7.8	10.5	11.0
65	44.5	1.3	.0	3.1	7.9	9.6	10.1
66	55.7	3.2					
67	56.6	4.5	0.1		8.7	9.8	8.3
68	58.0	5.2	0.1	2.3	6.0	7.3	5.6
69	56.8	5.5	0.0	3.0	1.2	0.7	4.0
70			0.2	1.5	6.6	5.4	7.0
71		5.3	.0	4.9	8.0	7.7	8.4

Table A.5c : Experimental results from Modified Bardenpho system

Day No.	PO4in (mgP/l)	PO4,1 (mgP/l)	PO4,2 (mgP/l)	PO4,3 (mgP/l)	PO4,4 (mgP/l)	PO4out (mgP/l)	Pupt,1 (mgP/l)	Pupt,2 (mgP/l)	Pupt,3 (mgP/l)	Pupt,4 (mgP/l)	Prem (mgP/l)
1	25.5	33.3	24.5	12.7	7.0	5.8	-34.1	-17.4	47.2	22.8	18.5
2	23.5	31.5	22.2	14.2	7.3	7.1	-32.2	-11.2	32.0	27.6	16.2
3	20.9	32.4	22.2	13.4	7.7	5.7	-36.2	-8.6	35.2	22.8	13.2
4	20.0	35.1	24.2	15.6	9.2	7.0	-41.0	-8.2	34.4	25.6	10.8
5	20.4	35.4	26.3	15.2	8.9	7.7	-41.5	-16.6	44.4	25.2	11.5
6	20.9	33.5	22.5	14.9	8.5	6.8	-37.6	-6.0	30.4	25.6	12.4
7	21.2	37.4	25.6	16.2	10.0	8.1	-43.6	-7.6	37.6	24.8	11.2
8	20.0	33.2	20.2	12.5	8.6	7.4	-37.8	2.8	30.8	15.6	11.4
9	20.6	32.6	23.8	16.3	10.3	8.8	-34.3	-36.4	45.0	36.0	10.3
10	20.4	28.5	20.9	19.2	14.6	12.1	-22.0	-10.0	10.2	27.6	5.8
11	20.3	29.4	23.0	24.8	19.2	17.3	-19.3	-2.4	-10.8	33.6	1.1
12	21.3	18.6	22.1	18.6	15.7	13.4	-0.2	-32.6	21.0	17.4	5.6
13							NA	NA	NA	NA	NA
14	22.1	24.0	20.0	19.7	20.0	17.6	-5.9	8.0	1.8	-1.8	2.1
15	23.0	23.6	20.4	19.8	18.8	19.5	-5.4	.0	3.6	6.0	4.2
16	20.5	22.7	28.0	19.0	17.9	17.1	-7.0	-51.0	54.0	6.6	2.6
17	25.0	24.0	21.5	19.0	17.1	17.5	-5.9	-12.6	15.0	11.4	7.9
18	25.3	24.0	21.4	18.9	17.3	18.4	-5.4	-11.2	15.0	9.6	8.0
19	23.8	24.0	20.1	18.9	16.5	16.0	-7.7	-6.6	7.2	14.4	7.3
20	26.7	25.8	20.1	21.0	20.1	19.6	-4.8	11.4	-5.4	5.4	6.6
21	26.2	25.5	21.1	19.9	19.0	18.5	-5.8	0.4	7.2	5.4	7.2
22	25.2	26.0	21.0	19.0	17.6	17.7	-9.2	-3.6	12.0	8.4	7.6
23	26.2	28.2	24.7	22.8	18.7	17.1	-11.5	-17.0	11.4	24.6	7.5
24							NA	NA	NA	NA	NA
25							NA	NA	NA	NA	NA
							NA	NA	NA	NA	NA
26	25.4	23.2	19.3	18.4	18.0	17.5	-3.0	2.6	5.4	2.4	7.4
27	24.8	24.8	17.6	16.3	15.0	11.8	-9.8	4.0	7.8	7.8	9.8
28	25.2	26.4	19.3	18.6	16.9	15.4	-10.7	4.6	4.2	10.2	8.3
29	25.0	22.9	19.4	20.2	17.1	18.6	-3.7	-2.2	-4.8	18.6	7.9
30							NA	NA	NA	NA	NA
31	25.2	21.6	15.7	18.5	17.9	17.6	-0.1	20.6	-16.8	3.6	7.3
32	25.0	21.6	18.6	18.8	17.4	14.1	-0.8	1.2	-1.2	8.4	7.6
33	25.4	22.2	19.6	19.6	18.6	17.9	-0.4	1.2	0.0	6.0	6.8
34	25.9	22.8	22.6	20.7	18.0	18.0	-1.7	-18.0	11.4	16.2	7.9
35	25.3	22.6	19.2	18.8	18.0	17.7	-1.9	2.0	2.4	4.8	7.3
36	25.2	23.2	19.2	18.6	17.4	17.4	-3.8	0.8	3.6	7.2	7.8
37	25.6	22.3	19.1	19.1	18.0	17.6	-1.0	2.0	0.0	6.6	7.6
38	25.9	25.0	20.4	19.3	18.1	17.8	-6.0	.0	6.6	7.2	7.8
39	25.4	23.0	19.2	18.8	17.9	18.1	-2.7	2.4	2.4	5.4	7.5
40	26.1	23.3	21.0	20.1	19.0	19.0	-1.5	-3.4	5.4	6.6	7.1

Day No.	PO4in (mgP/l)	PO4,1 (mgP/l)	PO4,2 (mgP/l)	PO4,3 (mgP/l)	PO4,4 (mgP/l)	PO4out (mgP/l)	Pupt,1 (mgP/l)	Pupt,2 (mgP/l)	Pupt,3 (mgP/l)	Pupt,4 (mgP/l)	Prem (mgP/l)
41	23.3	22.0	20.8	20.4	20.0	19.3	-0.7	-0.8	2.4	2.4	3.3
42	29.2	22.2	21.4	20.1	19.0	19.3	3.8	-8.0	7.8	6.6	10.2
43	27.8	29.8	23.1	21.9	20.8	20.7	-11.0	4.2	7.2	6.6	7.0
44	27.6	25.6	20.5	19.0	16.9	19.6	-6.7	-4.2	9.0	12.6	10.7
45	28.4	25.5	18.8	17.0	16.0	17.0	-6.6	2.2	10.8	6.0	12.4
46	27.4	24.8	21.0	19.1	17.1	15.2	-5.1	-8.0	11.4	12.0	10.3
47	26.7	25.7	20.5	18.5	17.9	18.3	-6.8	.0	12.0	3.6	8.8
48	20.4	21.0	16.8	16.2	15.6	16.0	-6.0	3.6	3.6	3.6	4.8
49	24.7	25.3	26.3	23.6	21.6	18.4	-4.3	-20.8	16.2	12.0	3.1
50	23.0	25.8	19.0	17.6	18.0	22.2	-10.6	9.6	8.4	-2.4	5.0
51	24.3	23.2	16.6	16.4	14.0	16.9	-8.1	2.8	1.2	14.4	10.3
52	25.2	30.4	20.4	16.7	14.3	15.2	-21.3	-4.4	22.2	14.4	10.9
53	21.2	28.0	17.6	14.2	11.8	13.0	-23.0	-2.4	20.4	14.4	9.4
54	21.8	29.0	18.0	13.7	10,8	12.6	-25.4	-6.8	25.8	17.4	11.0
55	22.9	29.4	18.9	15.5	13.7	14.0	-22.2	0.2	20.4	10.8	9.2
56	24.8	33.8	19.7	13.0	13.7	15.8	-29.1	4.2	40.2	-4.2	11.1
							NA	NA	NA	NA	NA
57							NA	NA	NA	NA	NA
58	24.3	29.3	20.4	14.1	12.9	11.1	-21.4	-12.2	37.8	7.2	11.4
59	23.2	41.2	23.7	19.2	14.2	13.2	-45.0	-3.0	27.0	30.0	9.0
60							NA	NA	NA	NA	NA
61	23.8	33.4	19.5	14.0	10.7	9.9	-32.3	-7.4	33.0	19.8	13.1
62	23.8	29.2	17.5	12.7	10.0	9.4	-24.6	-6.6	28.8	16.2	13.8
63	23.5	27.4	20.0	14.7	12.0	12.0	-19.3	-17.2	31.8	16.2	11.5
64	24.6	31.0	19.8	19.2	13.4	12.9	-24.0	-3.2	3.6	34.8	11.2
65	26.0	37.9	23.4	16.8	13.2	14.0	-36.6	-11.8	39.6	21.6	12.8
66	25.6	24.8	19.0	17.2	15.4	15.7	-8.6	-2.8	10.8	10.8	10.2
67	25.8	30.4	20.6	19.3	17.8	16.6	-17.2	8.4	7.8	9.0	8.0
68	20.8	23.0	20.7	18.5	18.5	17.1	-6.7	-4.2	13.2	0.0	2.3
69	28.1	25.6	22.2	20.0	18.7	21.1	-4.4	-7.2	13.2	7.8	9.4
70	29.7	27.1	22.4	20.8	19.4	24.1	-5.1	-2.6	9.6	8.4	10.3
71	25.4	23.3	20.6	20.4	19.6	19.1	-1.6	1.4	1.2	4.8	5.8

Table A.6a : Experimental results from U.C.T system

Day No.	CODin (mgCOD/l)	CODout (mgCOD/l)	Sbsi (mgCOD/l)	OUR,3 (mgO/l/h)	OUR,4 (mgO/l/h)	VSS,1 (mgVSS/l)	VSS,2 (mgVSS/l)	VSS,3 (mgVSS/l)	VSS,4 (mgVSS/l)	DSVI (ml/g)
1	495.8	33.6	117	108	65	1119	2091	2133	2110	110
2	498.8	37.7	115	106	66	1148	1949	1975	1944	
3	497.8	39.7	109	105	65	1233	2178	2336	2124	
4	500.9	38.6	97	104	71	1431	3011	2901	2623	108
5	450.1	36.6	101	108	60	1085	1811	1803	1754	
6	517.1	32.5	107	106	62	NA	NA	NA	NA	115
7	528.3	38.6	103	NA	NA	NA	NA	NA	NA	
8	518.1	45.1	80	NA	NA	NA	NA	NA	NA	
9	500.7	38.8	75	NA	NA	2336	2231	1143	2066	
10	516.1	40.0	82	NA	NA	1093	1773	1951	1951	
11	516.1	40.0	79	73	52	1171	2250	2299	2234	
12	499.7	46.2	83	85	41	1250	2843	2443	2490	116
13	510.9	39.0	107	91	49	1349	2191	2388	2286	
14	518.2	45.9	119	83	42	NA	2207	2204	2069	
15	520.2	42.8	88	76	34	1293	2141	2171	2093	128
16	513.0	42.1	76	NA	NA	1153	1879	2176	2046	
17	514.1	41.8	95	75	39	1425	NA	2565	NA	
18	498.6	36.9	84	68	34	1348	2347	2501	2482	121
19	486.3	32.8	92	55	26	1427	2495	2599	2494	
20	491.5	41.1	86	80	26	1311	2347	2388	2220	141
21	478.1	32.8	91	86	43	1332	2476	2547	2561	
22	480.2	30.8	101	NA	NA	1369	2645	2654	2764	174
23	488.6	36.7	NA	NA	NA	1323	2603	2621	2554	
24	421.3	36.7	NA	95	46	1393	2366	2377	2417	
25	422.3	34.7	82	76	40	1380	2450	2495	2419	197
26	433.5	37.7	69	68	31	1154	2102	2150	2129	
27	510.0	35.7	91	66	45	1000	2075	2072	2017	178
28	503.9	42.7	105	80	58	1146	2254	2233	2182	
29	519.2	42.7	NA	87	51	1258	2654	2350	2124	160
30	514.1	30.5	87	79	47	1093	2143	2230	2182	
31	NA	NA	102	NA	NA	NA	NA	NA	NA	
32	555.8	45.7	94	85	64	1374	2620	2690	2842	162
33	533.5	26.7	85	81	48	1249	2253	2219	2281	
34	512.0	32.9	91	87	72	1089	1942	2285	2157	176
35	534.6	52.4	96	87	52	1049	1982	2188	2323	
36	458.5	41.1	69	68	47	1176	2163	2151	2222	170
37	514.0	31.9	NA	75	48	1205	2223	2343	NA	
38	505.8	39.1	NA	NA	NA	1284	2237	2399	2316	
39	480.1	30.8	95	80	48	1280	2242	2317	2208	172
40	503.7	41.1	85	73	48	1228	2041	2073	2072	
41	NA	NA	NA	74	47	1186	2056	2114	2087	174
42	NA	NA	NA	NA	NA	NA	NA	NA	NA	

Day No.	CODin (mgCOD/l)	CODout (mgCOD/l)	Sbsi (mgCOD/l)	OUR,3 (mgO/l/h)	OUR,4 (mgO/l/h)	VSS,1 (mgVSS/l)	VSS,2 (mgVSS/l)	VSS,3 (mgVSS/l)	VSS,4 (mgVSS/l)	DSVI (ml/g)
43	507.9	34.8	NA	NA	NA	NA	NA	NA	NA	166
44	525.3	39.9	74	74	44	1177	2116	1143	2265	
45	510.0	36.9	100	77	42	1731	3068	3382	3409	
46	515.1	38.9	93	79	44	1326	NA	2427	2394	143
47	527.4	28.7	NA	88	47	1375	2559	2655	2520	
48	528.4	47.5	NA	78	42	1369	2678	2658	2686	156
49	513.9	47.5	NA	88	56	1641	3226	3092	2948	
50	510.8	40.2	NA			1396	2690	2484	2501	155
50	517.0	39.2	NA			1399	2417	2592	2594	
51	513.9	57.8	NA			1577	2917	2909	2882	
52	489.2	48.5	NA	82	46	1458	2542	2677	2696	128
53	499.5	53.7	NA	84	43	1494	3027	2928	2714	
54	507.7	43.3	NA	82	44	1351	2499	2663	2610	115
55	516.0	37.2	NA	NA	NA	1297	2437	2574	2452	
56	529.4	41.2	NA	76	35	1408	2509	2659	2615	112
57	525.3	34.0	NA	NA	NA	1324	2856	2476	2459	
58	526.3	52.5	NA	NA	NA	1260	2352	2517	2377	
59	510.9	65.9	NA	77	48	1395	2590	2758	2643	104
60	533.5	45.3	NA	80	45	NA	NA	NA	NA	

Table A.6b : Experimental results from U.C.T system

Day No.	TKNin (mgN/l)	TKNout (mgN/l)	NO3,1 (mgN/l)	NO3,2 (mgN/l)	NO3,3 (mgN/l)	NO3,4 (mgN/l)	NO3out (mgN/l)
1	59.9	2.8	0.9	6.3	15.4	16.0	15.5
2	59.4	3.2	1.4	7.5	15.5	23.0	17.9
3	60.2	3.6	1.8	8.5	19.0	18.1	20.7
4	60.8	3.5	0.8	7.2	15.5	20.0	17.9
5	60.5	3.6	0.6	6.5	15.3	20.0	24.0
6	50.4	3.4	0.7	3.9	10.3	12.0	15.4
7	NA	NA	NA	NA	NA	NA	NA
8	NA	NA	NA	NA	NA	NA	NA
9	44.0	4.9	0.7	2.4	7.5	9.7	11.7
10	47.6	4.5	0.9	3.6	7.2	10.4	11.9
11	44.0	4.3	1.5	3.2	8.9	11.1	12.2
12	44.0	4.8	0.0	2.7	9.2	10.5	8.2
13	45.6	2.7	0.0	3.2	8.8	9.7	9.7
14	46.5	3.4	0.6	4.4	10.0	13.2	10.9
15	46.5	4.2	0.0	3.2	8.5	10.2	11.6
16	43.4	3.4	0.6	3.1	9.4	10.2	10.9
17	43.4	2.4	0.4	3.2	9.6	10.7	10.5
18	43.7	2.9	0.9	4.0	9.1	9.6	10.8
19	44.2	3.9	2.9	2.9	9.0	10.4	11.9
20	44.0	3.1	1.6	4.0	11.6	12.3	12.3
21	45.4	6.2	2.3	4.0	9.1	10.0	11.2
22	43.4	3.1	1.6	2.7	8.5	12.3	10.9
23	44.5	4.3	3.0	3.8	9.8	10.7	11.6
24	40.6	3.8	1.7	4.8	9.2	11.9	12.1
25	40.6	3.3	1.2	3.4	10.2	11.1	12.3
26	46.5	5.7	1.1	5.7	12.7	13.5	13.0
27	47.3	2.7	1.2	1.6	6.7	9.8	13.8
28	47.3	3.4	1.9	3.4	10.0	12.2	12.2
29	48.7	3.4	1.6	2.2	7.3	10.3	10.6
30	47.9	4.2	1.6	6.3	12.9	11.1	19.6
31	NA	NA	NA	NA	NA	NA	NA
32	48.2	3.9	0.7	0.9	6.0	9.5	12.5
33	47.9	3.9	0.3	4.3	11.6	11.6	6.8
34	48.7	3.9	0.3	1.7	7.4	11.5	6.6
35	48.2	3.9	0.6	0.7	7.4	9.8	3.8
36	47.6	3.6	0.3	0.6	9.2	9.4	5.3
37	47.6	3.8	4.2	1.8	13.0	15.3	5.3
38	48.7	3.9	0.9	1.5	15.3	16.1	6.2
39	45.4	3.6	0.7	1.3	12.8	16.3	8.8
40	49.4	3.5	0.7	0.8	5.2	12.5	9.1
41	47.9	4.8	1.6	1.8	4.7	16.1	10.0
42	NA	NA	NA	NA	NA	NA	NA

Day No.	TKNin (mgN/l)	TKNout (mgN/l)	NO3,1 (mgN/l)	NO3,2 (mgN/l)	NO3,3 (mgN/l)	NO3,4 (mgN/l)	NO3out (mgN/l)
43	41.2	3.6	0.5	1.9	7.0	10.9	4.5
44	40.6	3.4	0.8	1.2	14.2	12.7	10.1
45	41.7	2.8	0.4	1.1	12.5	12.5	10.6
46	41.7	2.8	1.1	0.7	10.8	12.8	14.0
47	41.2	3.4	0.3	2.9	10.4	9.1	10.4
48	41.4	2.8	0.9	2.3	6.2	9.9	9.3
49	41.7	4.1	0.7	2.2	9.1	9.5	10.7
50	41.2	3.8	0.6	2.3	9.3	11.4	11.0
50	40.0	3.6	0.7	5.4	9.1		9.9
51	40.6	3.6	0.6	2.3	9.5	9.8	9.9
52	39.5	3.4	0.7	1.9	9.7	11.3	11.4
53	45.1	4.5	0.4	1.5	7.8	10.6	10.8
54	42.6	2.5	0.4	0.7	10.4		12.0
55	42.3	3.1	0.3	0.9	11.0	10.3	10.3
56	42.6	6.7	0.4	0.7	9.5	9.2	9.3
57	43.1	3.2	0.1	1.2	7.7	10.1	11.5
58	44.2	3.9	0.1	0.9	10.2	11.2	11.4
59	45.6	3.5	0.3	0.9	8.9	10.2	11.4
60	41.7	2.7	0.3	1.0	7.9	9.6	9.9

Table A.6c Experimental results from U.C.T system

Day No.	PO4in (mgP/l)	PO4,1 (mgP/l)	PO4,2 (mgP/l)	PO4,3 (mgP/l)	PO4,4 (mgP/l)	PO4out (mgP/l)	Pupt,1 (mgP/l)	Pupt,2 (mgP/l)	Pupt,3 (mgP/l)	Pupt,4 (mgP/l)	Prem (mgP/l)
1	27.4	25.8	23.0	23.6	20.3	20.0	-1.2	-2.5	-2.4	13.2	7.1
2	27.7	26.4	22.6	21.5	20.4	20.4	-2.5	1.0	4.4	4.4	7.3
3	27.6	26.2	22.4	21.8	20.3	20.3	-2.4	1.3	2.4	6.0	7.3
4	27.2	25.7	23.3	25.2	20.2	20.1	-0.9	-4.5	-7.6	20.0	7.0
5	27.4	26.2	23.2	21.6	21.3	21.2	-1.8	0.3	6.4	1.2	6.1
6	28.4	30.8	22.6	21.0	19.9	21.3	-10.6	8.3	6.4	4.4	8.5
7	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
9	26.6	22.7	21.4	20.1	19.5	18.7	2.6	-3.1	5.2	2.4	7.1
10	26.9	25.3	23.0	21.6	19.8	19.6	-0.7	-5.0	5.6	7.2	7.1
11	27.8	24.2	21.6	20.5	21.3	19.1	1.0	4.3	4.4	-3.2	6.5
12	26.8	22.4	18.3	17.7	15.8	19.6	0.3	0.7	2.4	7.6	11.0
13	26.8	22.5	19.6	18.4	17.3	16.8	1.4	-1.1	4.8	4.4	9.5
14	25.6	24.3	23.2	22.2	19.4	17.7	0.2	-9.2	4.0	11.2	6.2
15	25.6	24.3	20.6	20.1	19.1	18.4	-2.4	2.9	2.0	4.0	6.5
16	25.0	25.5	22.2	20.5	19.5	18.8	-3.8	-1.5	6.8	4.0	5.5
17	23.2	24.5	21.1	20.4	18.4	18.4	-4.7	-1.3	2.8	8.0	4.8
18	25.3	25.7	23.5	21.8	20.6	18.6	-2.6	-4.3	6.8	4.8	4.7
19	27.6	28.4	23.7	21.2	18.3	19.0	-5.5	-6.8	10.0	11.6	9.3
20	27.4	26.4	22.1	19.8	18.7	19.4	-3.3	-1.6	9.2	4.4	8.7
21	27.1	25.8	21.0	20.0	18.6	19.0	-3.5	2.4	4.0	5.6	8.5
22	27.0	25.7	22.4	20.1	17.8	18.4	-2.0	-7.2	9.2	9.2	9.2
23	27.8	25.7	21.3	19.7	18.4	18.7	-2.3	0.1	6.4	5.2	9.4
24	27.8	26.1	20.5	18.7	18.4	19.2	-3.9	4.9	7.2	1.2	9.4
25	25.7	26.5	23.8	17.9	16.8	16.8	-3.5	-15.6	23.6	4.4	8.9
26	20.4	21.2	18.8	17.2	16.0	16.4	-3.2	-3.6	6.4	4.8	4.4
27	27.6	28.4	24.0	20.5	19.4	19.8	-5.2	-5.0	14.0	4.4	8.2
28	23.8	24.4	23.0	19.4	18.8	19.8	-2.0	-9.8	14.4	2.4	5.0
29	27.2	27.0	23.5	20.8	18.7	19.0	-3.3	-7.4	10.8	8.4	8.5
30	23.4	25.4	21.6	20.3	20.0	19.6	-5.8	2.8	5.2	1.2	3.4
31	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
32	24.8	24.3	21.6	19.4	17.1	22.0	-2.2	-8.1	8.8	9.2	7.7
33	27.9	28.5	20.8	20.0	17.8	18.5	-8.3	6.4	3.2	8.8	10.1
34	21.7	22.0	19.1	17.2	16.0	21.8	-3.2	-3.5	7.6	4.8	5.7
35	22.0	23.3	20.8	17.7	16.1	20.9	-3.8	-4.4	9.3	4.8	5.9
36	22.6	27.1	25.5	19.7	18.0	22.3	-6.1	-11.8	17.4	5.1	4.6
37	23.9	24.1	21.4	18.3	16.7	22.1	-2.9	-4.0	9.3	4.8	7.2
38	23.4	27.0	21.6	18.8	16.6	20.1	-9.0	0.8	8.4	6.6	6.8
39	23.1	26.5	21.4	18.0	15.8	19.1	-8.5	-1.0	10.2	6.6	7.3
40	24.1	28.8	23.1	19.6	17.4	21.1	-10.4	.0	10.5	6.6	6.7
41	26.5	24.5	22.0	18.5	18.8	16.5	-0.5	-1.4	10.5	-0.9	7.7
42	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

Day No.	PO4in (mgP/l)	PO4,1 (mgP/l)	PO4,2 (mgP/l)	PO4,3 (mgP/l)	PO4,4 (mgP/l)	PO4out (mgP/l)	Pupt,1 (mgP/l)	Pupt,2 (mgP/l)	Pupt,3 (mgP/l)	Pupt,4 (mgP/l)	Prem (mgP/l)
43	23.8	24.0	22.9	20.4	18.2	16.5	-1.3	-7.2	7.5	6.6	5.6
44	24.5	30.8	23.4	18.8	16.3	19.9	-13.7	0.6	13.8	7.5	8.2
45	24.5	31.2	24.0	18.7	18.1	19.3	-13.9	2.6	15.9	1.8	6.4
46	24.7	31.9	25.0	19.6	16.2	19.6	-14.1	-3.8	16.2	10.2	8.5
47	24.2	30.1	22.3	17.4	15.0	17.5	-13.7	1.0	14.7	7.2	9.2
48	25.4	36.3	29.2	25.3	18.5	18.2	-18.0	-7.2	11.7	20.4	6.9
49	24.2	30.7	23.4	17.5	15.1	17.0	-13.8	-2.0	17.7	7.2	9.1
50	24.5	33.5	25.3	16.9	13.1	17.5	-17.2	-8.0	25.2	11.4	11.4
50	25.0	35.6	24.7	16.3	12.6	14.5	-21.5	-2.4	25.2	11.1	12.4
51	24.7	34.2	24.5	18.1	12.7	15.1	-19.2	-4.2	19.2	16.2	12.0
52	24.3	33.9	25.5	16.9	13.8	15.1	-18.0	-6.6	25.8	9.3	10.5
53	26.0	39.2	29.5	20.8	16.9	18.8	-22.9	-5.8	26.1	11.7	9.1
54	25.2	36.4	26.2	18.2	14.1	18.9	-21.4	-3.8	24.0	12.3	11.1
55	26.1	38.2	26.2	18.7	13.2	18.0	-24.1	-2.0	22.5	16.5	12.9
56	26.2	37.9	27.6	18.4	12.3	17.5	-22.0	-10.0	27.6	18.3	13.9
57	25.8	36.4	26.4	20.0	14.9	21.1	-20.6	-3.0	19.2	15.3	10.9
58	25.8	38.7	27.9	18.9	16.0	26.3	-23.7	-2.2	27.0	8.7	9.8
59	26.1	40.2	27.4	19.0	15.2	18.2	-26.9	1.2	25.2	11.4	10.9
60	25.4	38.0	26.6	19.3	14.1	17.3	-24.0	-2.2	21.9	15.6	11.3

