The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting biological enhanced phosphate removal.

DW de Haas

Thesis presented for the Degree of

DOCTOR OF PHILOSOPHY

in the Department of Civil Engineering

UNIVERSITY OF CAPE TOWN

June 1998

The University of Cape Town has been given the right to reproduce this thesis in whole or in part. Copyright is held by the author.

The copyright of this thesis vests in the author. No quotation from it or information derived from it is to be published without full acknowledgement of the source. The thesis is to be used for private study or non-commercial research purposes only.

Published by the University of Cape Town (UCT) in terms of the non-exclusive license granted to UCT by the author.

University of Cape Town

ABSTRACT

Since its first full-scale implementation in the late 1970s, considerable practical experience has been gained with biological enhanced phosphate removal (BEPR) in activated sludge systems for treating wastewater. However, BEPR tends to be sensitive and subject to many fluctuations, making it difficult to achieve full compliance with discharge standards. Simultaneous chemical addition in the activated sludge systems is a practical and economically attractive means of increasing the phosphate (P) removal capacity of these systems. However, it is also clear that the economic benefit of building a BEPR system could be lost if simultaneous addition of chemicals results in significant inhibition of the biological P removal mechanism. In South Africa anecdotal evidence of such inhibition has emerged. In view of its fundamental importance to the design and operation of BEPR plants which incorporate simultaneous chemical addition, it was considered imperative that the impact of simultaneous chemical addition on the biological P removal mechanism be investigated further, particularly with a view to addressing possible outstanding questions arising from re-interpretation of earlier work.

Experimental work was conducted using two identical pilot (or laboratory-scale) activated sludge plants operated such that the BEPR phenomenon was strongly exhibited. The two plants were operated in parallel under identical conditions. Chemical precipitant (aluminium sulphate, ferric chloride or ferrous chloride) was dosed into one plant (the Test unit), while the other served as Control. As a means of distinguishing the chemically-precipitated phosphate content of the mixed liquor from biologically-stored phosphate (or poly P) pool, methods for chemical fractionation of the phosphate compounds in activated sludge were investigated. A fractionation procedure was adopted which appeared to be capable of broadly distinguishing between chemical and biological forms of stored phosphorus in activated sludge and showed satisfactory agreement with the predicted results for BEPR obtained using a mathematical model of such systems. However, caution in interpretation of the fractionation data was advised since artefacts imposed by the fractionation procedure itself may be difficult to avoid.

From the experimental investigation, it was concluded that partial inhibition of the BEPR mechanism does occur in the presence of simultaneous chemical addition. The principal source of the apparent inhibition is competition for available phosphate, as was manifest under P-limited (i.e. low effluent P) conditions. The net effect is a reduction in the size of the biologically stored fractions in the mixed liquor dosed with chemical precipitant, which may be interpreted as a reduction in the number of polyphosphate accumulating organisms (PAO) in the system. On the one hand, a comparison of the chemical precipitation efficiency (or P:metal ion stoichiometry for precipitation) suggested that the biological mechanism is able to compete approximately as effectively as the chemical mechanism for available phosphate. On the other hand, the reduced pool of PAOs in the system implies that the BEPR potential is not fully exploited in the presence of simultaneous chemical dosing. The most important consequence arises from the latter and was obvious when the influent P load was increased such that the systems were no longer P-limited: with this change, preceded by a period of P-limitation, the system P removal in the Test unit was initially *less than* that of the Control system without chemical addition. Hence, under real operating conditions (which are basically P-limited in order to minimise effluent P concentrations), with a varying influent composition, the real danger exists that operators will choose progressively higher simultaneous chemical doses to keep effluent phosphate concentrations below the required standard. This is likely to have a negative impact on utilisation of the full BEPR potential. As an alternative, controlled dosing of chemicals into the primary treatment stage (pre-precipitation with primary settling tanks) may be more cost effective than simultaneous precipitation. However, despite the above-mentioned limitations, this study clearly showed that it is possible to obtain a sustained *net* additional P removal by simultaneous precipitation in the presence of BEPR in activated sludge systems, provided P concentrations are not severely limiting (i.e. provided metal ion doses are minimised as far as possible).