Table A.7a : Experimental results from Johannesburg system (Rs=3d)

Day No.	CODin (mgCOD/l)	CODout (mgCOD/l)	Sbsi (mgCOD/l)	OUR,3 (mgO/l/h)	OUR,4 (mgO/l/h)	OUR,sel (mgO/l/h)	VSS,1 (mgVSS/l)	VSS,2 (mgVSS/l)	VSS,3 (mgVSS/l)	VSS,4 (mgVSS/l)	DSVI (ml/g)
1	469.0	60.4	NA	32	27	78	2072	1128	1093	1024	680
2	501.8	51.2	NA	32	25	84	2376	1337	1371	1444	512
3	494.6	50.2	NA	NA	NA	NA	2128	1269	1382	1201	314
4	481.3	49.2	NA	46	38	96	2146	1341	1442	1433	314
5	479.2	65.5	NA	NA	NA	NA	2509	1541	1607	1671	301
6	499.7	71.7	NA	NA	NA	NA	2126	1243	1400	1811	339
7	489.5	50.2	NA	43	34	103	NA	NA	NA	NA	265
8	488.4	44.0	NA	43	42	120	2151	1301	1525	1583	265
9	475.1	38.9	NA	31	25	89	2341	1209	1425	1665	283
10	495.3	41.4	NA	36	27	108	2428	1237	1471	1609	324
11	504.6	36.2	NA	NA	NA	NA	1964	1214	1341	1176	NA
12	507.7	49.6	NA	NA	NA	NA	2625	1567	1513	1459	312
13	385.7	49.6	NA	NA	NA	NA	2001	1296	1324	1248	294
14	351.6	50.7	NA	30	24	88	1814	1053	1145	1023	288
15	499.4	60.0	NA	30	26	68	1865	1101	1122	1090	270
16	500.4	43.4	118	NA	NA	NA	1877	1163	1284	1104	247
17	519.1	50.7	162	38	31	112	2066	1257	1250	1209	246
18	533.5	49.1	NA	NA	NA	NA	2176	1266	1371	1261	249
19	534.5	39.9	144	34	33	104	2381	1341	1379	1281	287
20	528.4	58.3	NA	45	33	104	NA	NA	NA	NA	NA
21	511.0	42.9	152	42	36	112	2327	1332	1358	1317	312
22	507.9	47.0	NA	43	33	124	2527	1477	1530	1564	257
23	511.0	54.2	NA	37	35	92	2204	1321	1284	1414	249
24	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
25	502.9	51.0	NA	NA	NA	NA	2593	1529	1571	1515	293
26											NA
27	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
28	526.3	63.7	120	41	36	100	2573	1561	1517	1465	220
29	496.5	49.3	161	36	34	84	2437	1483	1443	1402	214
30	497.0	61.1	NA	35	33	84	2432	1425	1418	1409	208
31	490.0	47.1	NA	34	30	100	2596	1542	1500	1512	233
32	482.0	43.1	NA	32	28	78	2446	1365	1380	1372	232

Table A.7b : Experimental results from Johannesburg system (Rs=3d)

Day No.	TKNin (mgN/l)	TKNout (mgN/l)	NO3,1 (mgN/l)	NO3,2 (mgN/l)	NO3,sel (mgN/l)	NO3,3 (mgN/l)	NO3,4 (mgN/l)	NO3out (mgN/l)
1	45.9	10.8	2.0	0.4	NA	7.5	13.8	4.7
2	36.4	5.7	0.1	0.3	NA	8.0	9.8	5.9
3	NA	NA	0.0	0.2	NA	3.9	7.7	3.4
4	33.3	6.2	0.0	0.1	NA	2.9	5.7	2.8
5	36.7	4.2	0.8	0.8	NA	12.1	13.0	12.1
6	36.7	4.3	0.8	0.8	NA	12.6	13.0	11.8
7	37.2	4.3	1.9	0.9	NA	11.2	15.1	10.9
8	37.2	4.3	1.1	0.5	6.3	9.5	12.2	11.9
9	36.1	9.4	0.1	0.2	1.8	1.8	1.9	5.7
10	37.0	16.4	0.1	0.1	0.8	1.7	2.8	NA
11	36.7	13.4	0.1	0.2	1.1	2.4	3.9	3.4
12	43.7	11.8	0.1	0.3	1.3	1.3	5.4	4.3
13	37.8	9.2	0.5	0.3	1.6	3.9	6.6	5.1
14	35.6	10.1	1.5	0.3	1.4	3.7	10.2	5.7
15	37.5	8.3	0.2	0.2	1.3	3.9	6.5	5.5
16	36.7	8.0	0.5	0.3	3.1	4.6	7.1	6.9
17	49.6	13.0	0.4	0.4	2.2	5.1	7.2	6.6
18	51.0	15.3	0.3	0.4	2.2	5.3	7.6	7.7
19	51.2	16.4	0.4	0.3	2.5	5.4	7.8	7.5
20	51.0	16.8	0.7	0.4	2.4	6.0	8.9	8.1
21	51.5	15.4	0.2	0.4	2.3	6.5	9.1	8.7
22	49.0	13.6	1.6	0.5	2.3	9.0	12.4	10.9
23	47.6	9.9	4.0	0.6	4.1	7.5	11.5	11.2
24	NA	NA	NA	NA	NA	NA	NA	NA
25	49.0	8.3	3.1	0.6	4.1	8.6	11.2	10.8
26								
27	NA	NA	NA	NA	NA	NA	NA	NA
28	42.3	2.7	1.6	0.7	2.3	6.9	9.8	9.7
29	40.9	5.5	1.4	0.6	3.4	7.0	9.6	9.7
30	41.7	8.1	2.0	0.5	2.1	6.0	9.0	8.3
31	42.0	10.9	0.2	0.5	2.3	4.5	7.0	7.2
32	41.4	9.0	0.6	0.5	2.4	5.5	8.1	8.6

Table A.7c : Experimental results from Johannesburg system (Rs=3d)

Day No.	PO4in (mgP/l)	PO4,1 (mgP/l)	PO4,2 (mgP/l)	PO4,sel (mgP/l)	PO4,3 (mgP/l)	PO4,4 (mgP/l)	PO4out (mgP/l)	Pupt,1 (mgP/l)	Pupt,2 (mgP/l)	Pupt,sel (mgP/l)	Pupt,3 (mgP/l)	Pupt,4 (mgP/l)	Prem (mgP/l)
1	22.8	13.9	26.4	NA	17.4	13.1	13.0	-0.8	-16.1	NA	18.0	8.6	9.7
2	21.3	14.4	26.8	NA	17.7	12.9	12.6	-1.5	-17.9	NA	18.2	9.6	8.4
3	21.6	17.6	26.9	NA	19.2	16.0	14.7	-1.6	-14.6	NA	15.4	6.4	5.6
4	22.4	19.8	25.6	NA	19.5	15.8	14.7	-4.0	-9.0	NA	12.2	7.4	6.6
5	20.9	14.2	24.5	NA	15.4	11.6	12.0	-2.6	-13.9	NA	18.2	7.6	9.3
6	21.5	16.1	27.2	NA	18.1	13.5	12.2	-2.6	-16.8	NA	18.2	9.2	8.0
7	21.3	16.7	25.0	NA	17.4	14.2	13.5	-2.5	-12.0	NA	15.2	6.4	7.1
8	22.1	17.8	26.5	24.6	19.6	16.1	15.8	-1.7	-13.1	3.8	10.0	7.0	6.0
9	23.8	20.8	27.2	25.8	19.7	18.0	15.1	-2.8	-9.8	2.8	12.2	3.4	5.8
10	22.0	19.4	26.9	23.6	18.6	16.2	16.8	-3.2	-12.4	6.6	10.0	4.8	5.8
11	22.4	19.2	27.0	22.7	18.2	15.4	14.4	-3.8	-12.4	8.6	9.0	5.6	7.0
12	22.5	17.6	27.5	23.3	17.6	13.2	13.8	-4.4	-14.9	8.4	11.4	8.8	9.3
13	21.2	15.0	26.4	23.8	19.2	14.5	13.2	-0.5	-16.6	5.2	9.2	9.4	6.7
14	23.2	16.8	26.3	22.3	21.9	15.6	16.0	-1.2	-12.6	8.0	0.8	12.6	7.6
15	21.3	14.9	25.6	20.8	15.2	11.7	12.3	-3.2	-15.0	9.6	11.2	7.0	9.6
16	22.5	16.9	30.2	24.5	18.8	13.4	13.1	-3.5	-21.0	11.4	11.4	10.8	9.1
17	22.7	19.3	29.2	24.4	19.1	14.4	14.4	-4.9	-16.4	9.6	10.6	9.4	8.3
18	21.4	16.7	26.8	24.1	18.0	12.4	13.6	-4.3	-15.5	5.4	12.2	11.2	9.0
19	21.5	15.8	27.3	23.5	17.6	11.9	13.2	-3.9	-17.3	7.6	11.8	11.4	9.6
20	21.8	16.4	29.7	25.8	18.3	13.6	14.2	-2.8	-21.2	7.8	15.0	9.4	8.2
21	22.0	17.3	30.0	25.2	18.7	13.6	11.9	-3.7	-20.7	9.6	13.0	10.2	8.4
22	22.0	16.4	31.4	27.2	18.2	10.2	11.3	-6.2	-24.4	8.4	18.0	16.0	11.8
23	22.6	14.7	28.8	24.7	18.8	11.1	13.1	-3.6	-20.3	8.2	11.8	15.4	11.5
24	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
25	21.8	17.1	32.0	27.3	19.7	13.8	13.9	-3.3	-25.1	9.4	15.2	11.8	8.0
26								NA	NA	NA	NA	NA	NA
27	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
28	22.1	16.7	29.8	26.1	18.4	13.5	12.4	-3.2	-20.8	7.4	15.4	9.8	8.6
29	23.3	17.6	29.8	24.6	18.8	13.5	13.1	-4.1	-18.7	10.4	11.6	10.6	9.8
30	22.5	17.4	30.3	24.7	18.9	13.4	14.4	-4.0	-20.7	11.2	11.6	11.0	9.1
31	24.4	18.0	28.9	25.3	19.2	14.5	15.1	-3.5	-15.4	7.2	12.2	9.4	9.9
32	22.6	16.7	28.7	24.8	19.1	14.3	13.5	-2.4	-18.1	7.8	11.4	9.6	8.3

Table A.8a : Experimental results from Johannesburg system (Rs=5d)

Day No.	CODin (mgCOD/l)	CODout (mgCOD/l)	Sbsi (mgCOD/l)	OUR,3 (mgO/l/h)	OUR,4 (mgO/l/h)	OUR,sel (mgO/l/h)	VSS,1 (mgVSS/l)	VSS,2 (mgVSS/l)	VSS,3 (mgVSS/l)	VSS,4 (mgVSS/l)	DSVI (ml/g)
1	474.2	53.1	NA	27	36	86	3785	1541	1663	1606	217
2	482.4	57.2	NA	NA	NA	NA	3916	1511	1622	1669	217
3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
4	453.8	45.0	NA	NA	NA	NA	2493	1083	1164	1135	215
5	486.5	40.9	NA	NA	NA	NA	NA	NA	NA	NA	234
6	469.1	38.8	NA	40	32	82	4199	1651	1660	1585	233
7	515.1	46.0	NA	44	33	77	4213	1642	1686	1640	226
8	503.5	52.8	NA	45	32	87	4200	1685	1639	1634	219
9	534.6	39.4	NA	NA	NA	NA	4204	1684	1689	1619	228
10	523.2	48.7	NA	46	37	82	4188	1641	1613	1601	237
11	509.7	43.5	NA	47	36	70	4193	1685	1716	1669	227
12	501.4	46.6	NA	49	36	84	NA	NA	NA	NA	NA
13	524.2	53.9	100	NA	NA	NA	3874	1498	1497	1444	226
14	513.9	42.3	NA	39	33	93	4062	1590	1554	1511	220
15	492.0	52.2	NA	54	50	96	4320	1701	1693	1614	245
16	463.8	42.2	NA	49	39	96	3883	1553	1606	1523	229
17	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
18	480.1	41.1	NA	NA	NA	NA	2890	1716	1691	1657	233
19	464.7	49.3	NA	NA	NA	NA	NA	NA	NA	NA	237
20	470.8	43.2	NA	NA	NA	NA	2713	1624	1561	1561	228
21	453.3	42.1	NA	NA	NA	NA	2685	1573	1553	1495	NA
22	452.3	36.0	126	39	32	80	2422	1474	1437	1434	222
23	477.0	NA	NA	35	35	80	2549	1519	1507	1460	217
24	460.0	34.7	NA	43	34	76	2720	1638	1551	1524	223
25	465.8	40.2	NA	NA	NA	NA	2732	NA	NA	1542	222
26	507.0	21.1	NA	NA	NA	NA	2717	1619	1620	1536	230
27	481.9	34.2	NA	54	40	87	2519	1468	1473	NA	NA
28	495.0	38.2	NA	53	43	80	2595	1524	1598	1546	NA
29	484.9	32.2	NA	50	44	86	2610	1553	1537	1489	228
30	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
31	503.0	46.3	NA	47	43	85	3191	1878	1817	1776	213
32	490.9	50.3	NA	41	36	82	3070	1821	1749	1699	186
33	464.8	48.3	NA	48	43	91	3074	1832	1752	1740	184
34	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
35	NA	35.9	NA	NA	NA	NA	3172	1828	1724	1715	165
36	463.8	36.9	NA	41	38	70	2807	1670	1621	1550	157
37	455.5	48.2	118	47	41	92	2899	1617	1600	1617	186
38	484.3	40.0	107	40	34	95	2649	1552	1457	1440	138
39	483.2	54.4	133	39	36	94	2501	1581	1461	1464	138
40	467.9	38.0	148	NA	NA	NA	2631	1590	1456	1470	132
41	491.5	81.0	NA	45	39	NA	2952	1783	1687	1650	141
42	438.6	45.9	NA	49	41	98	2443	1456	1377	1355	148

Day No.	CODin (mgCOD/l)	CODout (mgCOD/l)	Sbsi (mgCOD/l)	OUR,3 (mgO/l/h)	OUR,4 (mgO/l/h)	OUR,sel (mgO/l/h)	VSS,1 (mgVSS/l)	VSS,2 (mgVSS/l)	VSS,3 (mgVSS/l)	VSS,4 (mgVSS/l)	DSVI (ml/g)
43	506.9	89.8	NA	43	38	92	2555	1566	1413	1397	144
44	NA	NA	146	NA	NA	NA	NA	NA	NA	NA	NA
45	NA	NA	NA	NA	NA	NA	3050	1744	1723	1645	144
46	NA	NA	NA	NA	NA	NA	2420	1384	1463	1386	135
47	420.2	53.0	NA	NA	NA	NA	2053	1246	1202	1198	128
48	422.3	46.9	NA	NA	NA	NA	NA	NA	NA	NA	NA
49	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
50	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
51	452.9	65.3	NA	62	40	106	2155	1268	1202	1217	126
52	481.4	46.9	NA	44	42	74	2316	1349	1277	1231	132
53	495.7	41.8	106	44	42	88	2257	1286	1276	1184	135
54	520.2	40.8	148	48	47	100	2234	1222	1249	1197	136
55	531.4	53.0	NA	47	46	98	2225	1313	1289	1244	NA
56	526.3	44.9	NA	56	48	96	3149	1666	1605	1657	NA
57	522.2	44.6	131	51	49	115	2736	1564	1785	1857	129

Table A.8b : Experimental results from Johannesburg system (Rs=5d)

Day No.	TKNin (mgN/l)	TKNout (mgN/l)	NO3,1 (mgN/l)	NO3,2 (mgN/l)	NO3,sel (mgN/l)	NO3,3 (mgN/l)	NO3,4 (mgN/l)	NO3out (mgN/l)
1	41.4	9.8	0.2	0.6	4.1	9.5	13.2	13.1
2	40.3	9.7	0.3	0.6	5.0	9.8	14.0	13.4
3	NA	NA	NA	NA	NA	NA	NA	NA
4	43.1	7.8	0.3	0.6	5.0	7.8	10.2	11.5
5	40.9	10.1	0.3	0.6	4.8	8.1	11.5	10.6
6	43.1	7.7	0.2	0.6	4.0	9.2	12.7	13.4
7	45.4	9.5	0.2	0.5	5.0	8.6	12.0	11.9
8	41.7	8.0	0.3	0.5	4.4	9.2	12.9	13.3
9	39.5	8.7	.0	0.4	2.2	8.8	14.0	13.5
10	42.8	8.5	.0	0.4	2.4	10.1	15.8	14.5
11	41.4	5.3	0.1	0.5	4.0	11.3	17.0	16.2
12	39.5	6.4	0.0	0.0	3.8	10.4	19.3	14.7
13	42.6	7.7	0.1	0.5	2.9	10.4	17.2	15.6
14	38.9	9.1	0.1	0.5	2.6	10.1	15.2	14.7
15	42.6	12.2	0.1	0.2	3.7	1.7	7.2	10.4
16	44.8	8.8	0.2	0.4	1.6	7.2	11.1	12.6
17	NA	NA	NA	NA	NA	NA	NA	NA
18	42.3	6.9	0.2	0.4	2.4	7.6	9.8	13.5
19	43.4	7.3	0.4	0.2	3.1	9.4	13.5	14.0
20	40.6	6.7	0.8	0.5	3.2	8.1	12.9	13.2
21	40.6	5.6	1.5	0.3	3.1	8.6	13.2	14.4
22	42.0	5.9	1.4	0.5	3.0	8.3	12.6	13.2
23	40.0	8.1	0.6	0.4	2.6	7.1	NA	NA
24	44.5	5.9	2.1	0.5	2.1	7.8	11.7	13.0
25	40.3	3.8	2.9	0.1	2.6	8,2	12.0	13.4
26	47.0	1.7	2.2	0.4	2.9	7.9	12.3	13.3
27	45.9	4.2	4.6	0.1	1.1	9.1	13.8	14.2
28	45.4	4.5	4.5	0.1	2.8	9.0	14.4	14.6
29	45.9	4.5	3.1	0.1	2.3	7.4	12.5	13.3
30	NA	NA	NA	NA	NA	NA	NA	NA
31	45.4	5.5	1.4	0.1	2.3	7.3	12.6	12.6
32	45.6	3.6	0.6	0.1	2.2	8.3	13.4	12.5
33	48.7	4.8	0.9	0.1	2.3	7.3	13.0	13.0
34	NA	NA	NA	NA	NA	NA	NA	NA
35	NA	5.2	3.6	0.1	2.3	7.5	13.8	13.8
36	48.2	7.8	1.8	0.1	1.7	7.0	11.8	13.6
37	48.4	9.5	1.6	0.1	2.4	8.4	13.4	12.1
38	48.4	10.2	2.4	0.1	2.0	6.5	12.0	12.5
39	49.6	8.8	2.4	0.1	1.8	6.7	12.3	NA
40	49.6	9.4	3.8	0.1	1.6	8.0	13.5	12.9
41	48.7	9.4	2.9	0.1	1.8	7.5	14.1	13.5
42	50.4	8.0	2.8	0.1	1.3	6.8	12.1	14.2

Day No.	TKNin (mgN/l)	TKNout (mgN/l)	NO3,1 (mgN/l)	NO3,2 (mgN/l)	NO3,sel (mgN/l)	NO3,3 (mgN/l)	NO3,4 (mgN/l)	NO3out (mgN/l)
43	51.2	13.2	0.5	0.1	1.5	6.1	11.0	11.0
44	NA	NA	NA	NA	NA	NA	NA	NA
45	51.8	9.5	2.3	0.1	1.5	9.0	15.7	13.7
46	48.2	7.1	4.3	0.1	2.0	8.0	13.5	14.6
47	51.0	7.1	4.1	0.2	1.4	8.0	14.2	14.4
48	50.4	5.5	4.7	0.6	2.5	9.6	14.2	15.0
49	NA	NA	NA	NA	NA	NA	NA	NA
50	NA	NA	NA	NA	NA	NA	NA	NA
51	52.9	13.4	0.8	0.1	1.8	7.3	13.2	13.0
52	57.1	10.9	2.4	0.1	1.9	8.2	14.2	14.8
53	59.4	12.7	3.7	0.1	2.2	8.7	15.1	14.8
54	64.1	14.4	2.1	0.1	2.1	9.0	15.5	NA
55	63.8	14.4	3.5	0.2	2.2	8.4	15.7	15.5
56	64.7	12.9	3.8	0.1	2.1	9.6	16.9	16.3
57	61.9	12.2	2.1	0.1	2.2	8.7	15.5	15.9

Table A.8c : Experimental results from Johannesburg system (Rs=5d)

Day No.	PO4,in (mgP/l)	PO4,1 (mgP/l)	PO4,2 (mgP/l)	PO4,sel (mgP/l)	PO4,3 (mgP/l)	PO4,4 (mgP/l)	PO4out (mgP/l)	Pupt,1 (mgP/l)	Pupt,2 (mgP/l)	Pupt,sel (mgP/l)	Pupt,3 (mgP/l)	Pupt,4 (mgP/l)	Prem (mgP/l)
1	25.7	22.0	35.0	32.4	19.5	12.1	11.7	-5.0	-15.8	3.9	19.4	11.1	13.6
2	25.0	28.1	43.6	32.2	22.9	15.1	13.5	-6.5	-26.4	17.1	14.0	11.7	9.9
3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
4	21.4	18.3	33.4	25.4	18.9	14.4	12.4	-2.0	-19.6	12.0	9.8	6.7	7.0
5	25.4	52.1	43.8	30.7	24.1	14.3	13.0	-18.9	-14.2	19.7	9.9	14.7	11.1
6	20.8	20.1	35.4	26.0	16.0	8.6	8.2	-5.8	-22.2	14.1	15.0	11.1	12.2
7	22.8	30.0	40.7	31.4	21.5	12.7	10.4	-8.7	-23.3	14.0	14.9	13.2	10.1
8	23.1	32.3	41.7	30.8	20.7	12.1	10.3	-10.1	-23.3	16.4	15.2	12.9	11.0
9	23.2	28.2	41.4	32.2	19.2	10.7	10.0	-8.8	-24.8	13.8	19.5	12.8	12.5
10	23.2	28.0	46.0	36.1	20.1	10.1	9.3	-9.0	-31.8	14.9	24.0	15.0	13.1
11	22.1	23.0	40.3	29.6	16.1	9.2	8.1	-6.9	-26.9	16.0	20.3	10.4	12.9
12	21.9	20.3	45.5	33.0	18.0	10.3	9.6	-5.0	-36.2	18.8	22.5	11.6	11.6
13	22.1	21.0	41.4	33.2	17.4	9.6	8.5	-5.7	-29.5	12.3	23.7	11.7	12.5
14	22.8	28.4	42.1	31.7	18.9	9.5	9.5	-9.5	-26.2	15.6	19.2	14.1	13.3
15	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
16	22.6	28.0	40.4	31.3	16.4	9.6	9.8	-9.2	-24.0	13.6	22.4	10.2	13.0
17	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
18	20.5	18.1	29.9	25.7	18.1	11.6	10.6	-6.5	-21.2	8.4	15.2	13.0	8.9
19	20.9	17.8	28.3	23.1	18.1	13.7	12.4	-4.1	-17.9	10.4	10.0	8.8	7.2
20	19.6	15.0	28.6	23.5	16.4	12.0	13.0	-3.0	-22.6	10.2	14.2	8.8	7.6
21	19.4	13.7	27.0	22.3	14.0	9.4	12.7	-4.3	-20.9	9.4	16.6	9.2	10.0
22	20.5	16.7	28.9	23.4	17.6	12.2	12.4	-4.5	-20.6	11.0	11.6	10.8	8.3
23	20.2	15.2	28.0	24.3	16.6	10.8	12.2	-4.4	-20.6	7.4	15.4	11.6	9.4
24	20.6	17.5	27.1	23.5	17.0	9.9	9.6	-7.6	-16.1	7.2	13.0	14.2	10.7
25	20.6	15.8	27.0	23.0	15.6	10.8	10.4	-5.0	-17.6	8.0	14.8	9.6	9.8
26	21.4	18.7	29.1	24.3	18.5	13.3	13.2	NA	NA	NA	NA	NA	NA
27	20.4	18.0	28.6	20.7	13.8	8.7	12.3	-9.3	-18.8	15.8	13.8	10.2	11.7
28	21.3	17.0	26.2	21.6	16.9	10.8	11.0	-6.2	-14.1	9.2	9.4	12.2	10.5
29	21.2	21.5	27.4	22.8	21.0	17.8	14.0	-3.7	-12.1	9.2	3.6	6.4	3.4
30	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
31	21.5	18.2	29.5	22.1	19.8	12.8	12.4	-5.4	-19.3	14.8	4.6	14.0	8.7
32	21.9	17.9	31.1	22.5	19.7	15.4	14.1	-2.5	-22.4	17.2	5.6	8.6	6.5
33	23.4	23.3	31.6	24.4	21.3	18.0	13.0	-5.3	-16.5	14.4	6.2	6.6	5.4
34	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
35	22.0	19.4	30.6	24.9	22.0	18.2	13.8	-1.2	-19.8	11.4	5.8	7.6	3.8
36	22.0	22.9	28.2	22.4	22.4	20.1	16.0	-2.8	-11.5	11.6	0.0	4.6	1.9
37	22.0	19.6	25.8	20.5	18.3	16.9	16.1	-2.7	-10.0	10.6	4.4	2.8	5.1
38	22.1	18.5	26.5	22.2	20.0	16.1	15.9	-2.4	-12.4	8.6	4.4	7.8	6.0
39	23.6	17.7	29.0	23.3	19.4	15.4	15.7	-2.3	-16.7	11.4	7.8	8.0	8.2
40	23.1	18.9	29.0	21.9	19.4	15.2	14.5	-3.7	-16.0	14.2	5.0	8.4	7.9
41	23.7	23.1	40.2	31.4	27.4	20.4	15.7	-2.7	-33.6	17.6	8.0	14.0	3.3
42	24.2	27.4	40.5	27.3	28.5	21.6	17.7	-5.8	-29.4	26.4	-2.4	13.8	2.6

APPENDIX B

DETERMINATION OF TOTAL PHOSPHORUS CONCENTRATION

PRINCIPLE OF THE METHOD

In the presence of vanadates, phosphates react with molybdates to form yellow phosphovanadomolybdate. The intensity of the 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 autoclaving the sample with sulphuric acid and potassium persulphate.

REAGENTS

1. Sulphuric acid solution

   Add 6,1 mℓ of concentrated sulphuric acid to approximately 500 mℓ of distilled water. Allow solution to cool and make up to 1ℓ with distilled water.

2. Potassium persulphate solution

   Dissolve 3,0 g of potassium persulphate in 100 mℓ of distilled water. This should require about 5 minutes of vigorous stirring.

3. Vanadomolybdate reagent

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

   Solution B: 1 g ammonium metavanadate dissolved in 40 mℓ concentrated
   nitric acid and ± 200 mℓ distilled water

Mix solutions A and B, add 100 mℓ concentrated nitric acid, and dilute to 1000 mℓ with distilled water.

TECHNIQUE

1. To a 100 mℓ conical flask, add the following:
   (i) 20 mℓ of sample
   (ii) 5 mℓ of potassium persulphate solution
   (iii) 5 mℓ of sulphuric acid solution

   Cover the top of the flask with aluminium foil. This step should be carried out on the following samples; distilled water, standard solutions of known phosphate concentration (for example solutions containing 5, 10, 15, 20, 25 and 50 mgPO$_4^-$P/ℓ), a dummy sample of water and the samples of unknown concentration.

2. Pour water, to a depth of ± 1 cm, into the bottom of a pressure cooker and heat the water to boiling.

3. Place the conical flasks on a rack in the pressure cooker such that the base of the flasks is above the water level.

4. Cover the pressure cooker with its sealed top but only place the pressure regulator over the escape nozzle when steam is flowing freely from this outlet.

5. Allow the pressure to rise to 20 bar and maintain heating at that pressure for 30 minutes.

6. Allow the flasks to cool to room temperature.

7. Vacuum filter the dummy sample through 0,45 µ filter paper in order to remove any phosphate from the paper. Filter the remaining samples through the same filter paper.

   N.B. *If any of the samples contain solid particles that may block the 0,45 µ filter paper, then the paper must be replaced after filtering that particular sample. The new filter paper must again be cleaned with a dummy sample.*

8. To a 20 mℓ test tube add 5 mℓ of sample and 5 mℓ of vanadomolybdate solution. Cover the test tube with "parafilm" plastic, shake and allow to stand for at least 20 minutes for the colour to develop. (It was found that the colour did not fade after standing for 24 hours).

9. Set the spectrophotometer to a wavelength of 470 μ and zero it using the distilled water sample. Read the remaining samples.

10. Plot the known concentrations of the standard phosphate samples against their respective spectrophotometer readings. Read off the unknown samples from the plot.

APPENDIX C

AEROBIC BATCH TESTS

During the course of the investigation, 3 aerobic batch tests were performed to determine the maximum specific growth rates of the heterotrophs and the nitrifiers in the sludge. The procedure followed was that proposed by Ekama, Dold and Marais (1986). Briefly, a preselected volume of wastewater (V_{ww}) of known total COD strength (S_{ti}) is mixed with a preselected volume of mixed liquor ($V_{m\ell}$) of known MLVSS concentration (X_v) in an aerated and stirred batch reactor. From immediately after mixing, up to a period of 24 hours, the oxygen utilization rate (OUR) is measured approximately every 5 minutes by the method outlined in Chapter 3, Section 4.4. Hourly for the first 6 hours, and then two-hourly for the next 6 hours, 50 mℓ samples of mixed liquor are taken.

With correct selection of the F/M ratio, the OUR from the start of the test remains constant for a period of one to three hours (depending on the readily biodegradable COD fraction), whereafter the OUR decreases fairly rapidly and levels off at a second plateau level. The initial high OUR is a consequence of the utilisation of the readily biodegradable COD from the wastewater as well as that derived from hydrolysis of the particulate biodegradable COD. The OUR is constant over this period because the concentration of readily biodegradable COD is so high that the growth rate of the heterotrophs is at a maximum, $\hat{\mu}_H$, in accordance with Monod kinetics. Once the readily biodegradable COD from the wastewater is depleted, the OUR drops rapidly to the second plateau level which is the rate associated with the utilisation of the readily biodegradable COD generated by hydrolysis of the particulate biodegradable COD. The maximum specific growth rate of the heterotrophs ($\hat{\mu}_H$) is proportional to the vertical height of the initial high OUR provided nitrification has not occurred in the test. If nitrification has occurred, nitrate tests should be carried out on the mixed liquor samples in order to determine the OUR for nitrification. This value is then subtracted from the total OUR.

The data obtained from the 3 batch tests is provided in Tables C.1 to C.3. The calculation of the maximum specific growth rates is presented separately for each test below.

1. Aerobic batch test on sludge from Split-feed system prior to the introduction of the selector reactor (17/4/86)

The OUR data is plotted on 2 different time scales in Figs C.1 and C.2. The filtered COD, filtered TKN and filtered nitrate concentrations are plotted versus time in Figs C.3 to C.5.

(a) Parent system analysis

In order to determine μ_H, the active fraction of the sludge mass with respect to the volatile solids (f_{av}) is required. This may be determined from the parent system, in this case a 3 day sludge age Split-feed system

$$\frac{1}{f_{av}} = 1 + f.b_h.R_s + \frac{f_{up}\,(1+b_h.R_s)}{f_{cv}.Y_h.(1-f_{us}-f_{up})}$$

where f = endogenous residue (0,2 mgVSS/mgVSS)

b_h = endogenous respiration rate (0,24/d)

R_s = sludge age (days)

f_{up} = particulate unbiodegradable wastewater fraction (0,08)

f_{us} = soluble unbiodegradable wastewater fraction (0,07)

f_{cv} = COD:VSS ratio (1,48 mgCOD/mgVSS)

$$\therefore \quad \frac{1}{f_{av}} = 1{,}387$$

$$\therefore \quad f_{av} = 0{,}72$$

(b) Batch test analysis

V_{ww} = 1,75 ℓ

S_{ti} = 1018 mgCOD/ℓ

$V_{m\ell}$ = 1,75 ℓ

X_v = 1263 mgVSS/ℓ

$$\therefore \quad F/M = \frac{1{,}75.1018}{1{,}75.1263}$$

$$= 0{,}81$$

At time 0

X_v = 774 mgVSS/ℓ
filtered COD = 220 mgCOD/ℓ
TKN = 37,5 mgN/ℓ
NO_3 = 0,35 mgN/ℓ

At time 24 hours

X_v = 658 mgVSS/ℓ
filtered COD = 88,9 mgCOD/ℓ
TKN = 8,7 mgN/ℓ
NO_3 = 24,8 mgN/ℓ

<u>Mass Balance</u>

The VSS value used will be an average of the values at time 0 and after 24 hours, i.e.

$$X_v = (774 + 658)/2$$
$$= 716 \text{ mgVSS/ℓ}$$

$$MX_v = X_v.(V_{ww} + V_{mℓ})$$
$$= 716.3,5$$
$$= 2506 \text{ mgVSS}$$

(i) Oxygen requirements for synthesis (MO_s)

$$MO_s = 0,33.COD_{used}$$
$$= 0,33.(COD_{in} - COD_{out} - 0,08\ COD_{in})$$
$$= 0,33.(1,75.1018 - 3,5.89 - 0,08.1,75.1018)$$
$$= 438 \text{ mgO}$$

(ii) Endogenous respiration (MO_e)

$$MO_e = f_{cv}.b_h.f_{av}.MX_v.(1-f)$$
$$= 1,48\ .\ 0,24\ .\ 0,72\ .\ 2506\ .\ 0,8$$
$$= 512 \text{ mgO}$$

(iii) Oxygen requirements for nitrification (MO_n)

$$
\begin{aligned}
MO_n &= (V_{ww} + V_{m\ell}).4,57.(NO_{3out} - NO_{3in}) \\
&= (1,75 + 1,75)\ 4,57\ (24,8 - 0,4) \\
&= 391 \text{ mgO}
\end{aligned}
$$

(iv) Total oxygen requirements (MO_t)

$$
\begin{aligned}
MO_t &= MO_s + MO_e + MO_n \\
&= 438 + 512 + 391 \\
&= 1341 \text{ mgO}
\end{aligned}
$$

From Simpson's rule, the area under the curve in Fig C.1 is 410,1 mgO/ℓ

$$
\begin{aligned}
\therefore MO_t \text{ (from graph)} &= 410,1\ .\ 3,5 \\
&= 1435 \text{ mgO}
\end{aligned}
$$

$$
\therefore \text{Percentage balance} = \frac{MO_t \text{ (calculated)}}{MO_t \text{ (from graph)}}
$$

$$
= \frac{1341}{1435}
$$

$$
= 93,4\%
$$

<u>Maximum specific growth rate of nitrifiers ($\hat{\mu}_N$)</u>

From Fig C.5 we observe that, for the first 14 hours, there is a linear relationship between nitrate generated and time

$$
\begin{aligned}
\therefore \text{rate of nitrification} &= \text{nitrate generated/time} \\
&= (17,5 - 0,4)/14 \\
&= 1,2 \text{ mgNO}_3/\ell/h
\end{aligned}
$$

$$
\begin{aligned}
\therefore \text{OUR due to nitrifiers} &= 4,57.1,2 \\
&= 5,60 \text{ mgO}/\ell/h
\end{aligned}
$$

In order to determine the mass of nitrifiers in the batch test sludge, the fraction of the VSS that is composed of nitrifiers must be known. This is calculated from the parent system as follows:

Nitrogen requirements for synthesis in parent plant (N_s)

$$= \frac{f_n.MX_v}{R_s.Q}$$

$$= \frac{0,1.8800}{3.25}$$

$$= 11,7 \text{ mgN}/\ell$$

Nitrate generated in parent system

$$= TKN_{in} - TKN_{out} - N_s$$

$$= 40 - 12 - 11,7$$

$$= 16,3 \text{ mgN}/\ell$$

Mass of nitrifiers in parent system

$$= \frac{0,1.R_s}{(1+b_n.R_s)} . 16,3.Q$$

$$= 109 \text{ mgVSS}$$

$\therefore$ nitrifier to VSS ratio $= 109/8800$

$= 0,012$ mgN/mgVSS

The concentration of nitrifiers in the batch test (MX_n) can now be found

$X_n = 0,012.MX_v/(V_{ww}+V_{m\ell})$

$= 0,012.2506/3,5$

$= 8,9 \text{ mgX}_n/\ell$

$\therefore \hat{\mu}_N = Y_n$. mass of nitrate generated per mass of nitrifiers per day

$$= \frac{0,1 \; . \; 1,2 \; . \; 24}{8,9}$$

$$= 0,324/d$$

Maximum specific growth rate of the heterotrophs ($\hat{\mu}_H$)

$$K_{ms} = \left\{1/(1-f_{cv}.Y_h)\right\} . \; OUR \; . \; \frac{24.(V_{ww}+V_{m\ell})}{f_{av}.X_v.V_{m\ell}}$$

where the OUR is equal to the initial OUR minus the OUR for nitrification

$$\therefore K_{ms} = 6,6 \text{ mgCOD/mgAVSS/d}$$

$$\hat{\mu}_H = Y_h.K_{ms}$$

$$= 0,45.6,6$$
$$= 2,98/d$$

2. Aerobic batch test on sludge from Split-feed system 9 days after the introduction of the selector reactor (1/5/86)

The OUR data is plotted in Fig C.6. The filtered COD, filtered TKN and filtered nitrate concentrations are plotted versus time in Figs C.7 to C.9. Due to demand for the oxygen recording equipment, this test could only be carried out for 9 hours and therefore, a mass balance could not be performed on the data.

To prevent tedious repetition of the calculations in the previous batch test, only the results of the calculations will be presented.

V_{ww} = 1,7 ℓ
S_{ti} = 1303,5 mgCOD/ℓ
$V_{m\ell}$ = 1,7 ℓ
X_v = 1292 mgVSS/ℓ
f_{av} = 0,72 (from parent system)

$$\therefore F/M = MS_{ti}/MX_v$$
$$= (1,7.1303,5)/(1,7.1292)$$
$$= 1,01$$

At time 0

X_v = 646 mgVSS/ℓ
filtered COD = 300,2 mgCOD/ℓ
TKN = 58,7 mgN/ℓ
NO_3 = 1,7 mgN/ℓ

At time 8 hours

filtered COD = 96,6 mgCOD/ℓ
TKN = 35,0 mgN/ℓ
NO_3 = 20,0 mgN/ℓ

<u>Maximum specific growth rate of the nitrifiers</u> ($\hat{\mu}_N$)

From Fig C.9 we observe that, for the first 7 hours, there is a linear relationship between the nitrate generated and time

rate of nitrification = 1,99 mgNO_3/ℓ/h

∴ OUR due to nitrifiers = 9,07 mgO/ℓ/h

From the parent plant, the fraction of the VSS that is composed of nitrifiers is calculated to be 0,0137

∴ X_n = 8,9 mgX_n/ℓ

∴ $\hat{\mu}_N$ = 0,536 /d

<u>Maximum specific growth of the heterotrophs</u> ($\hat{\mu}_H$)

K_{ms} = 4,2 mgCOD/mgAVSS/d
$\hat{\mu}_H$ = 1,89 /d

3. <u>Aerobic batch test on sludge from the Johannesburg system operating at a 5 day sludge age (12/8/86)</u>

The OUR data is plotted on 2 different time scales in Figs C.10 and C.11. The filtered COD, filtered TKN and filtered nitrate concentrations are plotted versus time in Figs C.12 to C.14.

To prevent tedious repetition of the calculations presented in the first batch test, only the results of the calculations will be presented.

V_{ww} = 2,1 ℓ
S_{ti} = 1042 mgCOD/ℓ
$V_{mℓ}$ = 1,4 ℓ
X_v = 1569 mgVSS/ℓ
f_{av} = 0,64 (from parent system)

.˙. F/M = 0,996

At time 0

X_v = 808 mgVSS/ℓ
filtered COD = 277 mgCOD/ℓ
TKN = 68,6 mgN/ℓ
NO_3 = 4 mgN/ℓ

At time 24 hours

X_v = 800 mgCOD/ℓ
TKN = 13,7 mgN/ℓ
NO_3 = 47,5 mgN/ℓ

Mass balance

The VSS value used will be an average of the values at the start (time = 0) and after 24 hours

X_v = 804 mgVSS/ℓ
M_{xv} = 2814 mgVSS

Calculated oxygen requirements

MO_s = 1597 mgO
MO_e = 512 mgO
MO_m = 696 mgO
MO_t = 2805 mgO

From Simpson's rule, the area under the graph in Fig C.10 is 825 mgO/ℓ

∴ MO_t from graph = 2888 mgO

∴ Percentage balance = $\frac{2805}{2888}$ %

= 97,1 %

Maximum specific growth rate of nitrifiers ($\hat{\mu}_N$)

From Fig C.14 we observe that for the first 8 hours, there is a linear relationship between the nitrate generated and time

rate of nitrification = 3,23 $mgNO_3/\ell/h$

∴ OUR due to nitrifiers = 14,74 mgO/ℓ/h

From the parent plant, the fraction of the VSS that is composed of nitrifiers is calculated to be 0,022

∴ X_n = 17,7 mgX_n/ℓ

∴ $\hat{\mu}_N$ = 0,437 /d

Maximum specific growth rate of the heterotrophs ($\hat{\mu}_H$)

K_{ms} = 9,54 mgCOD/mgAVSS/d

∴ $\hat{\mu}_H$ = 4,30 /d

Table C.1a : Results from Batch Test 1 (16/4/86)

TIME (hours)	OUR (mgO/l/h)	TIME (hours)	OUR (mgO/l/h)	TIME (hours)	OUR (mgO/l/h)
0.06	52.9	5.19	22.2	13.68	15.0
0.15	54.6	5.31	20.8	13.87	14.3
0.24	53.7	5.46	20.9	14.07	14.6
0.32	52.9	5.59	20.1	14.26	14.6
0.40	52.2	5.74	19.8	14.46	14.6
0.49	52.2	5.89	20.0	14.67	14.5
0.57	52.2	6.03	19.4	14.86	14.4
0.65	48.0	6.18	18.6	15.06	13.5
0.73	45.6	6.33	18.8	15.26	13.7
0.81	42.4	6.48	18.2	15.44	14.1
0.90	34.6	6.63	19.6	15.62	13.7
0.99	34.3	6.78	17.3	15.81	14.3
1.08	31.9	6.94	18.4	16.01	13.2
1.18	31.6	7.09	18.4	16.21	14.3
1.28	31.9	7.25	18.2	16.41	13.3
1.38	31.0	7.41	18.0	16.63	13.7
1.47	30.5	7.57	17.8	16.83	14.4
1.56	29.8	7.73	17.6	17.25	12.9
1.66	30.8	7.89	17.3	17.47	13.2
1.75	30.0	8.06	17.6	17.69	14.4
1.85	30.0	8.22	17.3	17.91	13.2
1.95	30.0	8.39	16.8	18.13	12.6
2.04	28.8	8.57	16.5	18.37	12.5
2.14	27.7	8.74	16.8	18.60	11.9
2.24	27.9	8.91	16.7	18.83	12.2
2.34	27.1	9.10	16.4	19.06	12.2
2.44	28.6	9.29	16.7	19.29	12.4
2.54	28.6	9.46	16.4	19.54	12.4
2.65	27.7	9.64	16.7	19.77	12.9
2.75	27.9	9.82	16.5	20.00	12.1
2.85	27.9	10.00	16.1	20.23	11.9
2.96	26.7	10.19	16.7	20.48	11.9
3.07	26.1	10.37	16.9	20.72	12.1
3.18	26.9	10.55	16.5	20.97	11.5
3.28	25.9	10.73	17.2	21.23	11.2
3.39	25.5	10.91	16.5	21.49	11.5
3.50	25.4	11.09	16.4	21.75	12.1
3.62	25.5	11.27	16.4	22.03	11.7
3.73	24.8	11.45	15.8	22.30	11.5
3.84	24.3	11.61	16.1	22.57	12.0
3.95	24.0	11.79	15.4	22.84	11.7
4.07	23.4	11.98	16.2	23.13	11.2
4.19	23.8	12.17	15.8	23.41	10.7
4.30	23.8	12.37	15.4	23.69	10.7
4.42	22.4	12.54	15.1	23.98	11.0
4.54	21.9	12.74	15.1		
4.67	20.8	12.93	15.0		
4.79	21.6	13.11	14.9		
4.92	22.6	13.30	15.1		
5.05	22.8	13.49	15.0		

Table C.1b : Results from Batch Test 1 (16/4/86)

TIME (hours)	TKN (mgN/l)	COD (mgCOD/l)	NO3 (mgN/l)
0	37.5	220.2	0.4
1	33.6	125.2	2.1
2	25.2	105.0	3.2
3	23.8	112.1	4.2
4	21.0	109.1	5.7
5	20.9	89.9	6.8
6	19.2	134.3	8.8
8	16.8	100.0	10.6
10	NA	86.9	11.8
12	13.0	97.0	16.3
14	11.8	99.0	18.5
21	9.4	92.9	24.0
22	7.8	84.8	25.0
23	9.3	90.9	25.3
24	8.7	88.9	24.8

Table C.2a : Results from Batch Test 2 (1/5/86)

TIME (hours)	OUR (mgO/l/h)	TIME (hours)	OUR (mgO/l/h)
0.1	36.2	4.2	22.6
0.2	35.2	4.3	22.6
0.3	35.6	4.5	22.5
0.4	34.9	4.6	22.1
0.5	33.1	4.7	21.3
0.6	33.1	4.8	22.1
0.7	33.4	5.0	20.9
0.8	32.5	5.1	21.3
0.9	32.3	5.2	20.8
1.0	34.3	5.4	20.3
1.1	36.6	5.5	21.6
1.2	35.2	5.6	20.1
1.3	34.0	5.8	19.6
1.4	32.0	5.9	20.0
1.5	24.6	6.1	19.9
1.6	23.1	6.2	18.5
1.7	23.6	6.3	18.8
1.9	24.3	6.5	18.4
2.0	23.9	6.6	18.2
2.1	25.6	6.8	18.4
2.2	24.2	6.9	18.0
2.4	23.4	7.1	18.5
2.5	24.3	7.2	18.6
2.6	23.3	7.4	17.9
2.7	23.7	7.5	19.0
2.8	25.2	7.7	18.2
3.0	23.4	7.8	17.5
3.1	24.2	8.0	17.4
3.2	22.6	8.1	17.1
3.3	22.6	8.2	16.9
3.4	22.6	8.4	17.0
3.6	23.1	8.5	16.9
3.7	22.3	8.7	16.9
3.8	21.7	8.9	16.8
3.9	20.6	9.1	16.6
4.1	21.3		

Table C.2b : Results from Batch Test 2 (1/5/86)

TIME (hours)	TKN (mgN/l)	COD (mgCOD/l)	NO3 (mgN/l)
0	58.7	300.2	1.7
1	54.5	298.1	5.1
2	50.5	220.0	5.8
3	48.3	195.3	7.4
4	44.7	156.3	8.4
5	42.6	139.8	11.6
6	39.3	125.4	13.0
7	37.7	115.1	15.6
8	35.0	96.6	20.0

Table C.3a : Results from Batch Test 3 (12/8/86)

TIME (hours)	OUR (mgO/l/h)	TIME (hours)	OUR (mgO/l/h)	TIME (hours)	OUR (mgO/l/h)
0.2	83	4.5	59	9.9	44
0.4	79	4.6	59	10.1	43
0.5	80	4.8	59	10.2	42
0.6	80	4.9	58	10.4	41
0.7	79	5.0	59	10.6	42
0.9	80	5.2	56	10.7	42
1.0	79	5.3	56	10.9	41
1.1	79	5.4	55	11.1	41
1.2	79	5.6	57	11.3	42
1.3	80	5.7	54	11.5	42
1.4	79	5.9	55	11.6	41
1.5	81	6.0	53	11.8	42
1.6	81	6.1	53	12.0	42
1.7	80	6.3	53	12.2	40
1.9	79	6.4	53	12.4	41
2.0	81	6.6	54	12.5	39
2.1	81	6.7	52	12.7	39
2.2	74	6.9	51	12.9	38
2.3	64	7.0	51	13.1	35
2.4	64	7.2	49	13.3	34
2.5	64	7.3	49	13.5	30
2.6	63	7.5	49	13.8	27
2.7	63	7.6	50	14.1	24
2.9	63	7.8	49	14.4	20
3.0	63	7.9	48	14.7	18
3.1	64	8.1	50	15.1	16
3.2	62	8.2	49	15.5	14
3.3	63	8.4	47	16.0	12
3.5	63	8.6	48	16.6	10
3.6	63	8.7	47	22.2	5
3.7	62	8.8	46	22.9	5
3.9	61	9.0	47	23.6	5
4.0	61	9.2	46	24.3	5
4.1	60	9.4	45	25.0	5
4.2	59	9.5	45	25.6	5
4.4	58	9.7	44		

Table C.3b : Results from Batch Test 3 (12/8/86)

TIME (hours)	TKN (mgN/l)	COD (mgCOD/l)	NO3 (mgN/l)
0	68.6	277.0	4.0
1	61.3	205.2	7.2
2	60.3	158.0	11.5
3	55.3	133.4	14.3
4	50.3	112.9	17.0
5	45.2	100.5	20.3
6	41.0	102.6	24.0
7	37.0	96.4	27.0
8	31.6	133.4	29.8
10	25.8	88.2	35.0
12	20.4	71.8	40.5
22	13.2	119.0	43.8
23	13.2	121.1	45.5
24	13.7	119.0	47.5

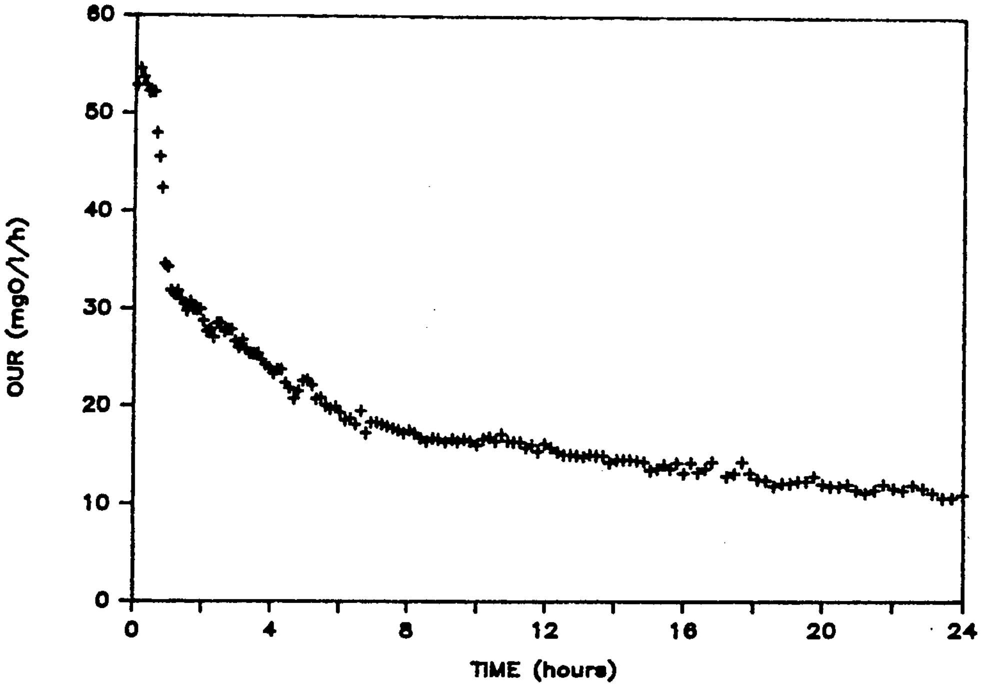


Fig C.1: OUR data from aerobic batch test on sludge from Split-feed system prior to the introduction of the selector.