This study also addressed a number of related issues, notably: evaluation of current mathematical models for simultaneous chemical-biological P removal in activated sludge systems and evaluation of the performance of a full-scale plant dosed with either alum or a ferrous-ferric chloride blend, not only in terms of P removal, but also in terms of sludge settleability, biological foaming and secondary settling tank (SST) performance. In respect of the latter, confirmation of modified flux theory as a predictor of safe operating limits for SSTs was obtained. In addition, issues were highlighted which require further research, in particular: the effect of solids retention time (sludge age) on precipitation kinetics as applied in the IAWQ Activated Sludge Model No.2; and the effect of pH and alkalinity on simultaneous chemical precipitation efficiency with alum as opposed to iron salts in modified activated sludge systems.

data during the trial. The results illustrated the strong dependence of clarifier performance on sludge settling characteristics. Observations of clarifier performance (sludge blanket depth and effluent suspended solids) were in general support of modified flux theory as a predictor of safe solids loading limits and required recycle ratio for secondary settling tanks under a range of operating conditions.

- For Darvill WWW, ferrous-ferric chloride dosing could offer a modest 12% (or R77 000 p.a.) saving on chemical costs relative to alum. However, it was recommended that prior to opting for ferrous-ferric chloride to replace alum, a further plant trial be conducted where Test and Control systems can be operated in parallel at full scale in order whether the apparent negative effect on P removal and sludge settleability over periods in excess of five sludge ages could be repeated using the iron salt.

8. Two principal models for simultaneous chemical P precipitation were reviewed: one based on an equilibrium approach and one using a kinetic approach. Whilst the equilibrium model was more fundamental, it was also considerably more complex and presented certain difficulties for integration with existing kinetic models of BEPR processes. Assuming a constant reactor pH, application of the kinetic model (IAWQ ASM Model No. 2) to pilot plant data of this study gave satisfactory prediction of combined chemical-biological P removal processes. This suggested that the added complexity of the equilibrium model could not be justified. Future work should focus on experimental verification of the kinetics of phosphate "precipitation" for modelling purposes, and the possible inclusion of a kinetic model for pH and alkalinity into the existing IAWQ model of combined chemical-biological P removal in activated sludge systems.

wastewater works operators will be to increase the chemical dose, which in fact, will exacerbate the problem of partial inhibition of the BEPR process.

5. Circumstantial evidence suggested that bicarbonate alkalinity influences both the biological and chemical removal mechanisms. The biological P removal mechanism appeared to be stabilised by addition of bicarbonate to the influent (approx. 50 to 150 mg/l as $CaCO_3$, depending on the chemical dose) and maintenance of a median process pH in the range 7.2 to 7.7. In the absence of supplemental influent bicarbonate alkalinity, some experimental periods showed a virtual complete loss of *additional* P removal in the presence of chemical dosing. This effect appeared to be more marked for alum than for ferric chloride and possible theoretical reasons for the difference was put forward on the basis of the expected chemical equilibria. However, the addition of bicarbonate appeared to reduce the efficiency of chemical P removal using alum, as judged by a smaller gain in system P removal for the Test unit relative to the Control. This suggests that future research should focus on the relative efficiencies of the biological versus chemical mechanisms with simultaneous alum dosing under low alkalinity conditions.

6. Future research should also be directed toward the effect of sludge age on chemical precipitation efficiency (P:Me stoichiometry). It appears that the formation of colloidal metal hydroxide precipitate in the mixed liquor solids plays a key role in the chemical removal of phosphate in activated sludge systems and may be more important than direct precipitation of metal phosphate under the prevailing conditions. The kinetics of phosphate "precipitation" (complexation/ ion exchange) may be significantly slower than currently assumed in the IAWQ ASM2 model. Moreover, the biological and chemical mechanisms may not operate entirely independently of one another, as a result of the likely complexation between metal hydroxide and extracellular polymers in activated sludge flocs.

7. From the a full-scale plant trial at Darvill Wastewater Works (WWW), the following conclusions were drawn:

   - Over a period of several years, the alum dose applied varied considerably for various operational reasons, including the variable impact of trade effluent discharges to the Works. However, no increasing trend in alum dose could be discerned over a two year period, during which the average secondary effluent ortho P concentration was usually below 1 mgP/l. It was inferred that alum dosing does not appear to be severely inhibitory to the biological P removal mechanism under low (and potentially limiting) effluent P conditions.
   - A three month full-scale plant trial using ferrous-ferric chloride instead of alum as simultaneous precipitant at Darvill WWW showed excellent P removal (96% compliance with the 1 mgP/l orthophosphate Special P Standard) for the first two months, followed by a marked deterioration in P removal. During the third month of the trial, compliance with the Special P Standard fell to <20%. The absence of a control reactor at full scale made it impossible to determine conclusively to what extent the deterioration in P removal performance was directly attributable to iron dosing. Several grab samples of influent (settled sewage) showed high total P and/or ortho P concentrations (up to approximately twice the average concentration). Given a history of trade effluent-related treatment problems at this Works, the possibility could not be ruled out that the deterioration in P removal observed during the latter part of the ferrous-ferric chloride plant trial may have been largely related to changes in influent composition. A similar conclusion was reached from data for the ensuing three month period when the plant was switched back to alum dosing.
   - Circumstantial evidence suggested that iron (ferrous-ferric) dosing played a role in stabilising biological scum/ foam formation in the full-scale plant, to a greater extent than alum. The dominant nuisance organism in the scum was identified as the filamentous organism *Nocardia*. *Nocardia* probably also have played a role in the deterioration on sludge settleability noted for the activated sludge plant during the ferrous-ferric plant trial. Seasonal trends in DSVI data for Darvill WWW and the likely impact of vegetable oil trade waste were examined in this regard.
   - Secondary clarifier stress tests conducted before, during and after the ferrous-ferric chloride plant trial confirmed the deterioration in sludge settleability observed from DSVI

presence of excess acetate, which suggests that it represents a significant portion of the poly P in the biomass.

From the experimental investigation with simultaneous chemical dosing to the pilot plant system exhibiting BEPR, the following conclusions were drawn:

1. Under conditions in which P was never limiting (average effluent ortho P >1.5 mgP/l), simultaneous chemical dosing produced sustainable additional P removal in the presence of a strong BEPR mechanism using semi-enhanced cultures over periods in excess of two sludge ages. Evidence of partial inhibition of the biological mechanism emerged, based on the results of fractionation studies as well as comparative observations of P release in the anaerobic zones of the Test and Control units and P release in anaerobic batch tests with excess acetate present. However, the extent of inhibition of the BEPR mechanism was usually ca. <20% under these conditions and the net effect of chemical precipitant addition was always an improvement in the system P removal.

2. Under partially limiting phosphate conditions (with variable low effluent total P concentrations ranging <1 to 2.2 mgP/l), in the presence of ferric chloride dosing, the Test unit continued to achieve greater P removal compared to the Control. However, the biological mechanism began to "compete" slightly less effectively with the chemical mechanism, as judged by the P release in the anaerobic zone of the Test unit compared to the Control, somewhat smaller complex P fractions in fractionation studies and less P release in anaerobic batch tests with excess acetate.

3. After a sustained period (approximately ten sludge ages) of true limiting phosphate conditions with very low effluent ortho P concentrations (average <0.5 mgP/l), a significant deterioration in the combined chemical-biological P removal of the Test unit (with ferric chloride addition) was observed, despite a constant dose of ferric chloride. The magnitude of the stored biological fractions in the Test unit was approximately 30% less than those of the Control unit under these conditions. The deterioration in biological P removal potential in the Test unit was manifest when the influent phosphate concentration was increased such that P was no longer limiting: During the first week after P-limitation was lifted, the system P removal in the Test unit (still ferric chloride addition) was slightly *less* than that of the Control unit (without chemical addition). The difference between system P removal in the two units was initially of the order of 1 mgP/ℓ (which would be sufficient to cause the Special P Standard in South Africa to be exceeded), but decreased with time and in the absence of P limitation, until removal in the Test unit again became greater than in the Control unit.