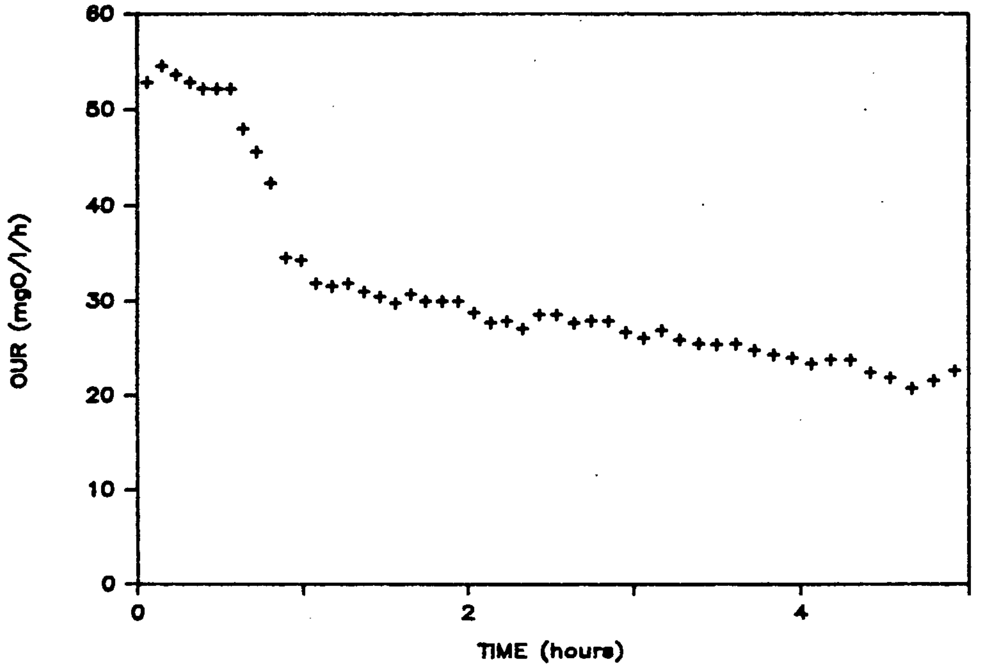


Fig C.2: OUR data from aerobic batch test on sludge from Split-feed system prior to the introduction of the selector.

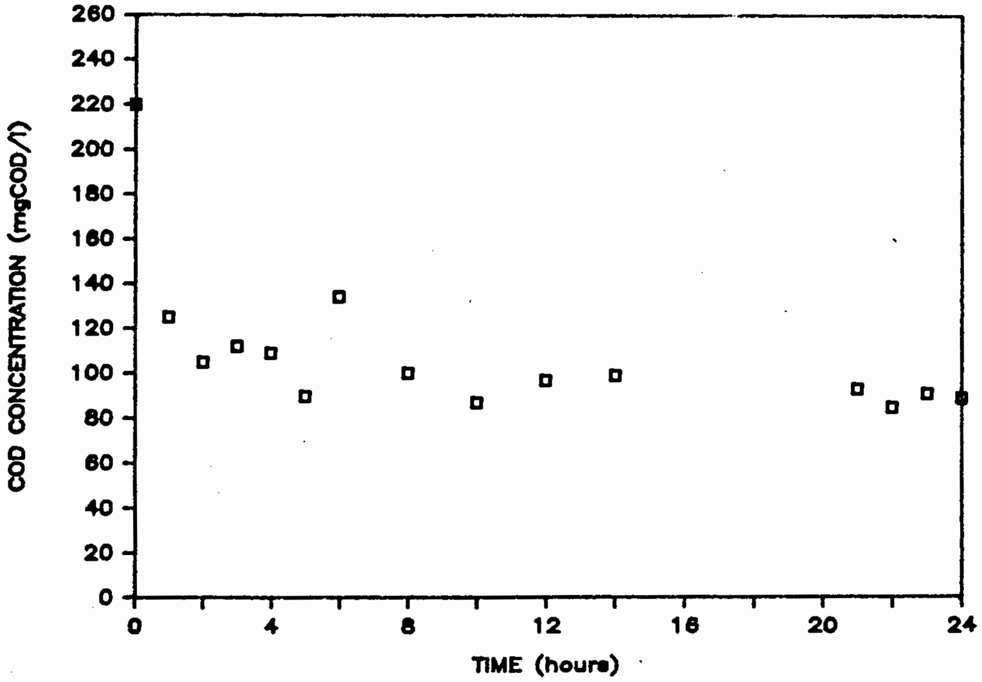


Fig C.3: Filtered COD data from aerobic batch test on sludge from Split-feed system prior to the introduction of the selector.

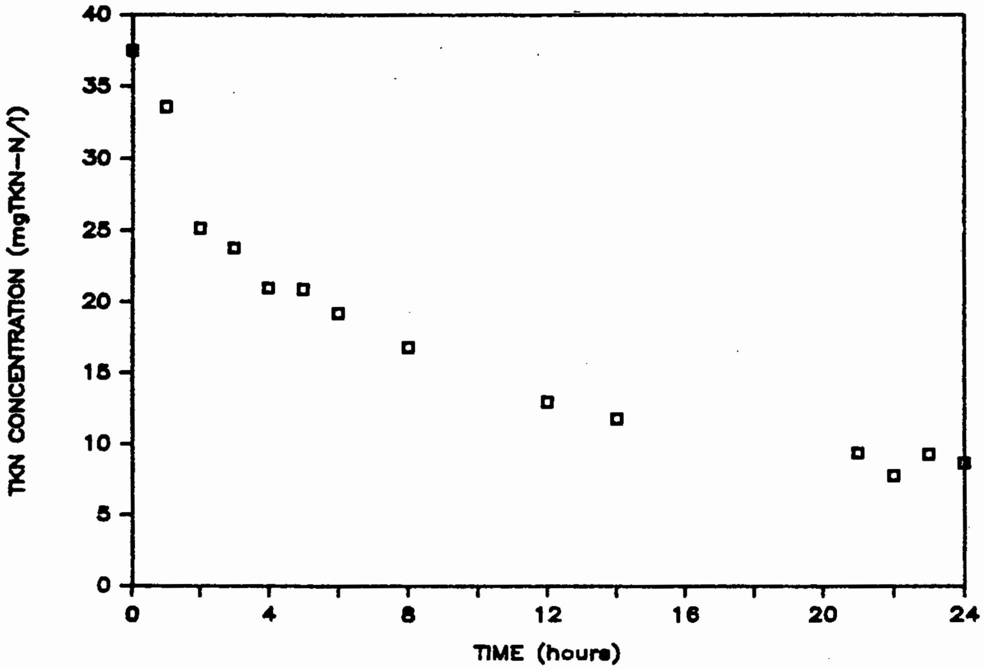


Fig C.4: Filtered TKN data from aerobic test on sludge from Split-feed system prior to the introduction of the selector.

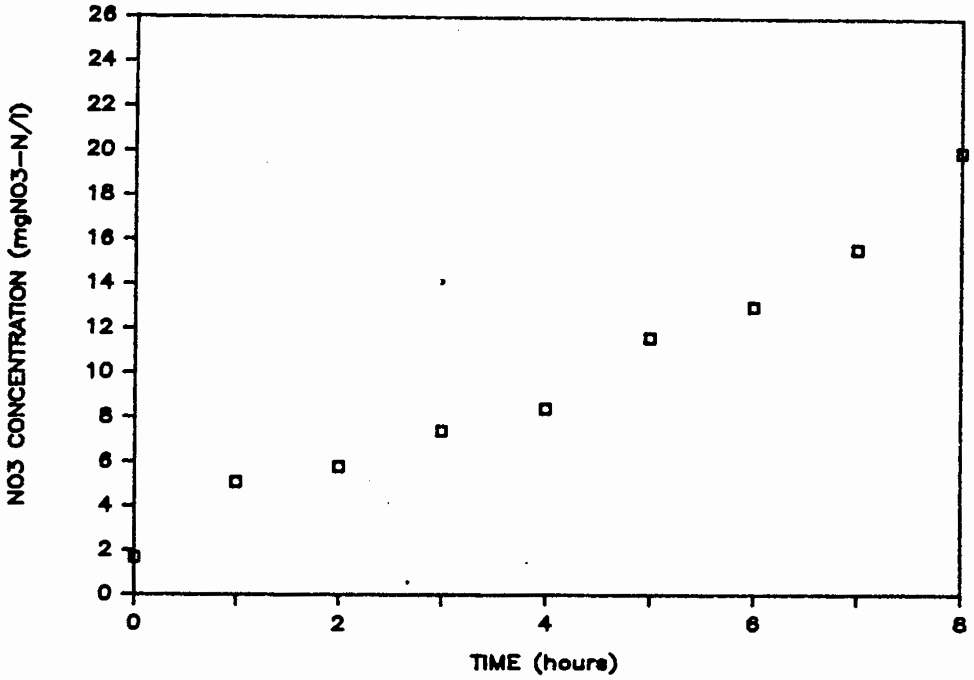


Fig C.5: Filtered nitrate data from aerobic batch test on sludge from Split-feed system prior to the introduction of the selector.

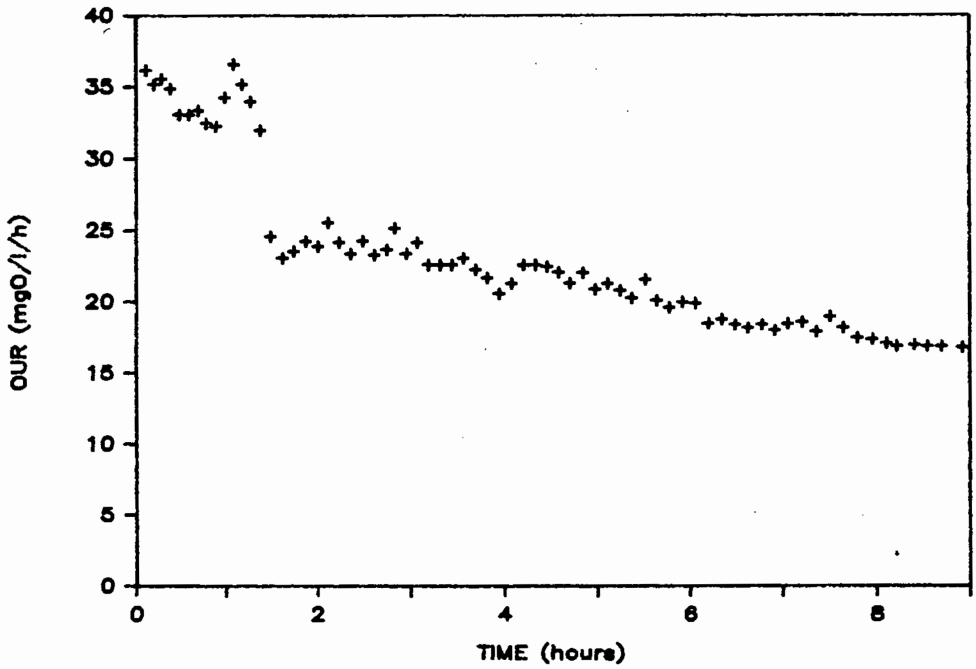


Fig C.6: OUR data from aerobic batch test on sludge from Split-feed system after the introduction of the selector.

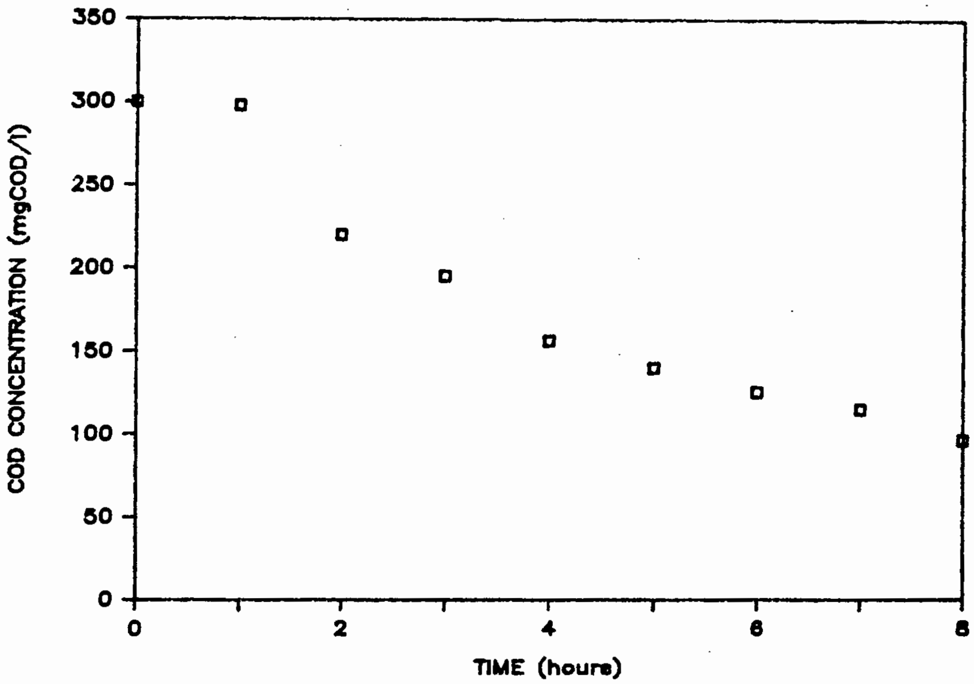


Fig C.7: Filtered COD data from aerobic batch test on sludge from Split-feed system after the introduction of the selector.

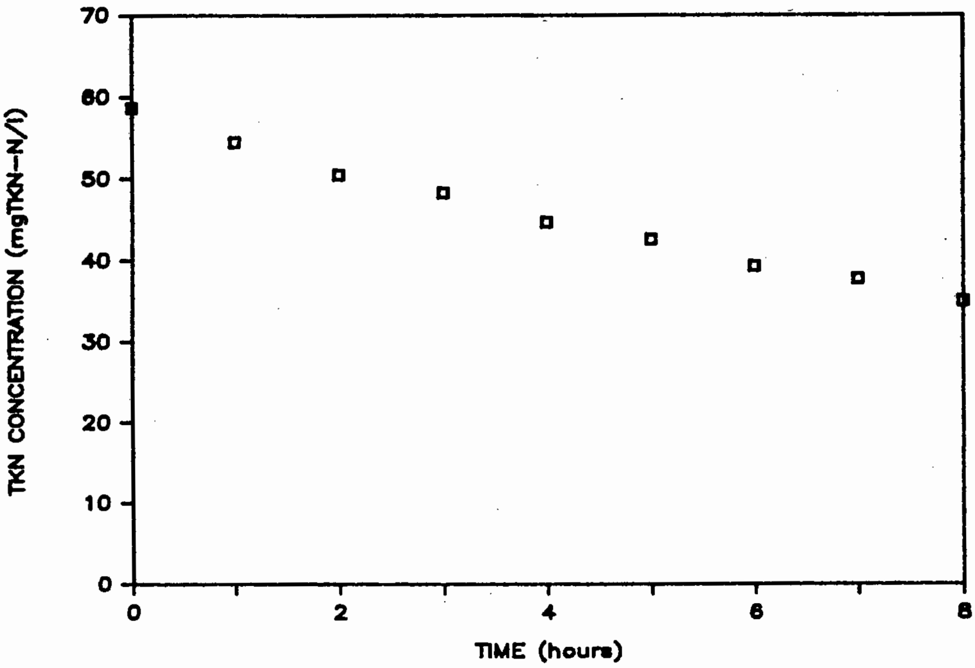


Fig C.8: Filtered TKN data from aerobic batch test on sludge from Split-feed system after the introduction of the selector.

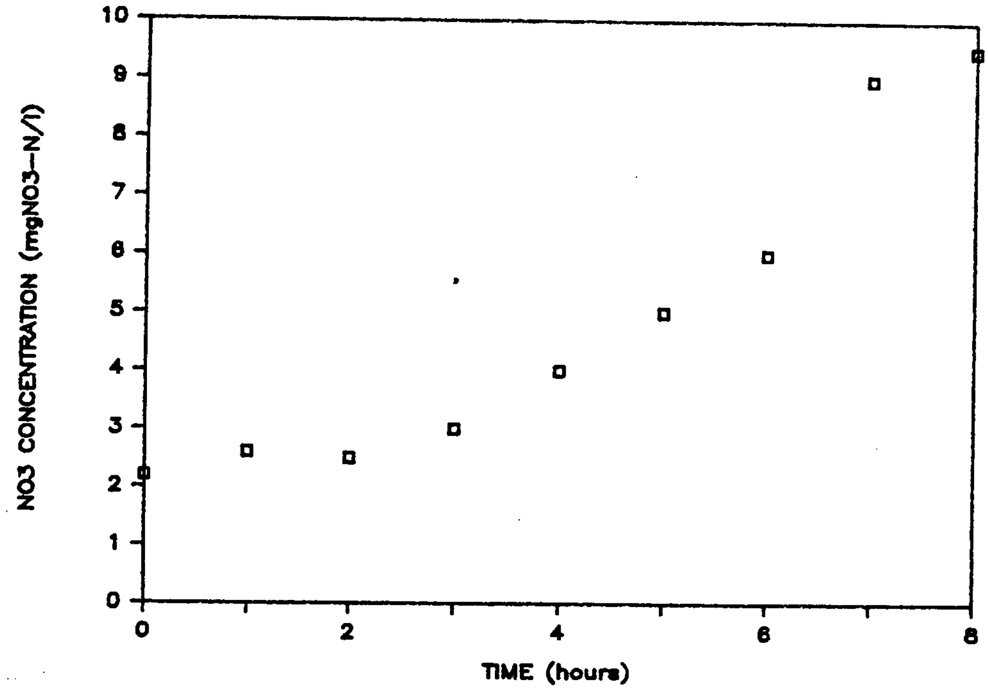


Fig C.9: Filtered nitrate data from aerobic batch test on sludge from Split-feed system after the introduction of the selector.

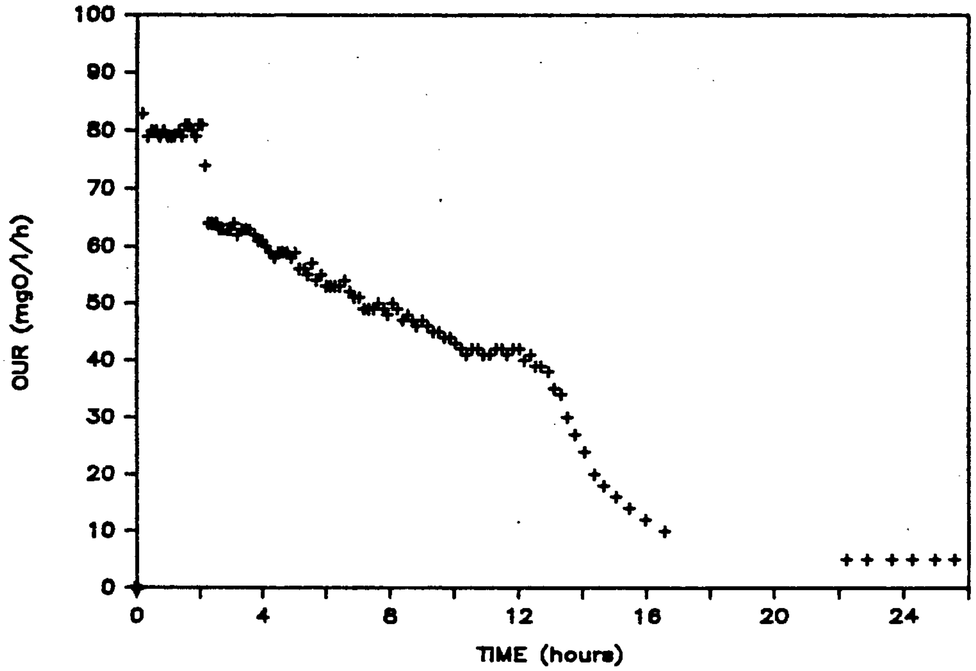


Fig C.10: OUR data from aerobic batch test on sludge from the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

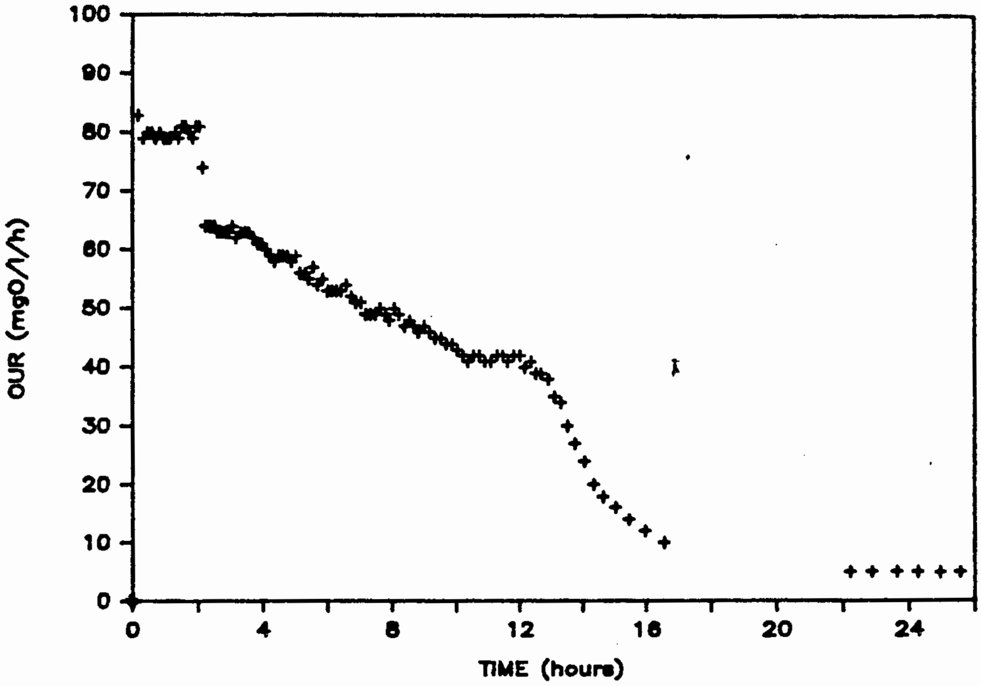


Fig C.11: OUR data from aerobic batch test on sludge from the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

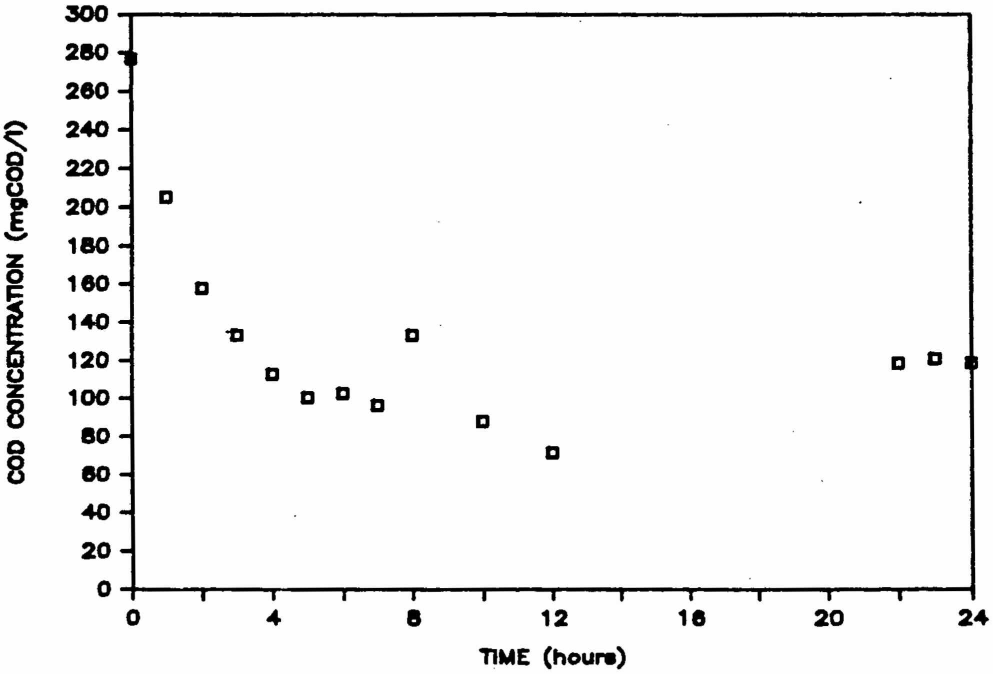


Fig C.12: Filtered COD data from aerobic batch test on sludge from the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

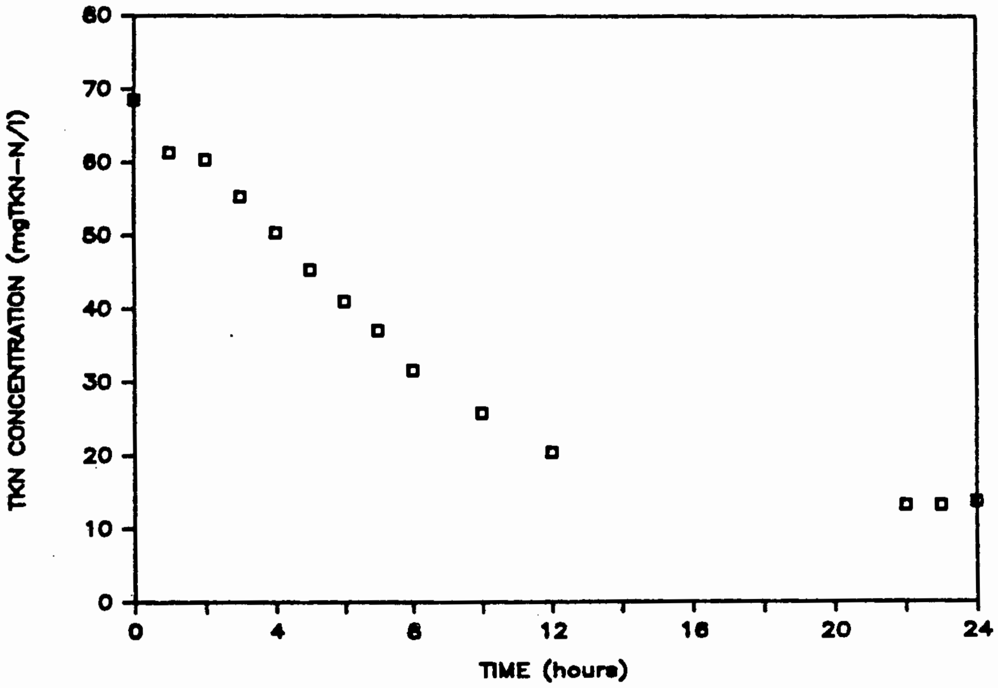


Fig C.13: Filtered TKN data from aerobic batch test on sludge from the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

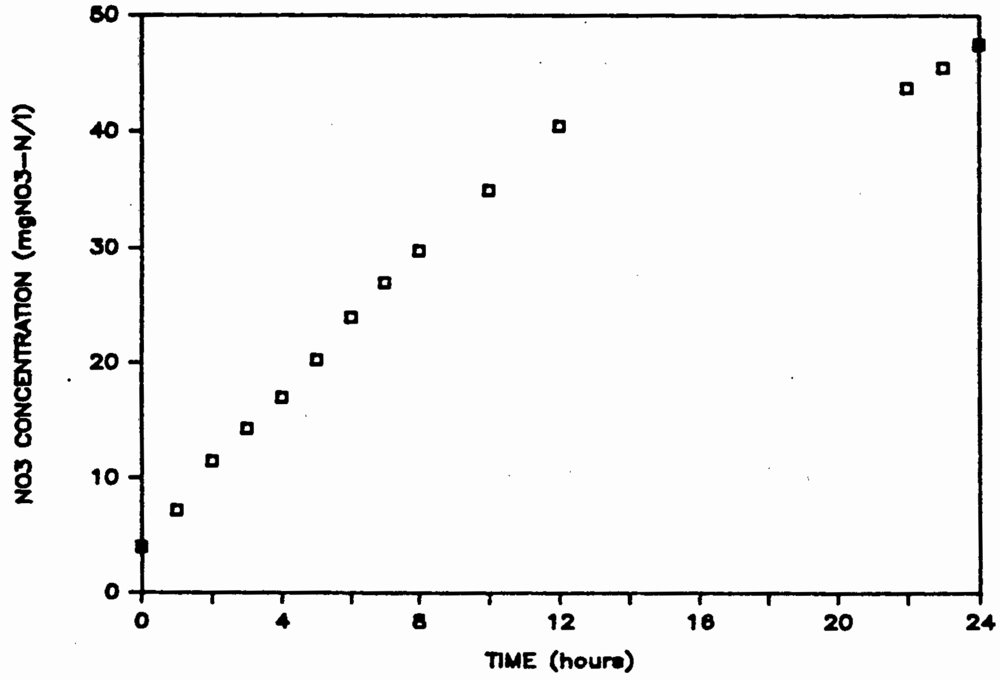


Fig C.14: Filtered nitrate date from aerobic batch test on sludge from the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

APPENDIX D

STATISTICAL ANALYSIS

In analysing the experimental data, it was necessary to obtain a set of values of the process parameters for each system such that the values accurately represented the behaviour of the system. The method chosen to obtain the set of representative values involved testing the experimental data for normality and, if the distribution appeared to be statistically normal, determining the mean and standard deviation of the mean for each process parameter. The detailed procedure followed is presented below.