4. The "efficiency" of chemical precipitation was measured in terms of the P:metal ion stoichiometry of precipitation, either from calculations of the difference in system P removal between the Test and Control units (i.e. with and without metal salt addition, respectively) or from fractionation data. It was found that estimates of the stoichiometry based on differences in system P removal may be unreliable at times where the biological P removal is depressed for some reason in either the Test or Control units. Moreover, this method is of no value where both the Test and Control units achieve virtually complete P removal due to P limitation. Fractionation data may be more reliable in this respect since it attempts to measure the chemical precipitate P fraction(s) independently of the biological fractions. From the fractionation data, it was found that the P:metal stoichiometry was usually in the range ca. 0.5 to 0.75 mol P/ mol Me (where Me is a trivalent metal ion) under conditions where P was never limiting, but decreased to between ca. 0.3 and 0.4 mol P/ mol Me under conditions when P became limiting. These observations agree with published data on stoichiometry observed for low residual (effluent) P concentrations in similar research conducted at laboratory scale elsewhere, or the required chemical doses for simultaneous chemical precipitation in full-scale activated sludge systems. The drop in chemical precipitation efficiency (P:Me stoichiometry) by approximately 30 to 40% under P-limiting conditions was similar to that observed for the biological fractions and implies that the biological mechanism is able to compete approximately as effectively as the chemical mechanism for available phosphate. However, the smaller biological fractions represent a loss of polyphosphate-accumulating organism biomass and a loss of potential to remove phosphate biologically. A restoration of the full biological potential will be growth-dependent. If the effluent phosphate concentration exceeds the required standard before growth can restore the biological potential, the tendency among

TABLE OF CONTENTS

VOLUME 1

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

Symbol	Definition
% ile	Percentile
Δ	Delta, meaning "difference in" or "change in" (e.g. $\Delta M,P_{rem}$ - see also below)
AE1 or 2	Aerobic zone or reactor
Al:P	Aluminium to phosphate ratio (usually molar ratio of mol Al/ mol P)
Al~P~O	Aluminium phosphate/ oxide precipitate (theoretical) after ashing of aluminium hydroxy phosphate
Al~P~OH	Aluminium hydroxy phosphate
Alk.	Alkalinity (unless otherwise stated: *bicarbonate* alkalinity)
AM	Atomic mass of some specified element
AN	Anaerobic zone or reactor
AX	Anoxic zone or reactor
Bicarb.	Bicarbonate (or sodium bicarbonate)
c_{Fe}	Concentration of Fe (III) ions in solution
c_{Fe}^{**}	Maximum residual concentration Fe (III) ions in solution *at equilibrium via precipitation/ redissolution/ complexation processes in the presence of both ferric (hydroxy) phosphate and ferric hydroxide precipitates* (Luedecke *et al.*, 1989)
CLAR	Clarifier (settling tank)
COD	Chemical oxygen demand
c_P	Concentration of dissolved orthophosphate
c_P^{**}	Maximum residual orthophosphate concentration in solution *at equilibrium via precipitation/ redissolution/ complexation processes in the presence of both ferric (hydroxy) phosphate and ferric hydroxide precipitates* (Luedecke *et al.*, 1989)
$c_{P,ads}$	Concentration of orthophosphate adsorbed to precipitate
$c_{P,eq}$	Concentration of dissolved orthophosphate in equilibrium via adsorption processes (= $c_{P,ads}$ + $c_{P,res}$) (Luedecke *et al.*, 1989)
$c_{P,in}$	Influent concentration of orthophosphate
$c_{P,res}$	Residual orthophosphate concentration normally determined analytically (i.e. $c_{P,eq}$ - $c_{P,ads}$) (Luedecke *et al.*, 1989)
d.s.	Dry solids
DSVI	Dilute sludge volume index
Eqn	Equation
f	*Italics:* denotes *filtered* (e.g. fP_t implies *filtered* total phosphate)
f_{ac}	Fraction of readily biodegradable COD which is acetate
f_{bs}	Fraction of biodegradable COD which is readily biodegradable
Fe:P	Iron to phosphate ratio (usually molar ratio of mol Fe: mol P)
Fe~P	Ferric phosphate precipitate (of uncertain formula)
Fe~P~O	Ferric phosphate/ oxide (theoretical) after ashing of iron hydroxy phosphate
Fe~P~OH	Ferric hydroxy phosphate (iron hydroxy phosphate)
FeOOH	Amorphous ferric hydroxide
f_{na}	Fraction of (influent) TKN which is ammonia
$f_{nob,p}$	Fraction of organic biodegradable nitrogen which is particulate
$f_{nou,s}$	Fraction of organic biodegradable nitrogen which is soluble
*f*PCA	Filtered PCA extract (in chemical fractionation studies) - see Chapter 2
fP_t	Filtered total phosphate
$fP_{t,a}$	Filtered total phosphate, anaerobic zone or reactor
$fP_{t,b1 \text{ or } b2}$	Filtered total phosphate, first or second aerobic zone or reactor, respectively
$fP_{t,d}$	Filtered total phosphate, second anoxic zone or reactor
*f*SUP	Filtered supernatant (in chemical fractionation studies) - see Chapter 2
f_{up}	Fraction of unbiodegradable particulate COD

f_{us}	Fraction of unbiodegradable soluble COD
g	grams
h	hours
i_{NBM}	N content of biomass (i.e. N content of X_H, X_{PAO}, X_{AUT})
i_{NSF}	N content of soluble (biodegradable) fermentable COD
i_{NSI}	N content of soluble inert (unbiodegradable) COD
i_{NXI}	N content of particulate inert (unbiodegradable) COD
i_{NXS}	N content of particulate (biodegradable) substrate COD
ISS	Inorganic suspended solids
Jhb or JHB	Johannesburg (e.g. Johannesburg process configuration of activated sludge plants)
K'_{sp}	Apparent solubility product
k_a	Adsorption coefficient
K_{fp}	Equilibrium constant for iron phosphate complex (ion pair): $FeH_2PO_4^{2+}$ (Luedecke et al., 1989)
K_{MeH}	Solubility product for metal hydroxide (Briggs, 1995)
K_{MeP}	Solubility product for metal (hydroxy) phosphate (Briggs, 1995)
k_{MHP}	Equilibrium constant for metal phosphate complex (ion pair): $MeH_2PO_4^{2+}$
k_{PRE}	Kinetic (rate) constant for precipitation (IAWQ, 1995)
k_{RED}	Kinetic (rate) constant for redissolution (IAWQ, 1995)
K_{sp}	Solubility product
ℓ	litre(s)
M	molar
M,P_{rem}	Mass of phosphate removed (mgP/d)
m/m	mass for mass (in chemistry for expression of concentration)
m/v	mass for volume (in chemistry for expression of concentration)
Max.	Maximum
Me	Metal (trivalent metal ion in the context of this study: Fe^{3+} or Al^{3+})
MeOH	Metal hydroxide (nominally $Fe(OH)_3$ or $Al(OH)_3$)
MeP	Metal (hydroxy) phosphate ($Me_rPO_4(OH)_{3r-3}$, or $FePO_4$ or $AlPO_4$)
meq	milli-equivalents
Me_T	Total metal ion concentration
mg	milligrams
Min.	Minimum
min.	minutes
MLSS	Mixed liquor suspended solids
mM	millimolar
mmol	millimoles
mol	moles
MW	molecular weight
n	Flux theory constant (volume per unit sludge mass)
N_{ae}	Concentration of ammonia in the effluent
N_{ai}	Concentration of ammonia in the influent
NaOH	Sodium hydroxide (fractionation studies)
nm	nanometres
No_3 or No3	Concentration of nitrate
$No_{3,a}$	Concentration of nitrate in the anaerobic zone/ reactor
$No_{3,b1 \text{ or } b2}$	Concentration of nitrate in the first and second zone/ reactor, respectively
$No_{3,d}$	Concentration of nitrate in the anoxic zone/ reactor
$No_{3,e}$	Concentration of nitrate in the effluent
$N_{ob,p}$	Concentration of organic, biodegradable, particulate nitrogen
N_{obi}	Influent concentration of organic, biodegradable nitrogen (particulate + soluble)
$N_{ou,p}$	Concentration of organic, unbiodegradable, particulate nitrogen
$N_{ou,s}$	Concentration of organic, unbiodegradable, soluble nitrogen
N_{oupi}	Influent concentration of organic, unbiodegradable, particulate nitrogen
N_{ousi}	Influent concentration of organic, unbiodegradable, soluble nitrogen
N_{te}	Effluent TKN concentration