Assume we have a set of m data points. Then

1. Rank the data in ascending order, say x_1, x_2 ... x_n ... x_m.

2. Assign a probability value of (n-1/2)/m to each, starting from x_1.

3. Plot the assigned prbability values against the x values on probability paper.

4. Draw the best straight line through the values.

5. Determine the mean ($\bar{x}$) from the 50 percent probability value.

6. Determine the standard deviation (σ) from the 84 percent probability value, i.e. $\sigma = x_{84} - x_{50}$.

7. Calculate the standard deviation of the mean (σ_m) using $\sigma_m = \sigma.2/\sqrt{m}$

   $\sigma.2/\sqrt{m}$

In order to demonstrate the strong normal characteristics displayed by the data, the probability graphs for a typical set of experimental results (Johannesburg system at 5 day sludge age with an s-recycle ratio of 1) are shown in Figs D.1 to D.23.

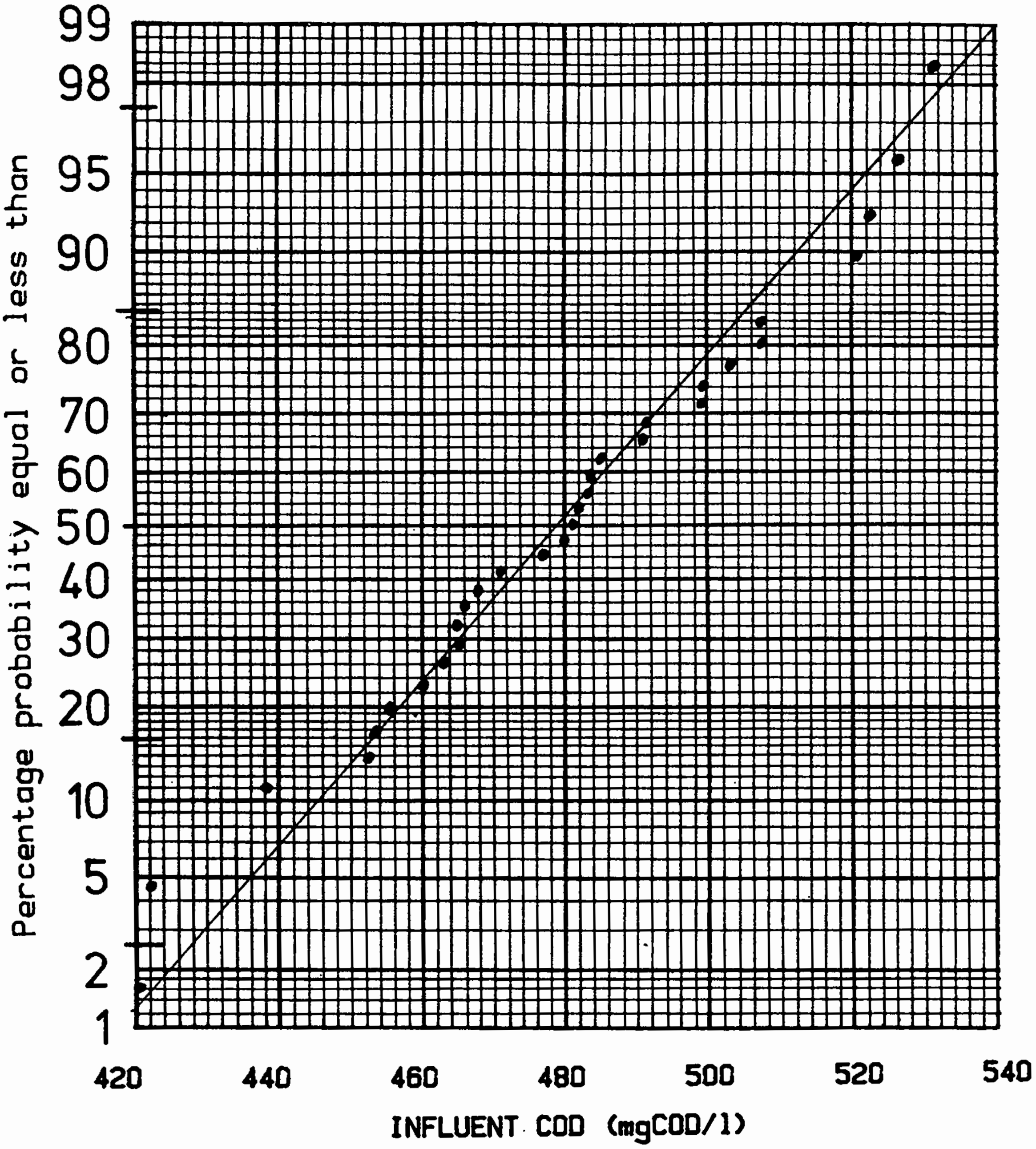


Fig D.1: Statistical plot of influent COD data for 5 day sludge age Johannesburg system with s-recycle ratio of 1:1.

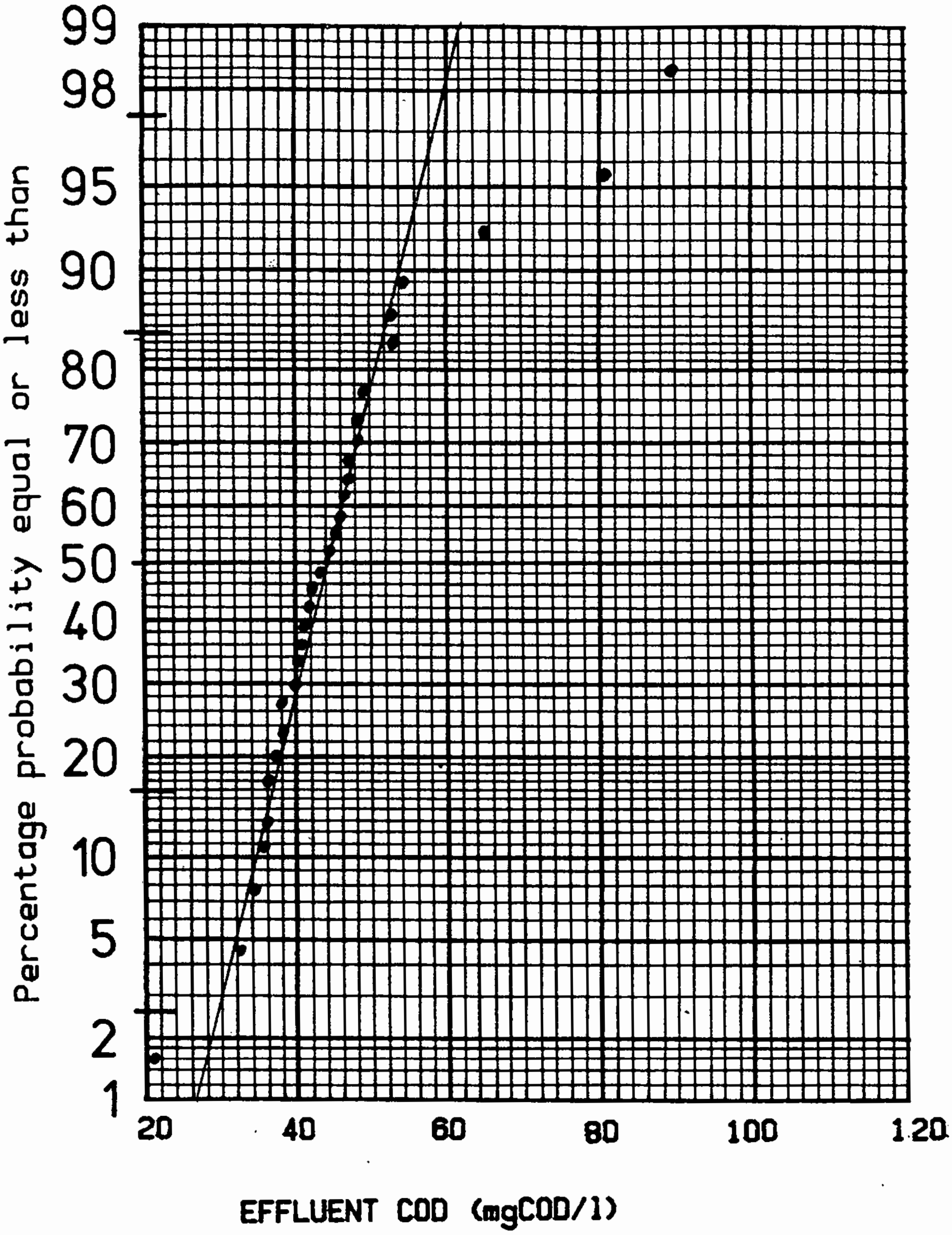


Fig D.2: Statistical plot of effluent COD data for 5 day sludge age Johannesburg system with s-recycle ratio of 1:1.

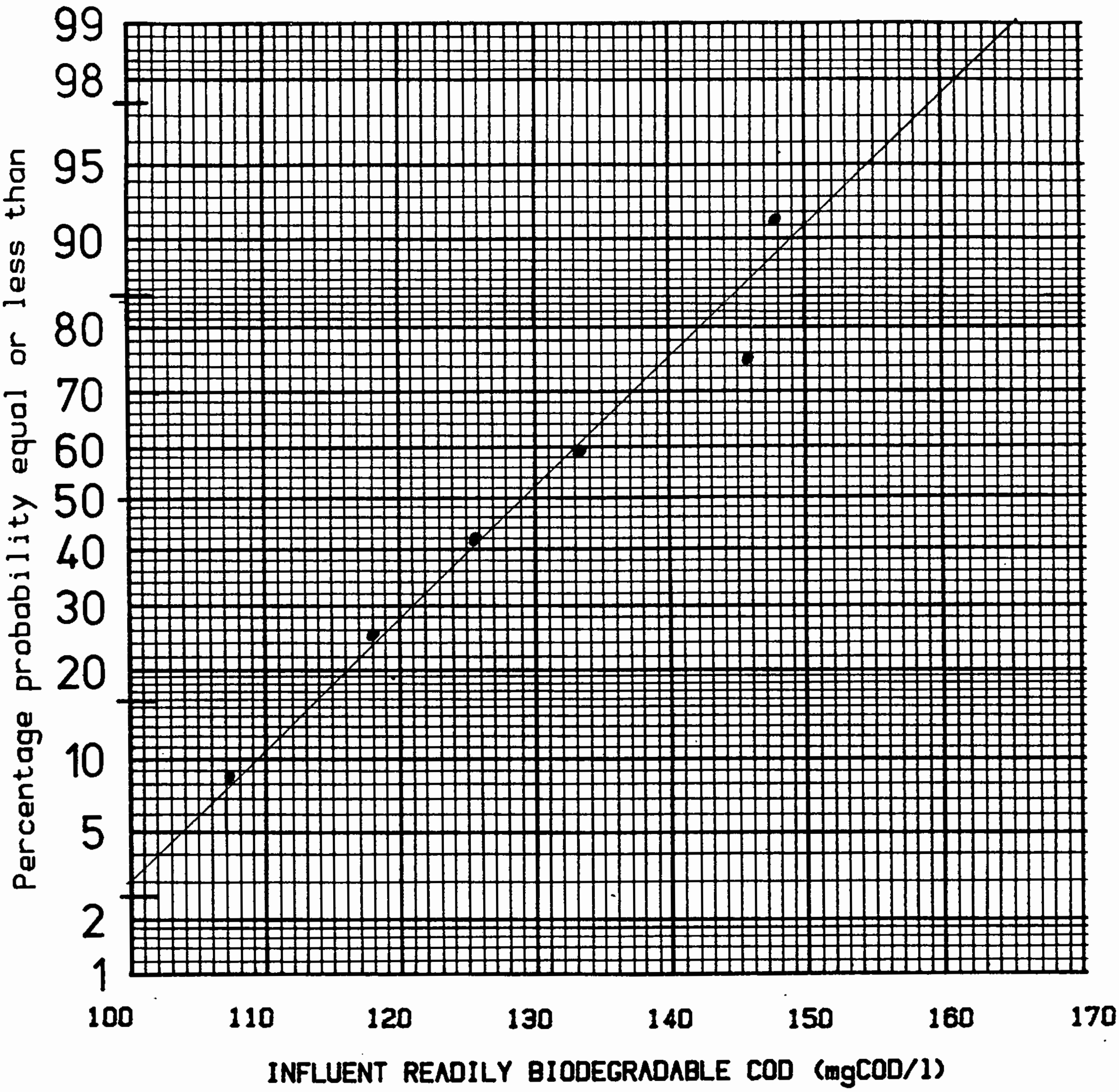


Fig D.3: Statistical plot of influent readily biodegradable COD data for 5 day sludge age Johannesburg system with s-recycle ratio of 1:1.

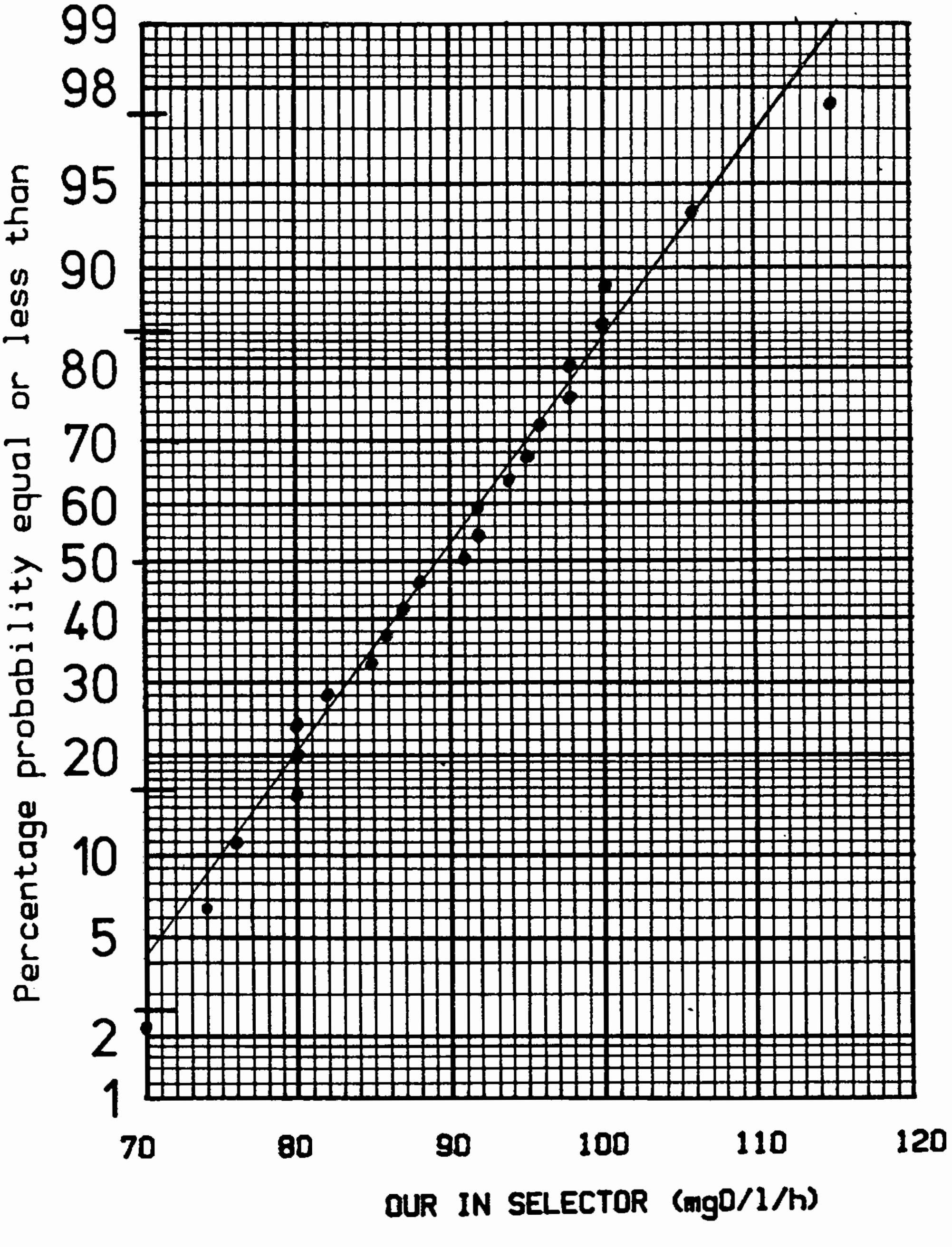


Fig D.4: Statistical plot of oxygen utilization rates in the selector of the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

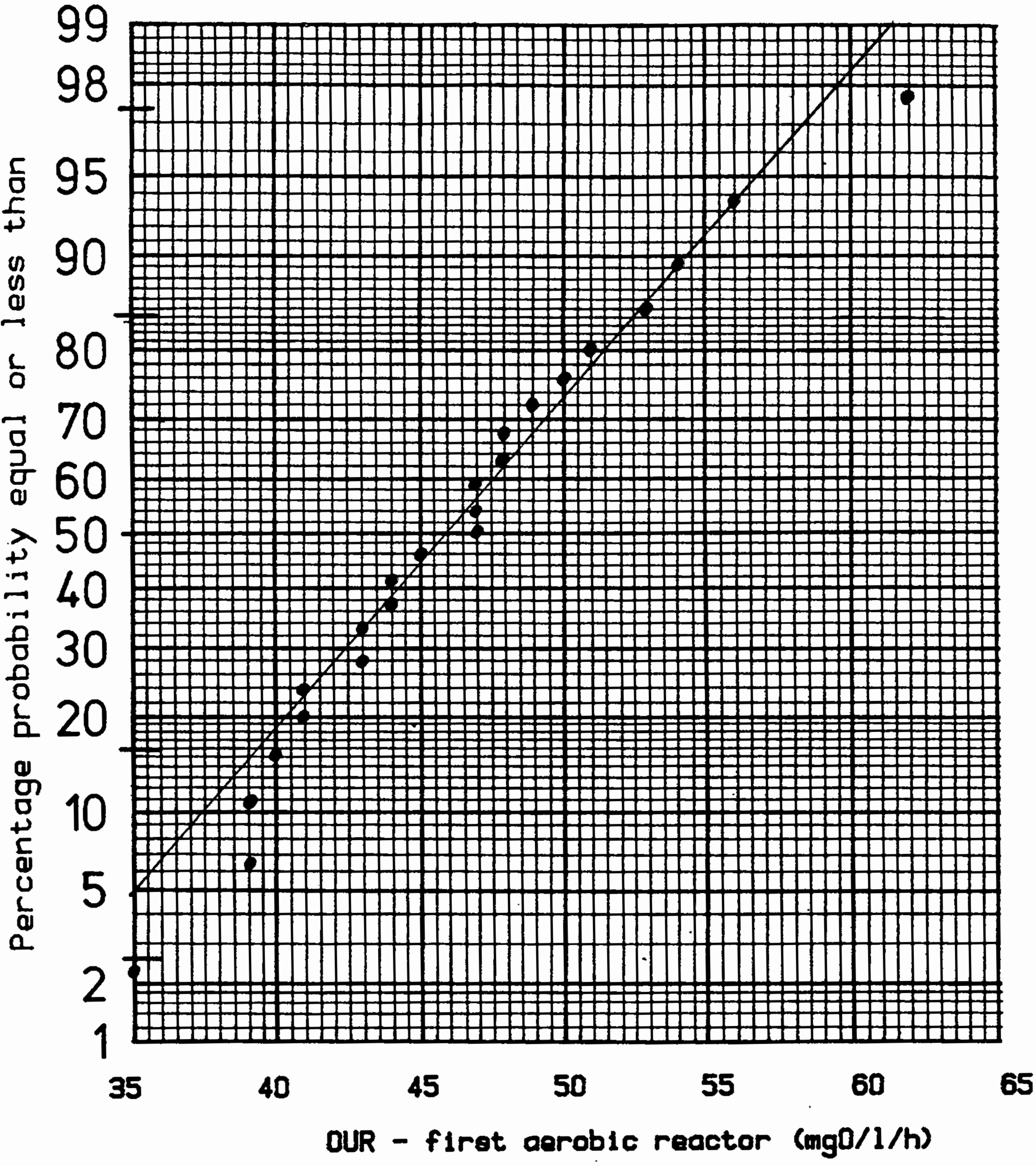


Fig D.5: Statistical plot of oxygen utilization rates in the first aerobic reactor of a 5 day sludge age Johannesburg system with s-recycle ratio of 1:1.