N_{ti}	Influent TKN concentration
ortho P	orthophosphate
O_t	Oxygen uptake rate (in mg/[ℓ.h])
PAO or PAOs	Polyphosphate accumulating organisms (or poly P organisms)
PCA	Perchloric acid (fractionation studies)
pK	-log K (where K is a given equilibrium constant)
pK'_{sp}	-log K'_{sp} (see K'_{sp} above)
pK'	-log K' (where K' is a given *apparent* equilibrium constant)
pK_{fp}	-log K_{fp} (see K_{fp} above)
pK_{sp}	-log K_{sp} (see K_{sp} above)
poly P	polyphosphate
$P_{P\ res}$	Maximum residual orthophosphate concentration in solution *at equilibrium via precipitation/ redissolution/ complexation* reactions in the presence of both metal (hydroxy) phosphate and metal hydroxide precipitates (Briggs, 1995)
P_P*	Residual orthophosphate concentration in solution (Briggs, 1995)
P_{pi}	Influent ortho P concentration (Briggs, 1995)
P_{pp}	Concentration of poly P
prec	Precipitate
P_{rel}	Concentration of P released (biologically)
P_{rem}	Concentration of P removed
PSTs	Primary settling tanks (or primary sedimentation tanks)
P_{ti}	Influent total P concentration
P_{trem}	Total P concentration removed
P_{ui}	Phosphate component of influent unbiodegradable (inert) soluble organic material
P_{upt}	Concentration of P taken up (biological uptake)
P_{xi}	Phosphate component of influent unbiodegradable (inert) particulate organic material
Q_i	Influent flow rate
Q_r	RAS (or s) recycle flow rate
r	RAS (or s) recycle ratio, relative to influent flow (Q_i)
r as in Me_r	Stoichiometric ratio of Me:P (where Me is a trivalent metal ion and P is ortho P)
R^2	Correlation coefficient squared (statistical parameter)
RAS	Return activated sludge
rem	Removal/ removed
RES	Residue (in fractionation studies)
res	Residual (e.g. ortho P) concentration
R_s	Sludge age (or solids retention time)
S_{bpi}	Influent particulate biodegradable substrate (COD) concentration
S_{bs}	Readily biodegradable (soluble) substrate (COD) concentration
$S_{bs,ai}$	Influent readily biodegradable (soluble) substrate (COD) concentration *which is acetate*
$S_{bs,ci}$	Influent readily biodegradable (soluble) substrate (COD) concentration *which is can be converted to acetate by fermentation*
S_{bsi}	Influent readily biodegradable (soluble) substrate (COD) concentration
S_{PO4}	Soluble orthophosphate concentration (IAWQ, 1995)
S_{te}	Effluent (total) COD concentration
S_{ti}	Influent (total) COD concentration
SUP	Supernatant (in fractionation studies)
S_{upi}	Influent unbiodegradable (inert) particulate COD concentration
S_{us}	Unbiodegradable (inert) soluble COD concentration
S_{usi}	Influent unbiodegradable (inert) soluble COD concentration
TKN	Total Kjeldahl Nitrogen
TSS	Total suspended solids
v/v	volume for volume (in chemistry for expression of concentration)
V_o	Flux theory constant (settling velocity of sludge at infinite dilution)

VSS	Volatile suspended solids
X_a	Concentration of active mass (biomass)
X_{AUT}	Concentration of active mass of autotrophs (IAWQ, 1995)
$X_{B,G}$	Concentration of active mass of (heterotrophic) poly P accumulating organisms (PAOs)
X_H	Concentration of active mass of heterotrophs (IAWQ, 1995)
X_{ii}	Influent unbiodegradable (inert) particulate COD (Briggs, 1995)
X_{MeH}	Concentration of metal hydroxide (Briggs, 1995)
X_{MeOH}	Concentration of metal hydroxide (IAWQ, 1995)
X_{MeP}	Concentration of metal (hydroxy) phosphate (IAWQ, 1995)
X_o	Reactor MLSS concentration
X_{PAO}	Concentration of PAOs (IAWQ, 1995)
X_r	Concentration of solids (TSS) in the RAS stream

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting biological enhanced phosphate removal.