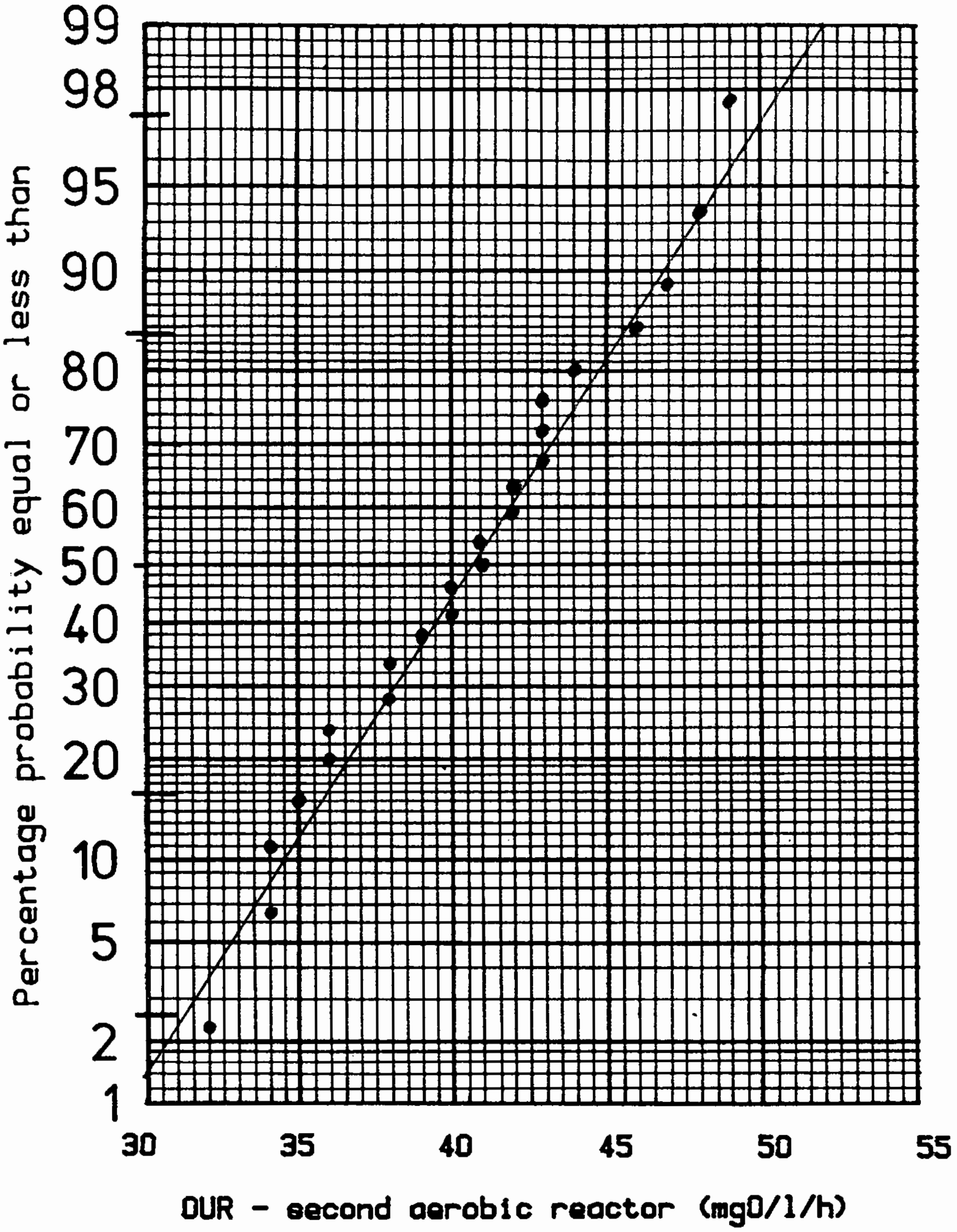
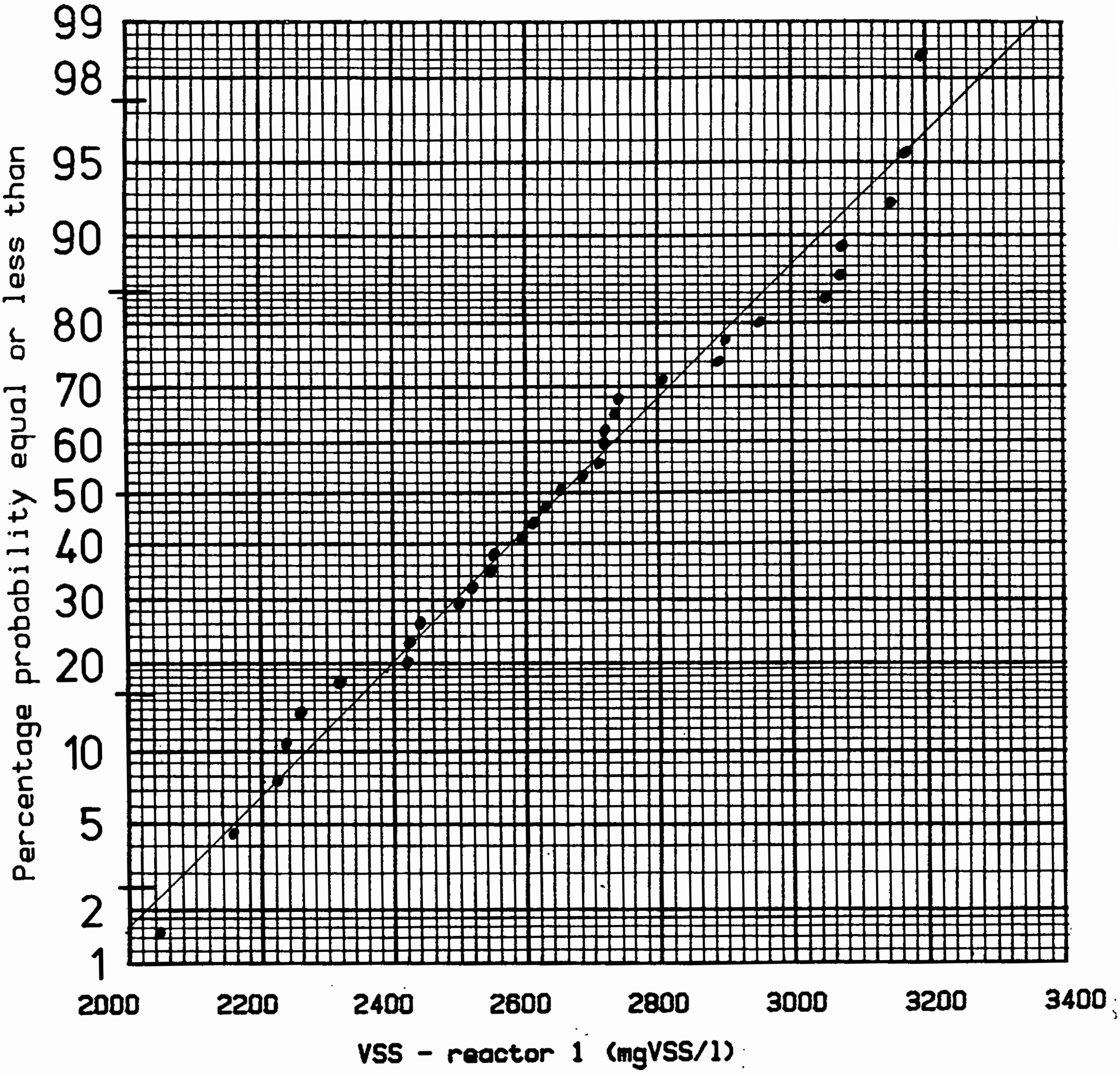


Fig D.6: Statistical plot of oxygen utilization rates in the second aerobic reactor of the 5 day sludge age Johannesburg system with s-recycle ratio of 1:1.



<u>Fig D.7</u>: Statistical plot of volatile suspended solids in the first reactor of the 5 day sludge age Johannesburg system with s-recycle ratio of 1:1.

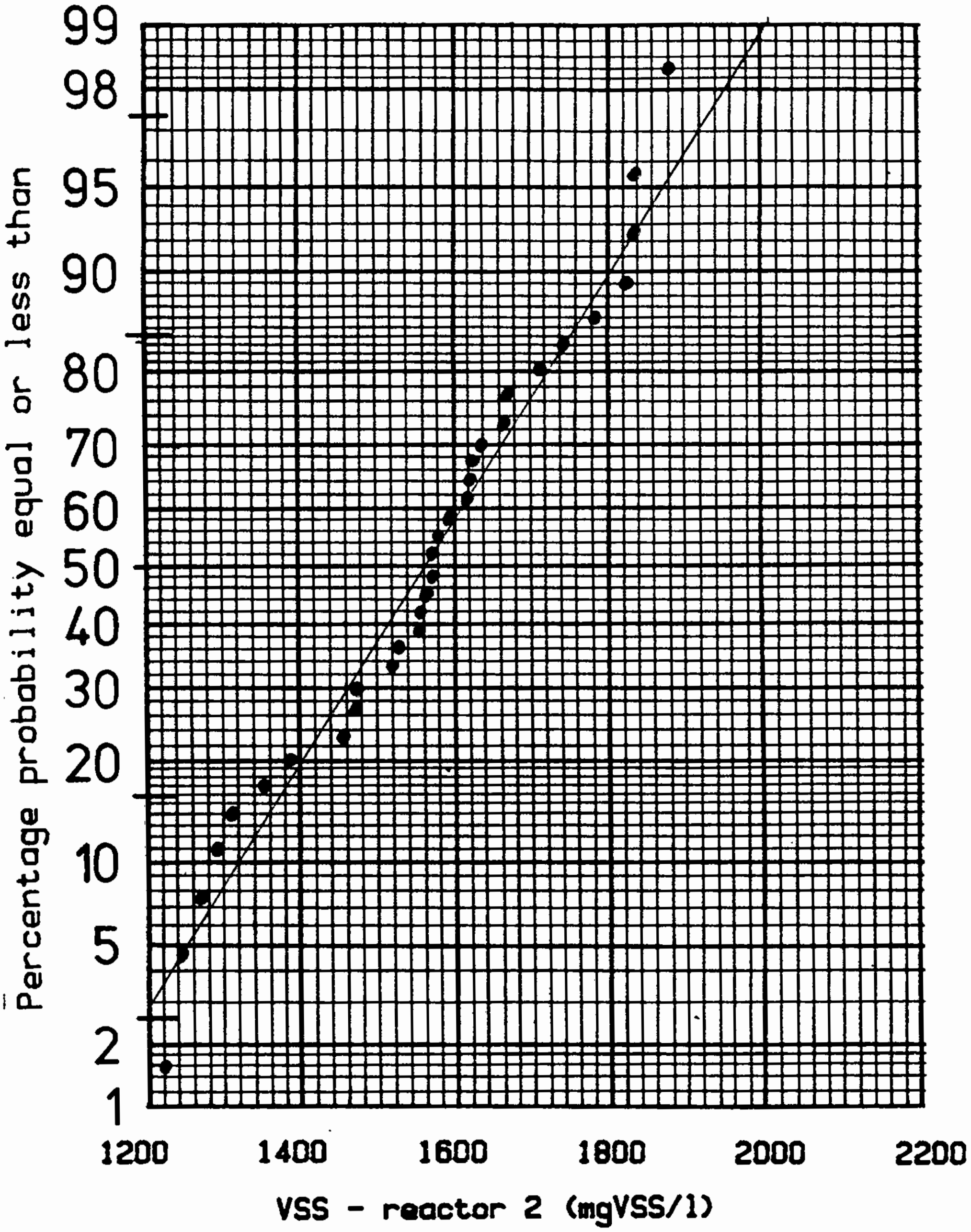


Fig D.8: Statistical plot of volatile suspended solids in the second reactor of the 5 day sludge age Johannesburg system with s-recycle ratio of 1:1.

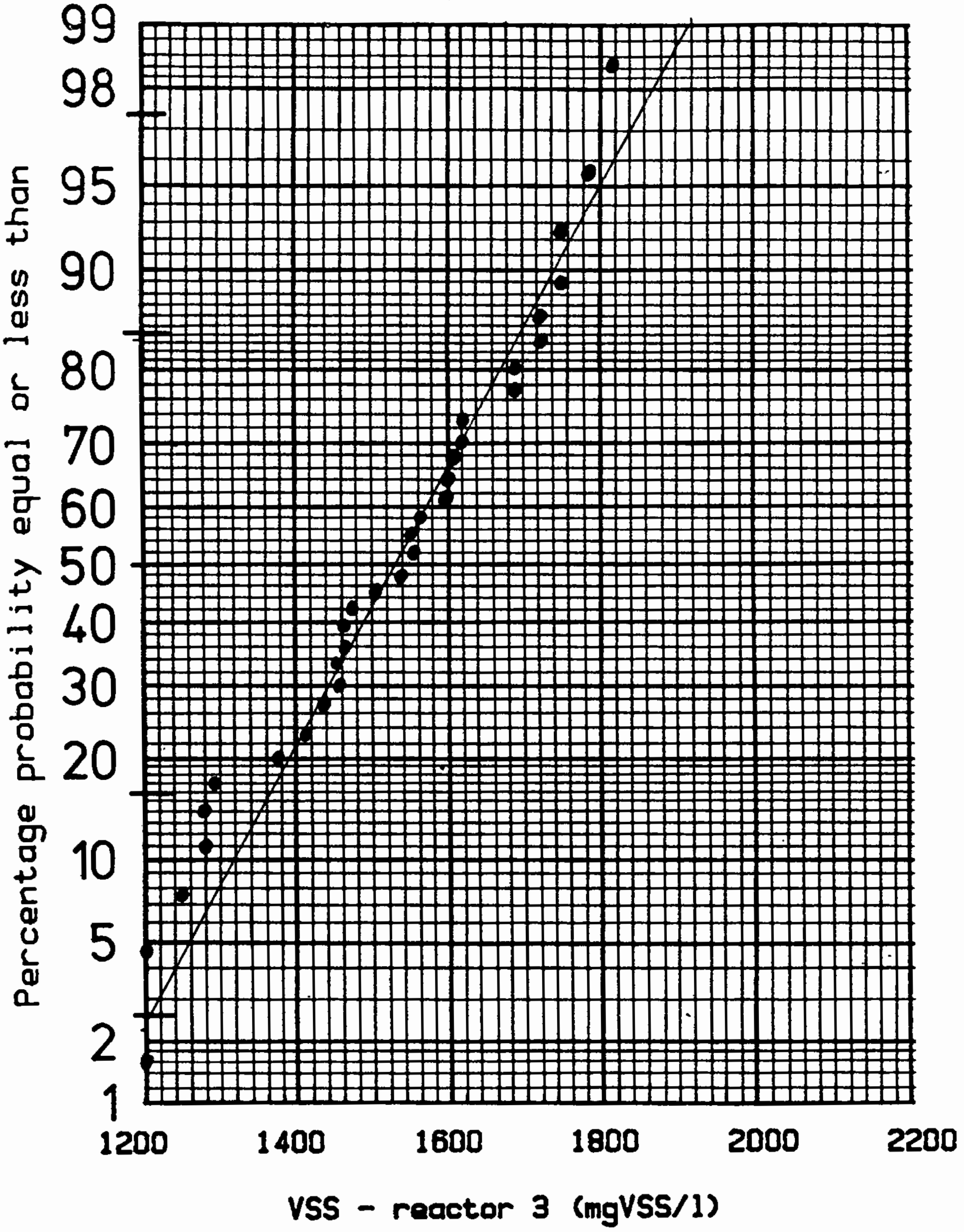


Fig D.9: Statistical plot of volatile suspended solids in the third reactor of the 5 day sludge age Johannesburg system with s-recycle ratio of 1:1.

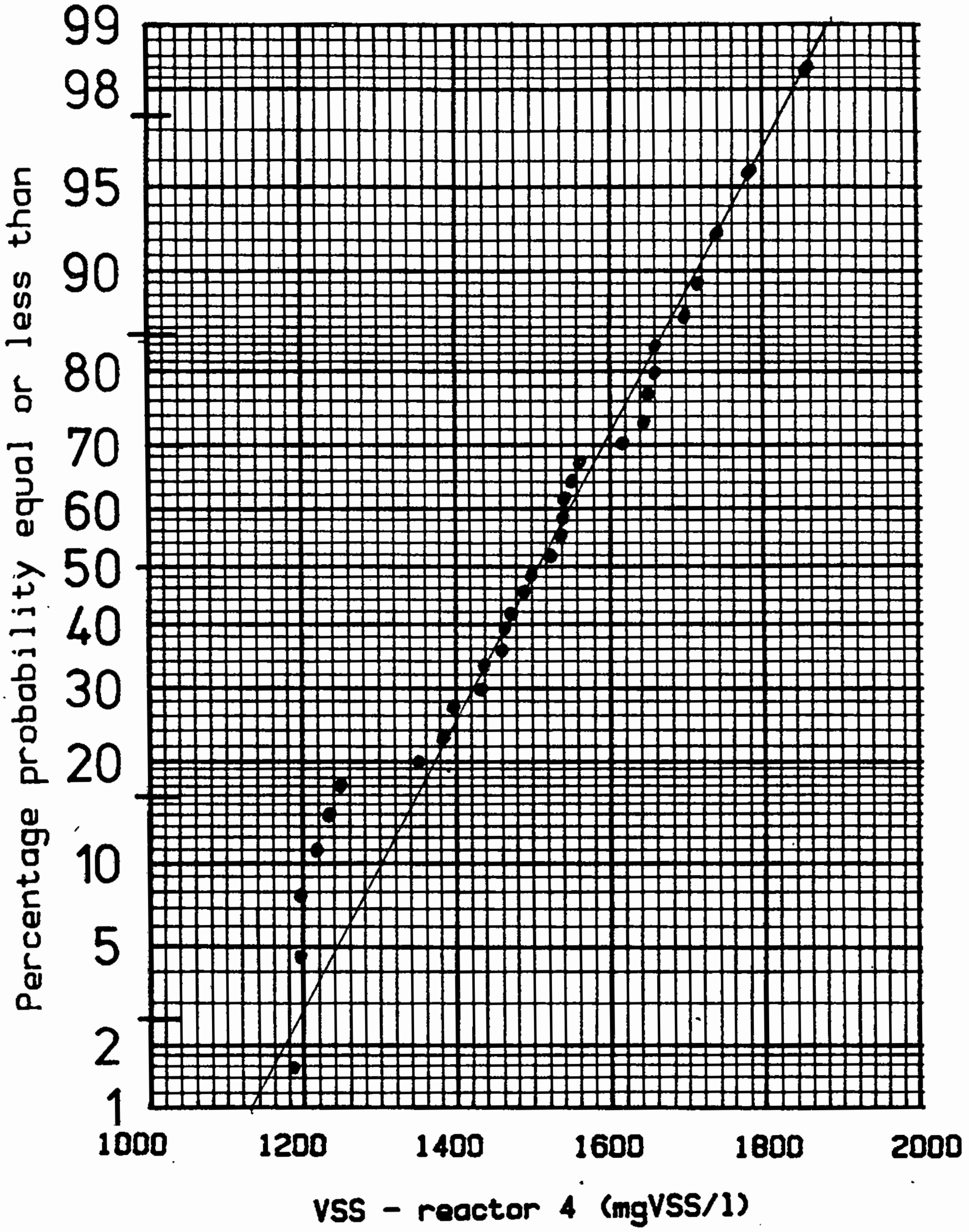


Fig D.10: Statistical plot of volatile suspended solids in the fourth reactor of the 5 day sludge age Johannesburg system with s-recycle ratio of 1:1.

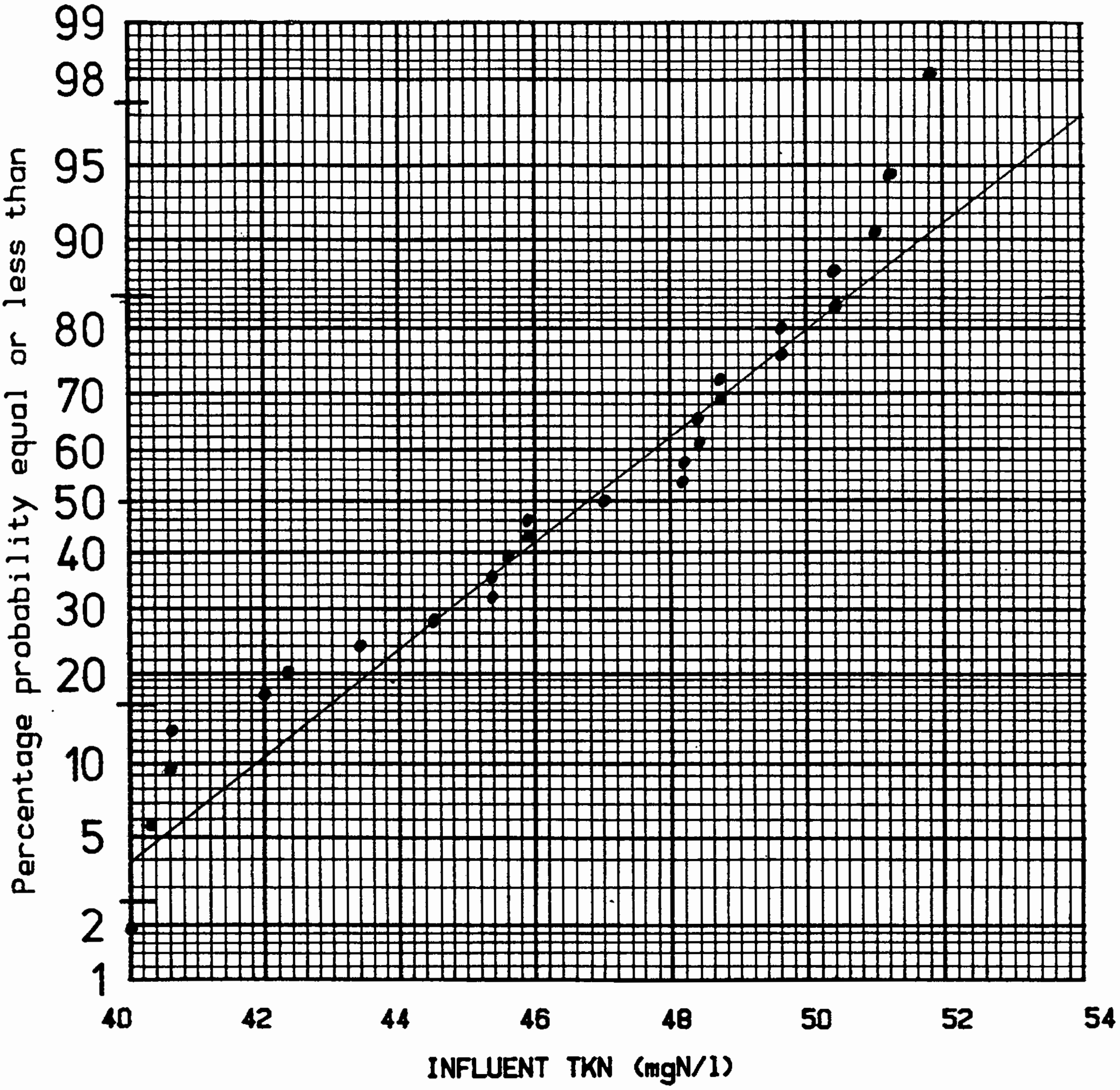


Fig D.11: Statistical plot of influent TKN concentrations for the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

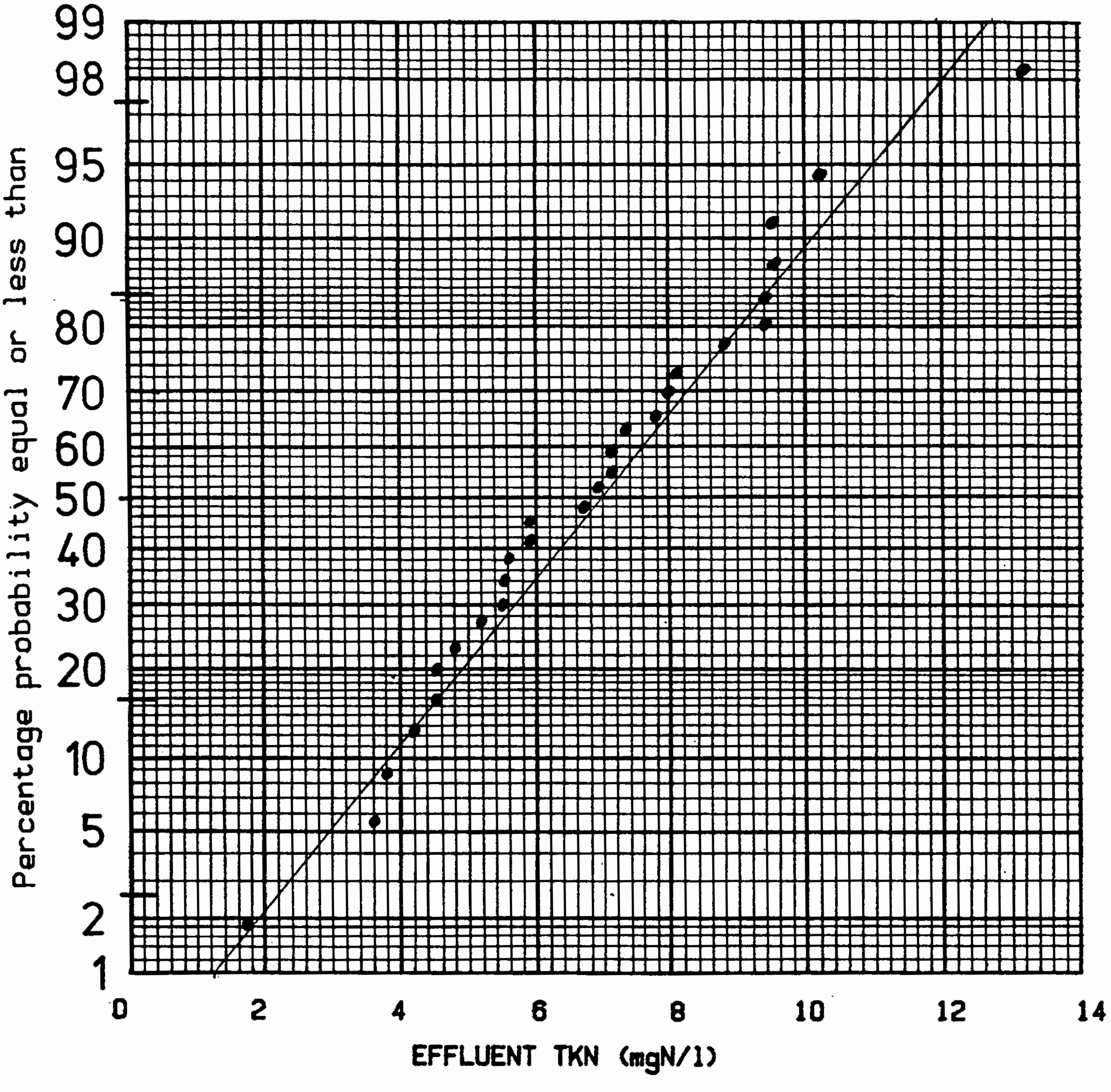


Fig D.12: Statistical plot of effluent TKN concentrations for the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