Chapter 1

Literature Review

&

Scope of Work

DW de Haas

CHAPTER ONE

LITERATURE REVIEW AND SCOPE OF WORK

1.1 INTRODUCTION

Eutrophication of natural and man-made impoundments has become a problem in many countries, including South Africa. Problems associated with eutrophication include profuse algal blooms, excessive growth of nuisance aquatic plants, negative aesthetics, deoxygenation, and water purification problems for drinking purposes. Many limnological studies have been conducted into the phenomenon, its causes and effects (*inter alia* Walmsley and Thornton, 1982; Walmsley and Thornton, 1984; Twinch, 1986; Grobler 1988 (a & b); Chutter, 1990; Dillon and Molot, 1996). Such studies have indicated that the limiting nutrients in eutrophication are usually phosphorus and nitrogen (in that order) and that eutrophication can be controlled by significantly reducing the phosphorus (P) load discharged in a catchment. World-wide this increasing awareness of the causative effect of phosphorus on eutrophication has led to the introduction of more stringent legislation controlling the discharge of P to receiving waters, and in particular the discharge of wastewaters. In South Africa, the Special Phosphate Standard was introduced, restricting the concentration of phosphorus in wastewater discharges to 1 mgP/ℓ as dissolved orthophosphate (Government Gazette, 1984). To comply with the new effluent legislation, a number of existing wastewater treatment plants in South Africa were modified or new plants constructed to implement biological excess phosphorus removal[1] (BEPR). The decision to opt for biological P removal in the 1970s and 1980s was based partly on the emergence of local expertise (Barnard 1974, 1976, 1983, 1984; Marais *et al.*, 1983; WRC, 1984) but mainly on cost considerations. BEPR processes typically involve higher capital investment than those using chemical P precipitation; however, BEPR processes have the potential to offer lower operating and maintenance costs than conventional activated sludge with chemical dosing, mainly because the chemical precipitants are expensive (Nutt, 1985; Lötter, 1991). Similar trends have emerged in several countries, such as Canada, Australia and Germany (Nutt, 1985; Yue *et al.*, 1987; Hartwig and Seyfried, 1991; Peter and Sarfert, 1991; Barnard, 1995). Since its implementation, considerable practical experience has been gained with BEPR systems. However, biological phosphorus (P) removal tends to be sensitive and subject to many fluctuations, making it difficult to achieve full compliance with discharge standards such as the Special P Standard in South Africa (1 mgP/ℓ as dissolved orthophosphate). Lötter (1991) illustrated this point with the research carried out over approximately eight years on full scale at Northern Works (Johannesburg), which discharges into the sensitive Crocodile River catchment and is subject to the Special P Standard. Although at least 75% compliance with the Special P Standard could be achieved by biological means alone, 100% compliance remained elusive[2].

The difficulty in consistently achieving the necessary effluent P standard, has led to alternatives being considered. One alternative for reducing P loads to receiving waters would be the elimination of phosphorus from detergents. Studies have been conducted on the impact of this alternative for South Africa. For example, taking the case of Inanda Dam in the Umgeni River catchment, Pillay *et al.* (1993) estimated that detergent phosphorus comprised almost two-thirds of the soluble reactive phosphorus (or dissolved orthophosphate) and one third of the total phosphorus entering the impoundment. Of the phosphorus load to the catchment arising from detergent consumption (ca. 20 tonnes P/annum), approximately 40% emanated from rural laundry practices (i.e. where rivers or streams are used directly), and 60% emanated from urban washing (i.e. discharged via wastewater treatment works). Pillay *et al.* (1993) reported that complete elimination of detergent phosphorus would greatly reduce the phosphorus load to the Umgeni catchment, with a predicted reduction by half of the total P concentration in the main river flow to

[1] Also known as enhanced biological phosphorus removal (EBPR).

[2] The Special P Standard, in effect, makes 100% compliance mandatory, although for practical reasons, the monitoring data may be interpreted at 95% confidence levels.

Inanda Dam. However, they noted that this reduction alone may not be sufficient to significantly improve the "impairment status" of the impoundment; additional restriction of P loading derived from other sources would be required. Moreover, the environmental cost of mining raw minerals for phosphate is equivalent to that for zeolites, the most common alternative detergent builders to phosphate. Cost-benefit calculations in the phosphate ban debate are complex. There may be hidden factors which are difficult to quantify. According to Pillay (1994), these may include: a variable response of aquatic ecosystems to nutrient loads; loss in aesthetic, recreation or agricultural value of impoundments due to nuisance algal and macrophyte plant growth; and potential human carcinogenic factors linked to algal by-products in water of eutrophic origin. However, with large costs projected from higher prices for phosphate-free detergents as well as associated shortened life cycles of both washing machines and clothing fabric, there appears to be economic incentive to retaining phosphorus in detergents (Wiechers and Heynicke, 1986; Pillay, 1994). For this reason the decision was taken in South Africa not to introduce a detergent phosphorus ban. It follows that continued effort is required to improve the use of existing technologies or to develop new technologies for removal of phosphate from wastewater.