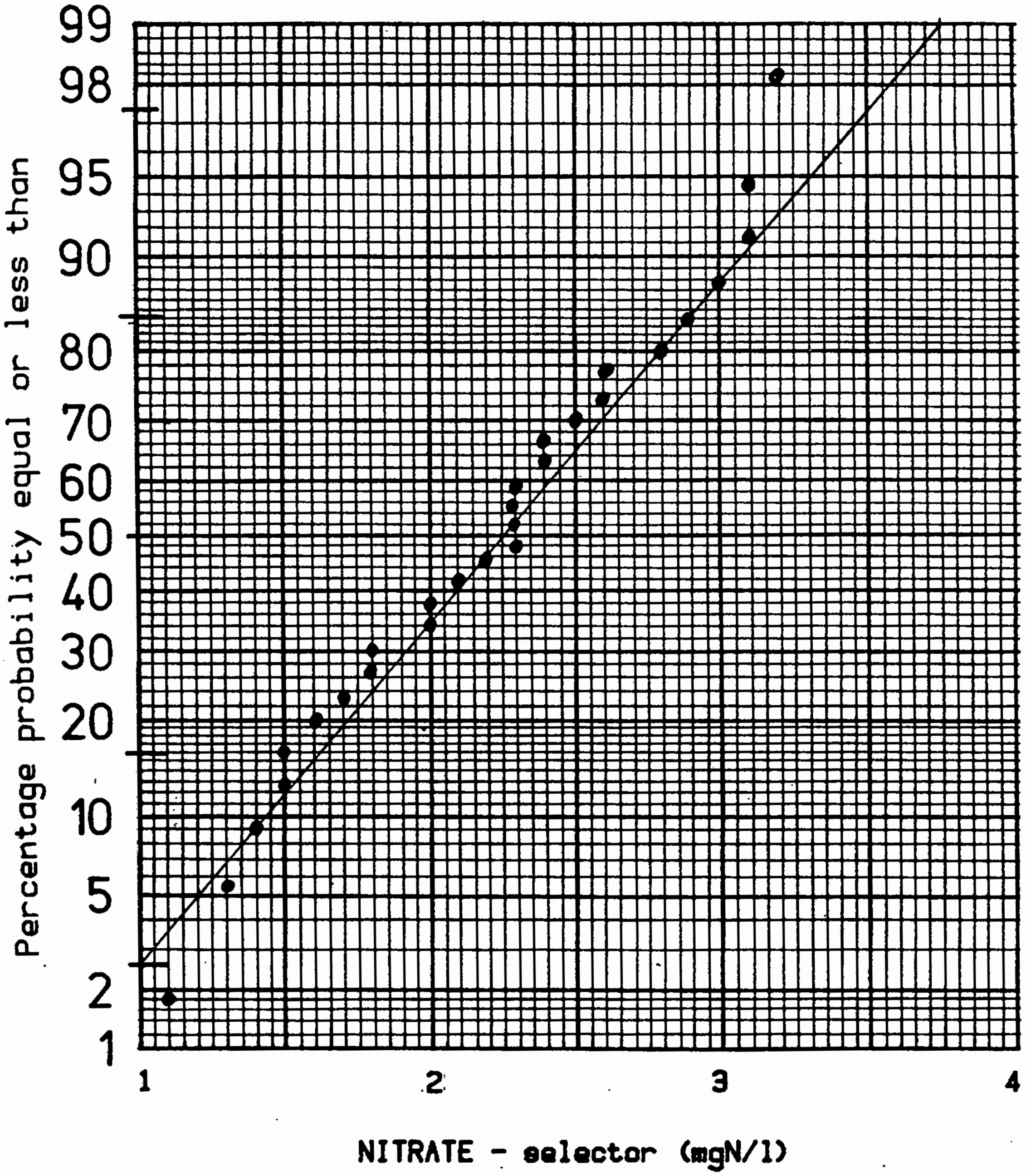
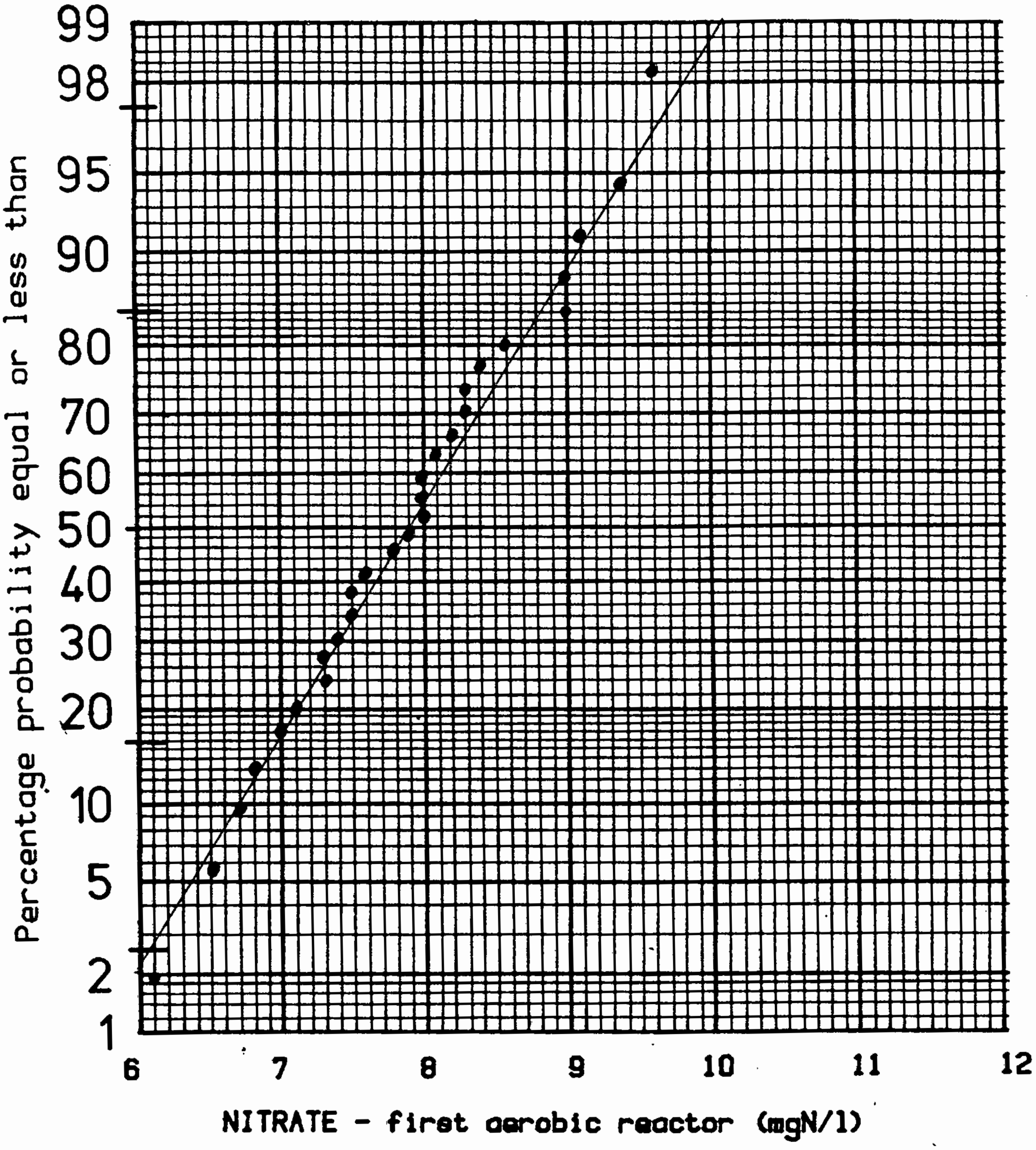


Fig D.13: Statistical plot of nitrate concentrations in the selector of the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.



<u>Fig D.14</u>: Statistical plot of nitrate concentrations in the first aerobic reactor of the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

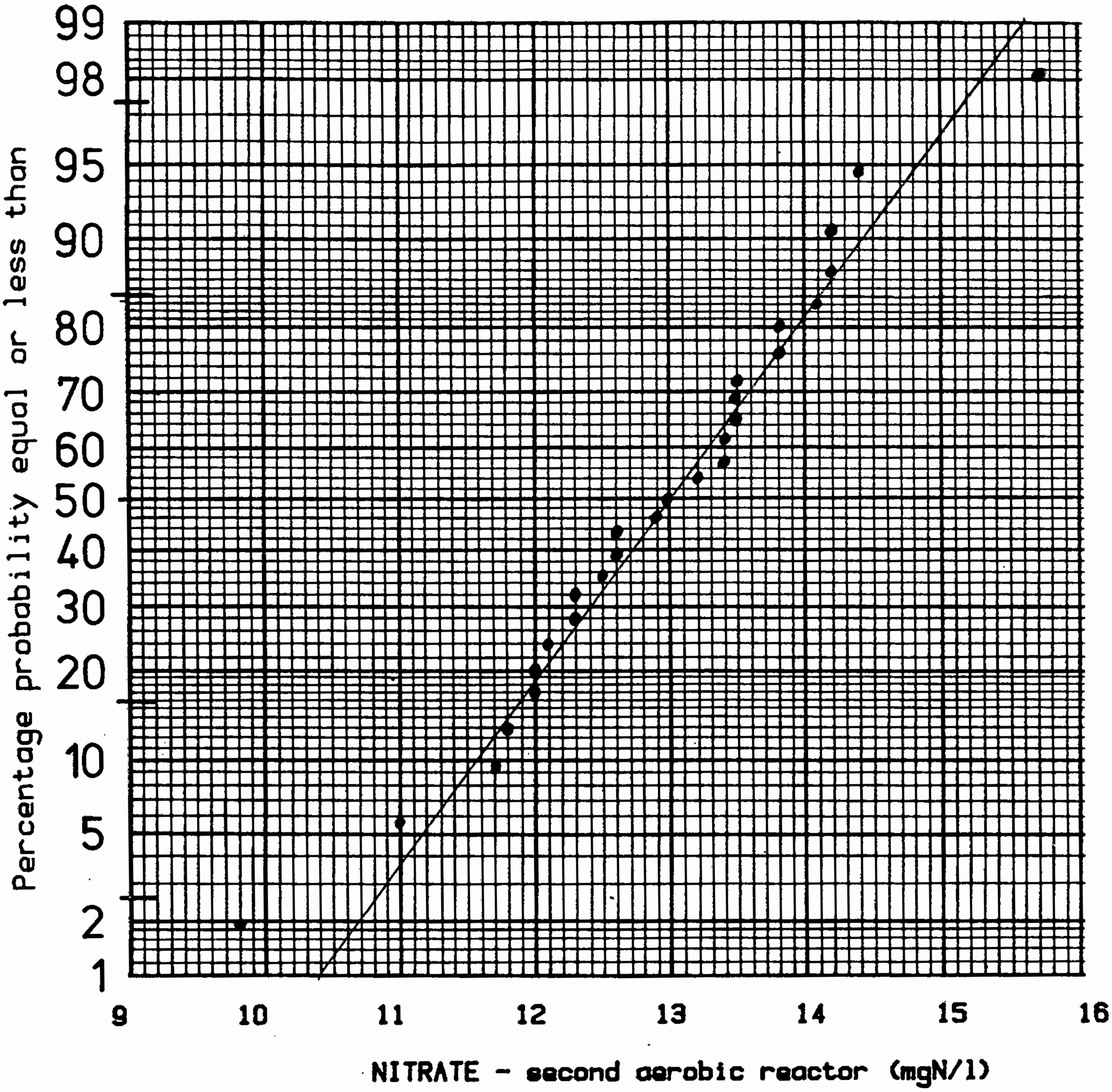


Fig D.15: Statistical plot of nitrate concentrations in the second aerobic reactor of the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

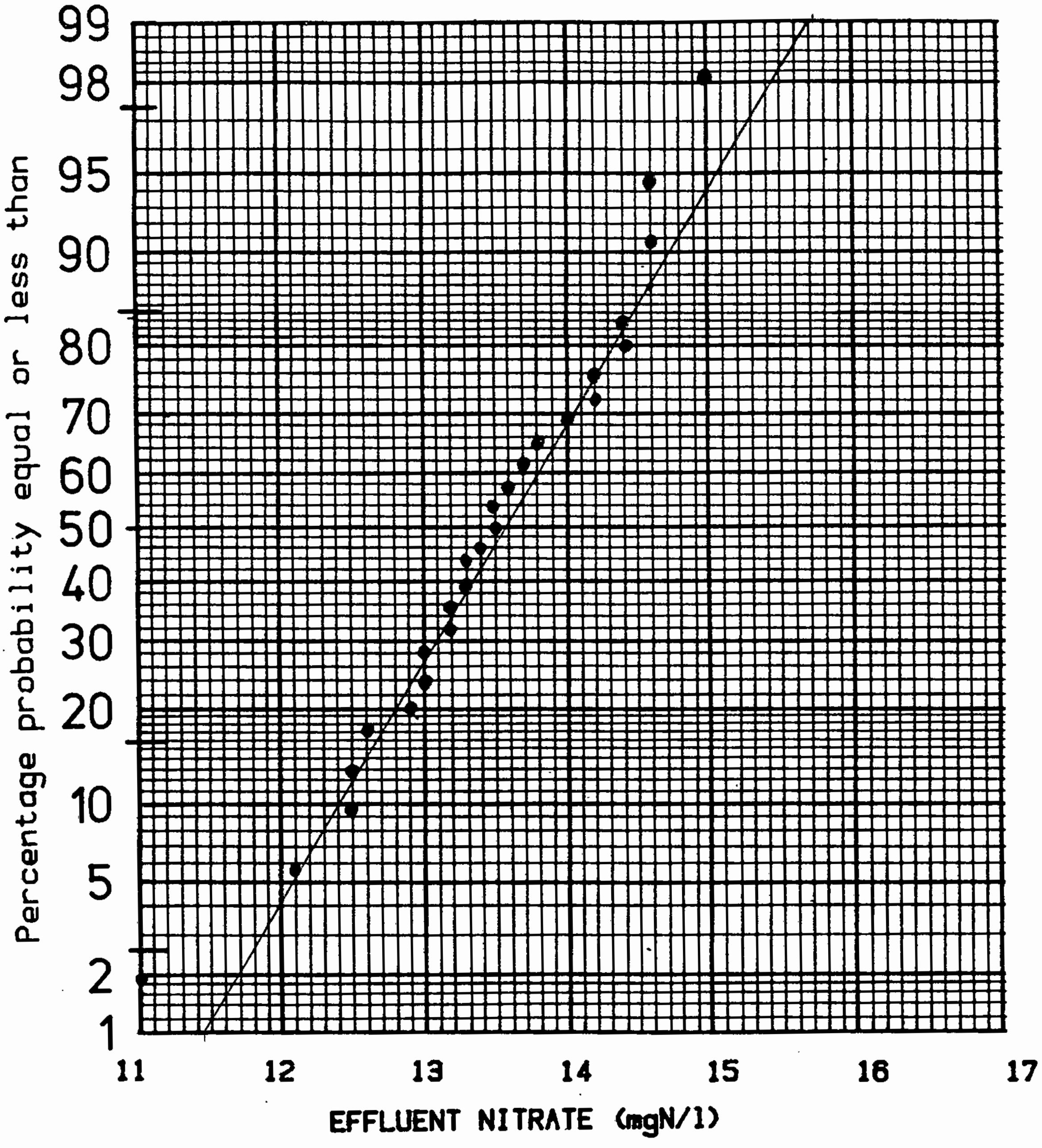


Fig D.16: Statistical plot of effluent nitrate concentrations for the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

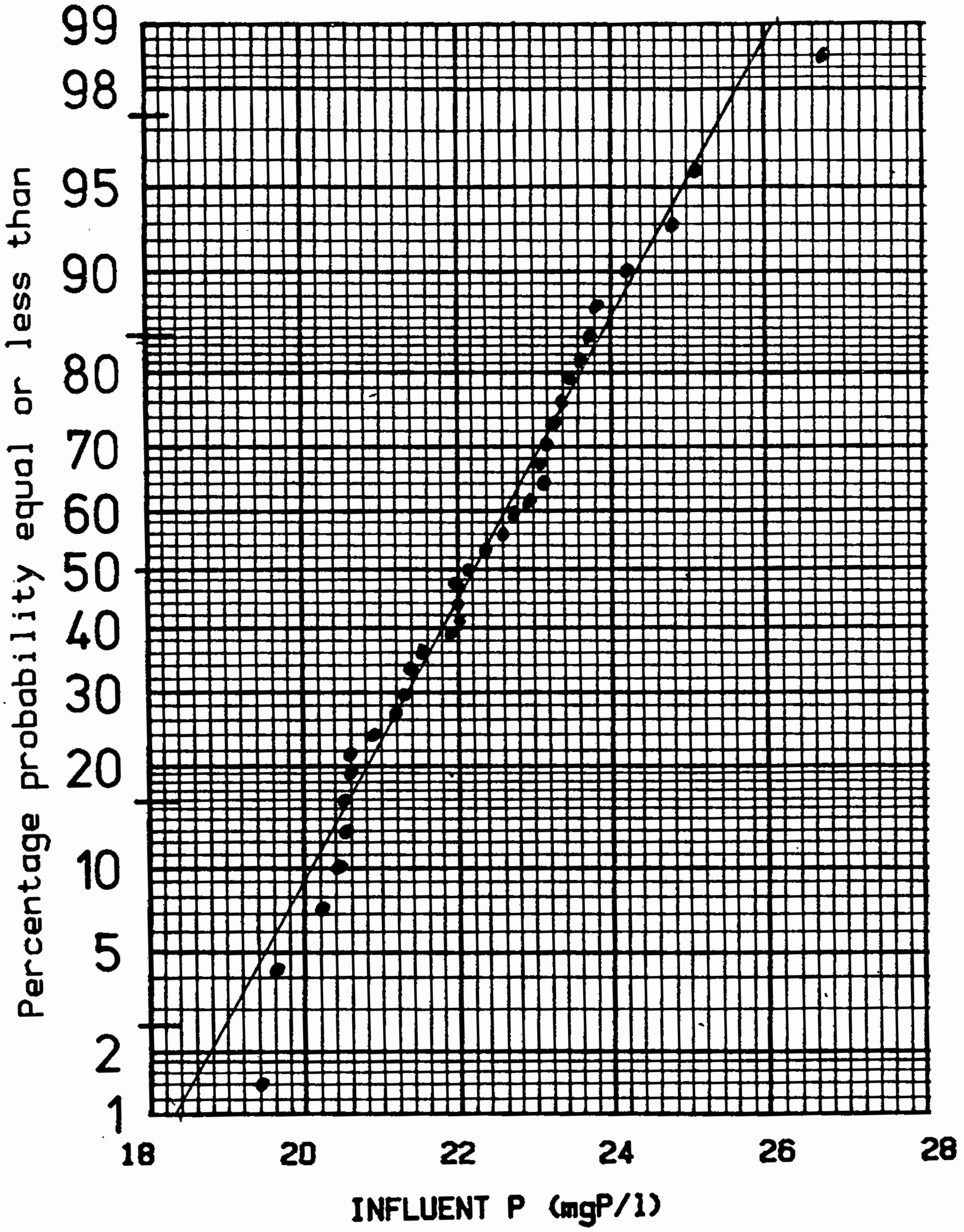


Fig D.17: Statistical plot of influent phosphorus concentrations for the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

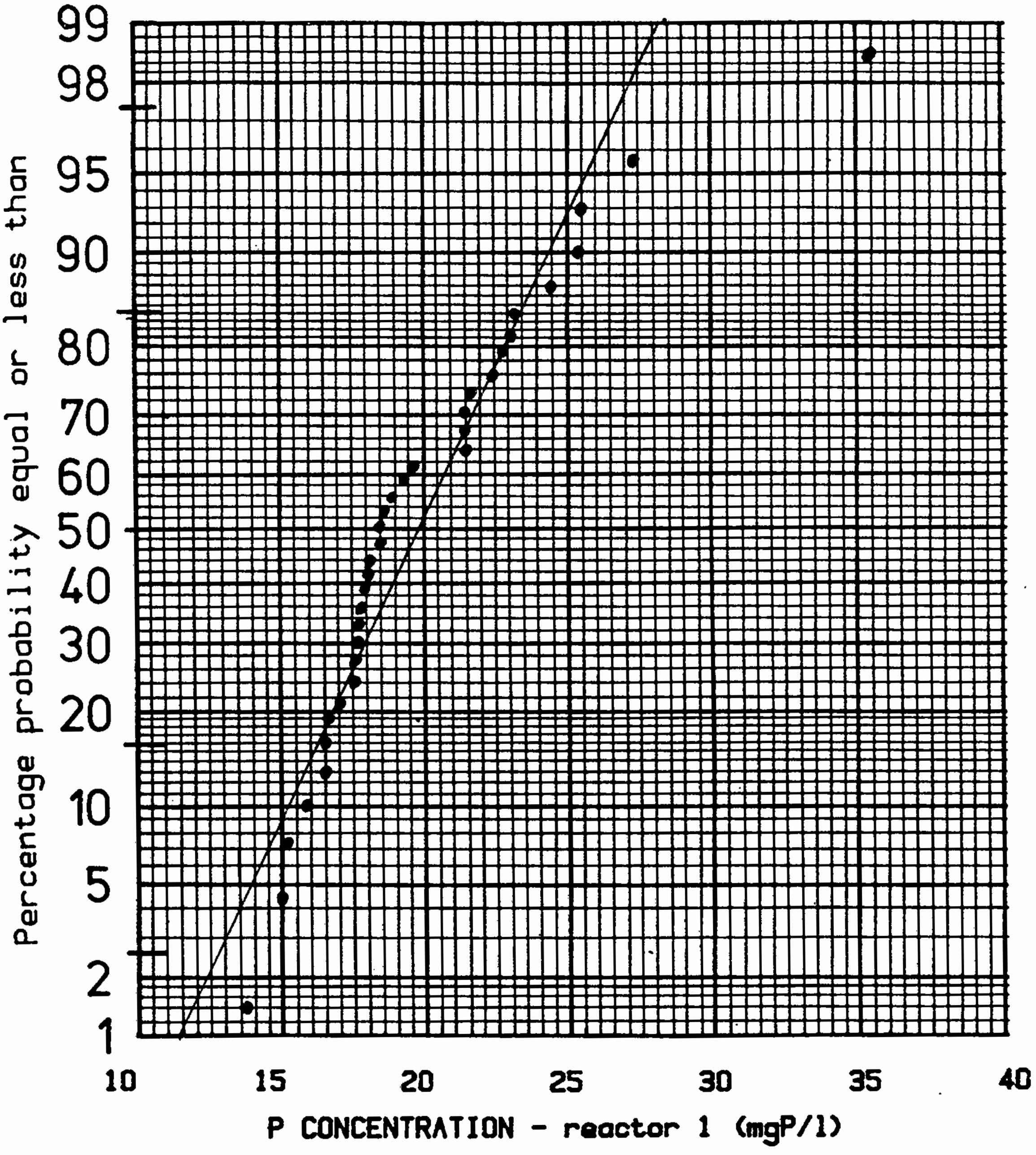


Fig D.18: Statistical plot of phosphorus concentrations in the first reactor of the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

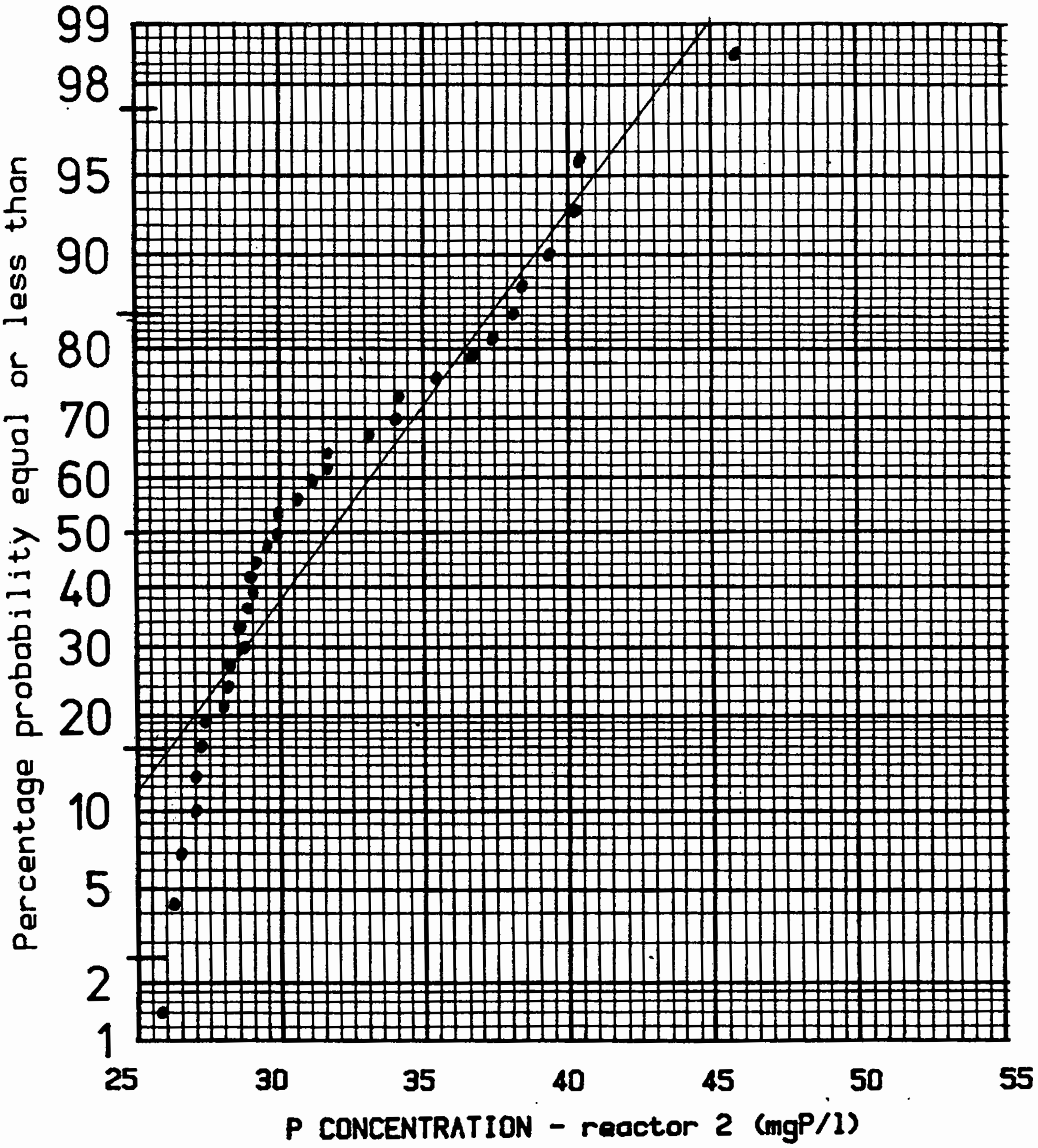


Fig D.19: Statistical plot of phosphorus concentrations in the second reactor of the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

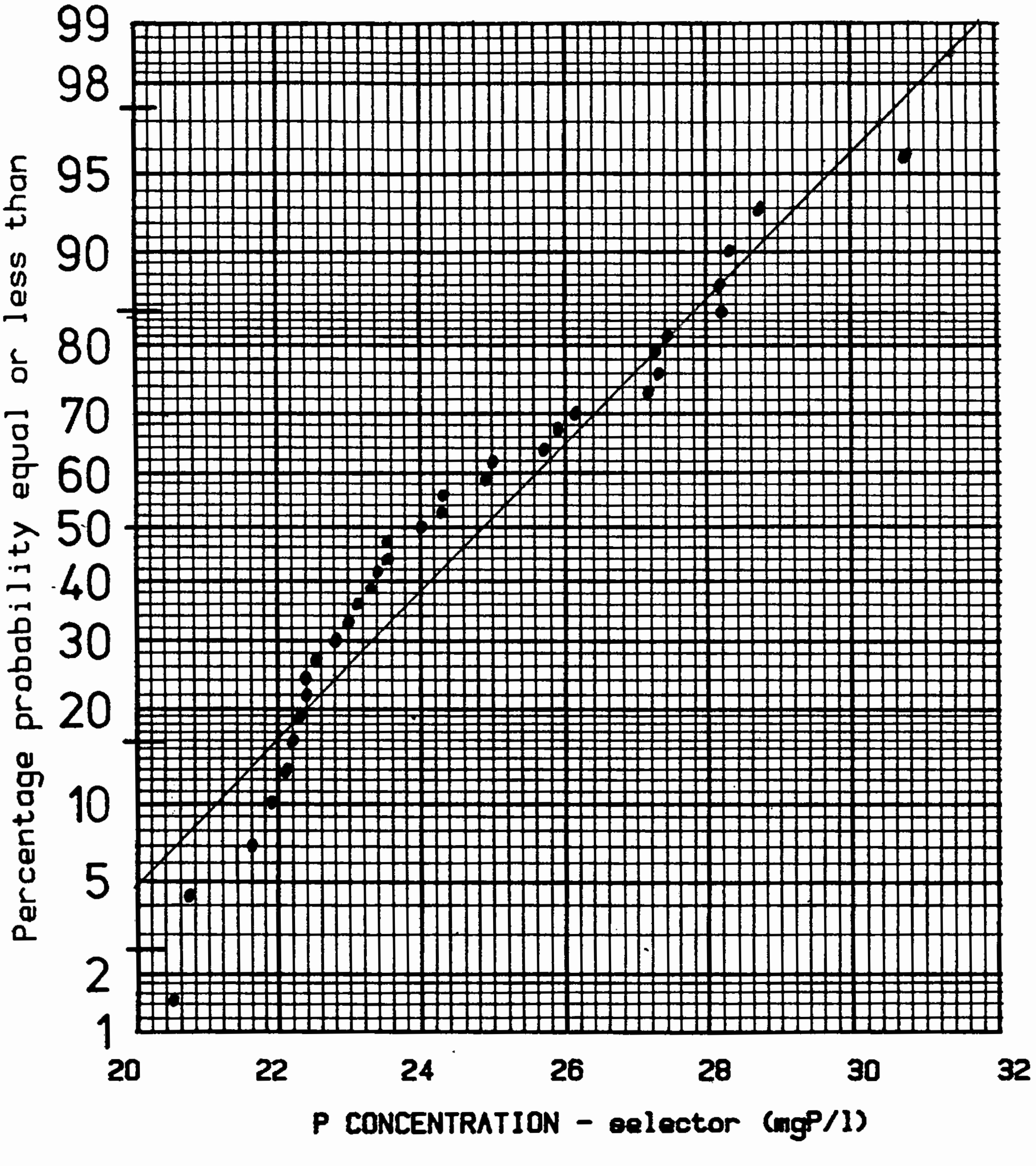


Fig D.20: Statistical plot of phosphorus concentrations in the selector of the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

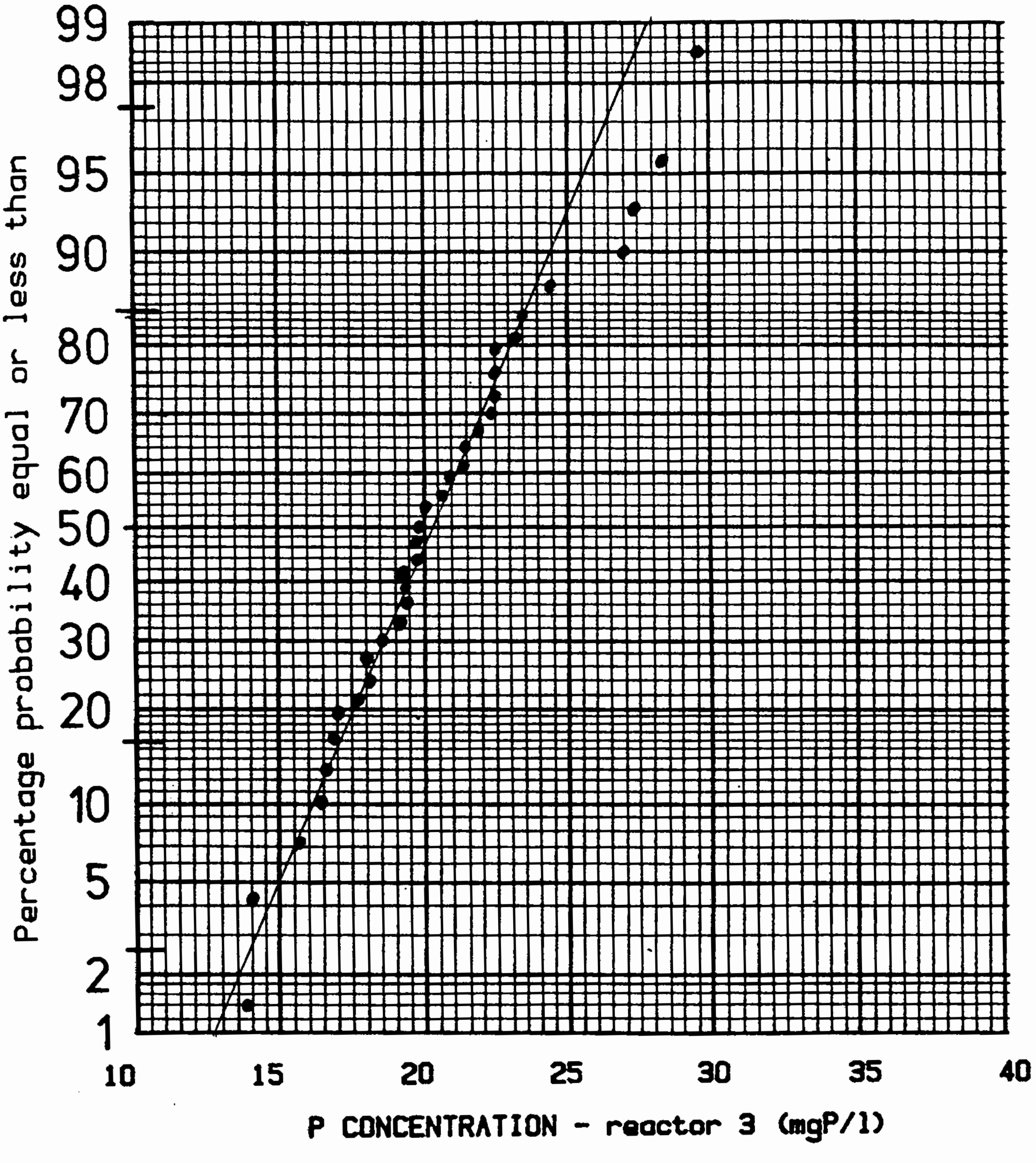


Fig D.21: Statistical plot of phosphorus concentrations in the third reactor of the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

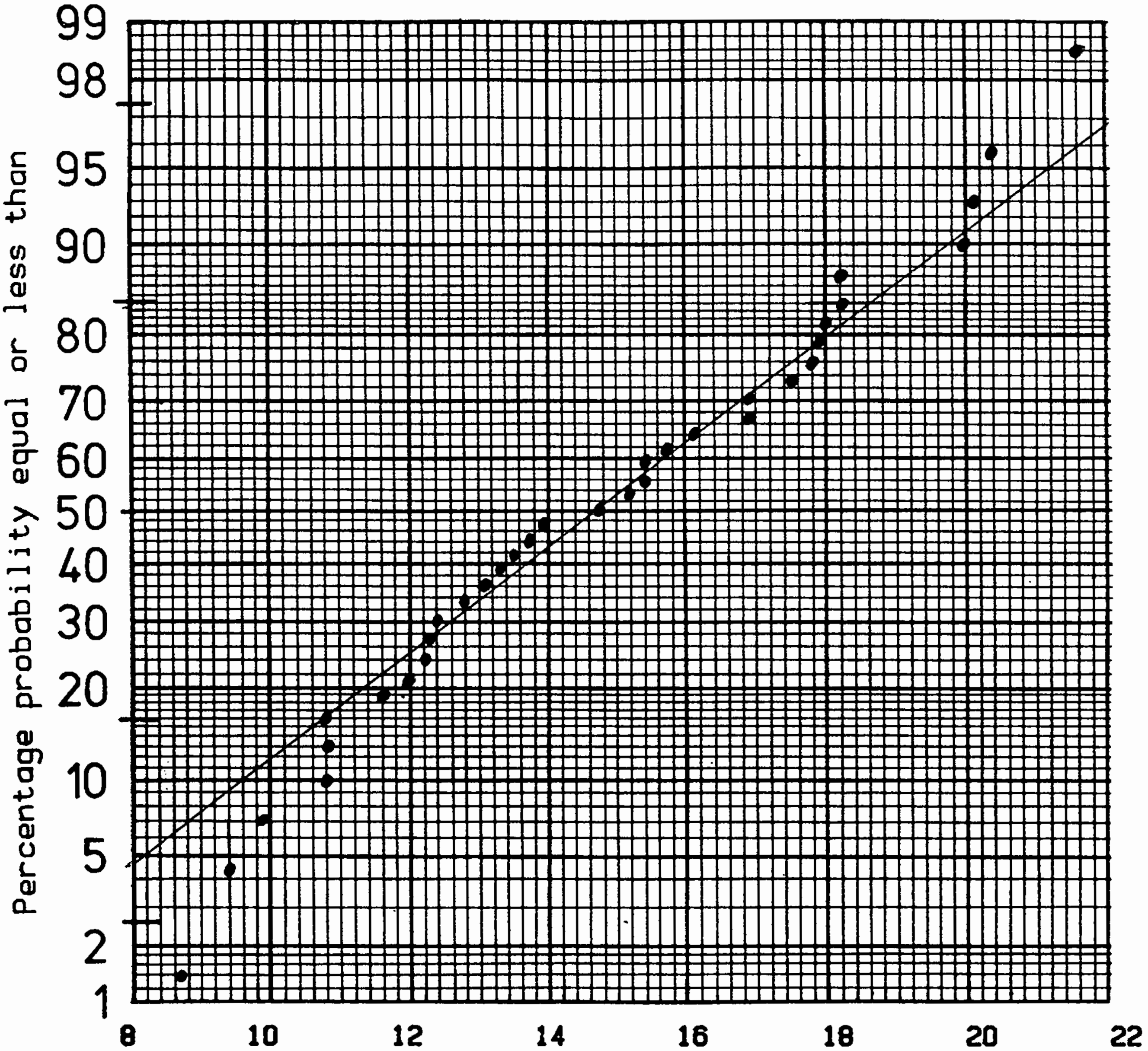


Fig D.22: Statistical plot of phosphorus concentrations in the fourth reactor of the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

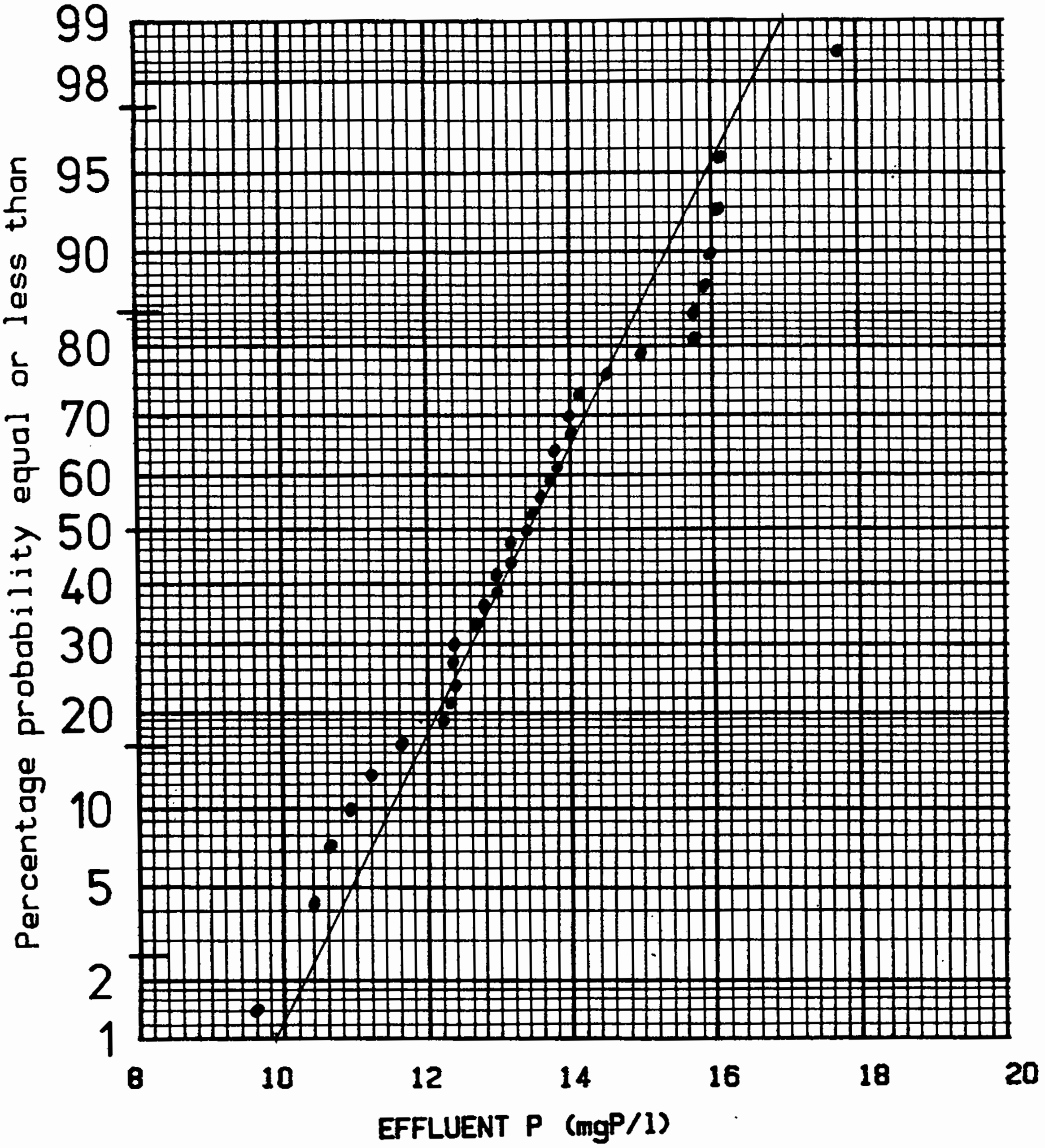


Fig D.23: Statistical plot of effluent phosphorus concentrations for the 5 day sludge age Johannesburg system with an s-recycle ratio of 1:1.

APPENDIX E

MASS BALANCES ON EXPERIMENTAL DATA

1. Carbonaceous Organic Material

Biodegradable carbonaceous organic material in wastewater serves as an electron donor in an environment containing heterotrophic organisms and a suitable electron acceptor. In this investigation, the chemical oxygen demand (COD) test was used to estimate the potential for electron transfer of organic material in wastewater. In the COD test, the concentration of organic material is measured in terms of the concentration of oxidant or electron acceptor (dichromate/sulphuric acid) that is required for the transfer of electrons from the organic material. From the half reaction for the reduction of oxygen;

$$4H^+ + O_2 + 4e^- \rightarrow 2H_2O$$

it can be seen that 1 mole of molecular oxygen (32g) is equivalent to 4 electron equivalents. By definition, when the equivalent of 1g of oxygen is used in the COD test, the mass of COD oxidised is also 1g. Therefore,

$$1\text{g COD} \equiv 1\text{g oxygen} \equiv 1/8 \text{ electron equivalent} \qquad (E.1)$$

Since all the organic material is oxidised in a COD test, it is possible to perform a mass balance on an activated sludge system under steady state conditions of flow and load. The mass of organic material entering the system in the wastewater can be accounted for in the following fractions:

1. A fraction leaves the system in the effluent.

2. A fraction is incorporated into the sludge mass by synthesis, absorption and enmeshment and leaves the system in the daily sludge wastage.

3. A fraction is oxidised (the electrons are transferred from the organic material to the electron acceptor). The extent of electron transfer can be calculated from the measured oxygen utilisation rate.

Therefore the COD balance for a purely aerobic system can be written as follows:

$$MCOD_{inf} = MCOD_{eff} + MCOD_{sl} + MCOD_{ox} \qquad (E.2)$$

where $MCOD_{inf}$ = mass of COD in the influent per day
$MCOD_{eff}$ = mass of COD in the effluent per day
$MCOD_{sl}$ = mass of COD in wasted sludge per day
$MCOD_{ox}$ = mass of COD oxidised per day.

Assuming that a proportional relationship exists between the COD concentration of a sludge and its volatile suspended solids (VSS) concentration.

$$COD_s = f_{cv}.X_v \qquad (E.3)$$

f_{cv} = proportionality constant (mgCOD/mgVSS)
X_v = volatile suspended solids concentration of sludge (mgVSS/ℓ)

Using Eq (E.3) and noting that the mass parameter is the product of the daily flow and the COD concentration, Eq (E.2) can be rewritten as follows:

$$Q.S_{ti} = Q.S_{te} + f_{cv}.X_v.q + 0_c.V_{aer} \qquad (E.4)$$

where Q = average influent flow (ℓ/d)
S_{ti} = total unfiltered influent COD (mgCOD/ℓ)
S_{te} = total unfiltered effluent COD (mgCOD/ℓ)
q = average waste sludge flow (ℓ/d)
0_c = carbonaceous oxygen demand (mg0/ℓ/d)
V_{aer} = volume of aerobic reactor (ℓ)

For systems which incorporate biological nitrification, the measured oxygen consumption rate is the sum of the carbonaceous and nitrification oxygen demands.

$$M(0_t) = M(0_c) + M(0_n) \qquad (E.5)$$

where $M(0_t) = V_{aer}.0_t$ = total mass of oxygen per day (mg0/d)
$M(0_c) = V_{aer}.0_c$ = mass of oxygen for carbonaceous degradation per day (mg0/d)
$M(0_n) = V_{aer}.0_n$ = mass of oxygen for nitrification per day (mg0/d).

The carbonaceous oxygen demand can be calculated by deducting the nitrification oxygen demand

$$M(0_c) = M(0_t) - M(0_n) \qquad (E.6)$$

The overall stoichiometric reaction for nitrification is

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ \qquad (E.7)$$

Therefore, 1 mole of ammonia requires 2 moles of oxygen for nitrification. Therefore, 1 mgN/ℓ of nitrogen requires 64/14 = 4,57 mg0/ℓ. Hence,

$$M(0_n) = 4{,}57.N_n.Q \qquad (E.8)$$

where N_n = reactor nitrate concentration (mgN/ℓ).

Therefore, for a purely aerobic activated sludge system in which nitrification is sustained, the COD mass balance equation is

$$Q.S_{ti} = Q.S_{te} + f_{cv}.X_v.q + 0_t.V_{aer} - 4{,}57.N_{ne}.Q \qquad (E.9)$$

where N_{ne} = effluent nitrate concentration (mgN/ℓ).

In a system which includes an anoxic zone for biological denitrification, nitrate becomes the final electron acceptor in the anoxic zone. The nitrate equivalent of oxygen can be determined from the following 2 half reactions;

$$\text{Oxygen} \quad : e^- + 1/4\ O_2 + H^+ \rightarrow 1/2\ H_2O \qquad (E.10)$$

$$\text{Nitrate} \quad : e^- + 1/5\ NO_3 + 6/5\ H^+ \rightarrow 1/10\ N_2 + 3/5\ H_2O \qquad (E.11)$$

The transfer of 1 electron equivalent involves the reduction of 1/4 mole of oxygen or 1/5 mole of nitrate, i.e.

$14/5g\ NO_3\text{-}N \equiv 32/4\ gO_2$ or $1\ mgNO_3\text{-}N \equiv 2,86\ mgO_2$.

Hence the oxygen equivalent of nitrate is 2,86 mgO/mgNO$_3$ and the mass of COD utilised will be given by $2,86.\Delta N_s.Q$ (mgO/d)

where ΔN_s = system nitrogen removal (mgN/ℓ influent).

Equation (E.9) can now be rewritten as

$$Q.S_{ti} = Q.S_{te} + f_{cv}.X_v.q + O_t.V_{aer} - 4,57.N_n.Q + 2,86.\Delta N_s.Q \qquad (E.12)$$

Now the term N_n must reflect the ammonia nitrified to nitrate and subsequently lost to the atmosphere as nitrogen by denitrification

$$N_n = (N_{ne} + \Delta N_s) \qquad (E.13)$$

Hence substituting for N_n in Eq (E.12) and simplifying, the general COD mass balance equation for a nitrification/denitrification system becomes

$$Q.S_{ti} = Q.S_{te} + f_{cv}.X_v.q + O_t.V_{aer} - 4,57.N_{ne}.Q - 1,71.\Delta N_s.Q \qquad (E.14)$$

The system nitrogen removal (ΔN_s) differs with the system configuration. Its value is obtained by a mass balance over the anoxic reactor. For example, with the Phoredox configuration the only nitrate entering the anoxic reactor is in the underflow (s) recycle stream. Since this stream is taken from the settler, the nitrate entering the anoxic reactor per litre of influent is $s.N_{ne}$. The nitrate leaving the anoxic reactor is then $(s+1).N_{nanox}$ where N_{nanox} is the nitrate concentration in the anoxic reactor. Therefore the denitrification per litre of influent (ΔN_s) is given by

$$\Delta N_s = s.N_{ne} - (s+1).N_{nanox}.$$

The system nitrogen removals were calculated, in this manner, for all the reactor configurations investigated. The following equations were derived,

Phoredox system

$\Delta N_s = s.N_{ne} - (s+1).N_{nanox}$

3-stage Bardenpho system

$\Delta N_s = s.N_{ne} + a.N_{n4} + - (a+s+1).N_{n2}$

UCT system

$\Delta N_s = a.N_{n4} + s.N_{ne} + - (a+s+1).N_{n2}$

Split-feed system

$\Delta N_s = s.N_{ne} - (s+x)N_{nanox}$

Johannesburg system

$\Delta N_s = s.N_{ne} - (s+1)N_{n2}$

where N_{ni} = nitrate concentrate in i^{th} reactor (mgN/ℓ)
i = reactor number
x = fraction of the feed entering the anoxic reactor.

2. Nitrogen mass balance

Nitrogen enters the system in the form of ammonia and organic compounds which is measured by the TKN test (Chapter 3, Section 4.4). If the system is nitrifying, most of the influent TKN is converted to nitrate and it leaves the system in this form in the effluent. If the system includes biological denitrification zones, then some of the nitrate will be converted to nitrogen gas and will leave the system in this form. A fraction of the influent TKN is utilised as nutrient requirements for sludge production and hence leaves the system in the sludge wastage. The nitrogen balance equation for an activated sludge system is therefore

$$Q.N_{ti} = Q.N_{te} + Q.N_{ne} + \Delta N_s.Q + f_n.X_v.q \qquad (E.15)$$

where N_{ti} = unfiltered TKN concentration in influent (mgN/ℓ)

N_{te} = unfiltered TKN concentration in effluent (mgN/ℓ)

N_{ne} = filtered nitrate concentration in effluent (mgN/ℓ)

f_n = nitrogen fraction of the sludge

= 0,1 mgN/mgVSS.

APPENDIX F

GENERAL ACTIVATED SLUDGE MODEL

The general activated sludge model of Dold and Marais (1985) incorporates carbonaceous matérial oxidation, nitrification and denitrification. The following processes are identified in the model.

1. <u>Aerobic growth of heterotrophs using ammonia as synthesis nitrogen source</u>: This process is responsible for a large portion of the removal of organic matter (and its oxygen requirement) and production of the bulk of the MLVSS. Concomitant with growth, the small nitrogen requirement for synthesis purposes is supplied from the pool of ammonia nitrogen, and there is an associated alkalinity change. The rate of growth reduces to zero in the absence of dissolved oxygen or when the ammonia concentration decreases to low values. At low dissolved oxygen concentrations, there is a switch to anoxic growth (Process 2), and when ammonia is limiting there is a switch to aerobic growth with the nitrogen requirement for synthesis being supplied from the nitrate pool (Process 9).

2. <u>Anoxic growth of heterotrophs using ammonia as synthesis nitrogen source</u>: In the absence of dissolved oxygen, a fraction, η_G, of the heterotrophic organism population is capable of using nitrate, if available, as a terminal electron acceptor. This process occurs at the expense of organic matter and results in the production of MLVSS; the product of nitrate reduction is N_2 gas. As with aerobic growth, ammonia nitrogen is incoprorated in the new cells and there is an alkalinity change. At low ammonia concentrations, the rate decreases to zero and there is a switch to anoxic growth with the nitrogen requirement for synthesis being supplied from the nitrate pool (Process 10).

3. <u>Decay of heterotrophs</u>: The process is modelled according to the 'death-regeneration' hypothesis. That is, the heterotrophic organism mass decays at a certain rate; a portion of the material from the decay is non-degradable and adds to the endogenous cell residue while the remainder adds to the pool of particulate biodegradable COD. Particulate nitrogen associated with the particulate biodegradable COD becomes

available as soluble organic nitrogen. The process of organism death is assumed to continue under aerobic, anoxic and anaerobic conditions.

4. 'Hydrolysis' of particulate COD: Particulate COD enmeshed in the sludge mass is broken down extracellularly, with the products of breakdown adding to the pool of readily biodegradable substrate available to the organisms for synthesis purposes. This 'hydrolysis' process is modelled on the basis of Levenspiel's surface reaction kinetics, and occurs only under aerobic or anoxic conditions; the rate of hydrolysis under anoxic conditions is reduced to a level of η_s times the rate in an aerobic environment. Hydrolysis does not occur under anaerobic conditions.

5. 'Hydrolysis' of particulate organic nitrogen: Biodegradable particulate organic nitrogen is broken down to soluble organic nitrogen at a rate defined by the hydrolysis reaction for carbonaceous particulate matter (4 above). The product of breakdown adds to the pool of soluble organic nitrogen.

6. Ammonification of soluble organic nitrogen: soluble organic nitrogen is converted to free and saline ammonia, a process mediated by the active heterotrophs. Acidity produced in the conversion process results in an alkalinity change.

7. Aerobic growth of autotrophs: The process of oxidation of ammonia nitrogen to nitrate is assumed to be a single-step one, requiring the presence of dissolved oxygen. This process has a marked effect on the prediction of the oxygen demand; the effect on total MLVSS is small, as the yield of autotrophic nitrifiers is low. As with the growth of heterotrophs, ammonia nitrogen is incorporated in the new cells and the alkalinity is affected.

8. Decay of autotrophs: The process parallels that for decay of heterotrophs.

9. Aerobic growth of heterotrophs using nitrate as synthesis nitrogen source: Under certain loading patterns in nitrifying systems, ammonia is not available in sufficient quantity at all times to supply the nitrogen requirement for synthesis. In this situation, the heterotrophs can use

nitrate as a nitrogen source for synthesis. The stoichiometry of this process parallels that for growth of heterotrophs using ammonia nitrogen for synthesis (Process 1).

10. Anoxic growth of heterotrophs using nitrate as synthesis nitrogen source: In the event of anoxic growth (Process 2) being limited by the availability of ammonia, there is a switch from ammonia to nitrate as the nitrogen source for synthesis purposes. (This switch parallels the switch from Process 1 to 9).