In the interim, the practical solution to meet effluent standards has been to supplement biological P removal with chemical P removal. Nutt (1985) investigated the technical and economic feasibility of retrofitting wastewater treatment plants with biological phosphorus removal. To consistently achieve less than 1.0 mg/ℓ as total P, Nutt (1985) found that BEPR processes require effluent filtration and/or supplementary chemical dosing. Similarly, the IAWQ Nutrient Removal Tour to South Africa (1993) highlighted that, in many cases, supplementary chemical dosing into biological nutrient removal (BNR) activated sludge plants was being used in an attempt to improve stability of P removal in the system and achieve higher compliance levels. Healey *et al.* (1989) and de Haas *et al.* (1991) showed the benefits of simultaneous alum addition to a BNR plant treating principally industrial effluent. However, concern over the optimisation of biological versus chemical phosphate removal mechanisms has led to the use of tertiary "back-up" chemical dosing followed by tertiary clarification or dissolved air flotation (DAF) in preference to simultaneous chemical addition at the secondary (activated sludge) stage (e.g. Hartwig and Seyfried, 1991; De Wet *et al.*, 1992). Alternatively, side-stream processes such as *Pho-Strip*, originally developed in the 1960s and early 1970s (Levin *et al.*, 1975) have been developed further and integrated with BNR systems, thereby attempting to keep the chemical and biological sludges separate. Szpyrkowicz and Zilio-Grandi (1995) gave an example of the use of this type of design. Lilley *et al.* (1993) compared the economic merits of the *Pho-Strip* process with various other processes, including conventional activated sludge and biological nutrient removal (BNR) (Phoredox) processes, as well as full chemical phosphate removal following primary and secondary treatment in a biofilter plant. They found that the BNR (Phoredox) process was significantly cheaper to build and operate than the other processes with P removal capability. For cases where the BNR process alone cannot achieve the necessary effluent P standard, simultaneous chemical addition is economically attractive in that it avoids the capital expense associated with building tertiary dosing and clarification or flotation equipment. However, it is also clear that the economic benefit of building a BNR system could be lost if simultaneous addition of chemicals resulted in significant inhibition of the biological P removal mechanism.

1.2 CHEMICAL PHOSPHORUS REMOVAL IN MODIFIED ACTIVATED SLUDGE SYSTEMS

In their review of chemical processes for phosphate removal, Jenkins *et al.* (1971) pointed out that iron or aluminium salts (with or without lime) were used for BOD and suspended solids removal since the early days of wastewater treatment in this century (ca. 1920s) and were also used at that time to improve the settling characteristics of activated sludge. However, because biological treatment processes were more economical and posed fewer sludge disposal problems, these early chemical treatment schemes became less frequently used (Jenkins *et al.*, 1971). Chemical treatment for phosphate removal from wastewater was revived in the 1960s when eutrophication problems emerged in several countries.

Systems for chemical and biological P removal were reviewed by Arvin (1985) and Yeoman *et al.* (1988). Chemical addition may take place at one of three stages of wastewater treatment (Figure 1), namely:

- primary treatment (i.e. primary sedimentation, if present), for which the term "pre-precipitation" is used;
- secondary treatment (typically an activated sludge or biofilter system) for which the term "simultaneous precipitation" is used;
- tertiary treatment (chemical flocculation followed by sedimentation or flotation, sometimes followed by filtration) for which the term "post-precipitation" is used.

Based on model treatment plants with idealised configurations for biological phosphorus removal, Nutt (1985) concluded that BEPR and chemical precipitation processes should ideally be applied simultaneously to optimise performance and minimise costs, particularly capital costs. Nutt (1985) also reported that simultaneous chemical precipitation in new or retrofitted conventional activated sludge plants may be more economically attractive than BEPR processes in some cases, depending on effluent nutrient limits, plant design and wastewater characteristics.

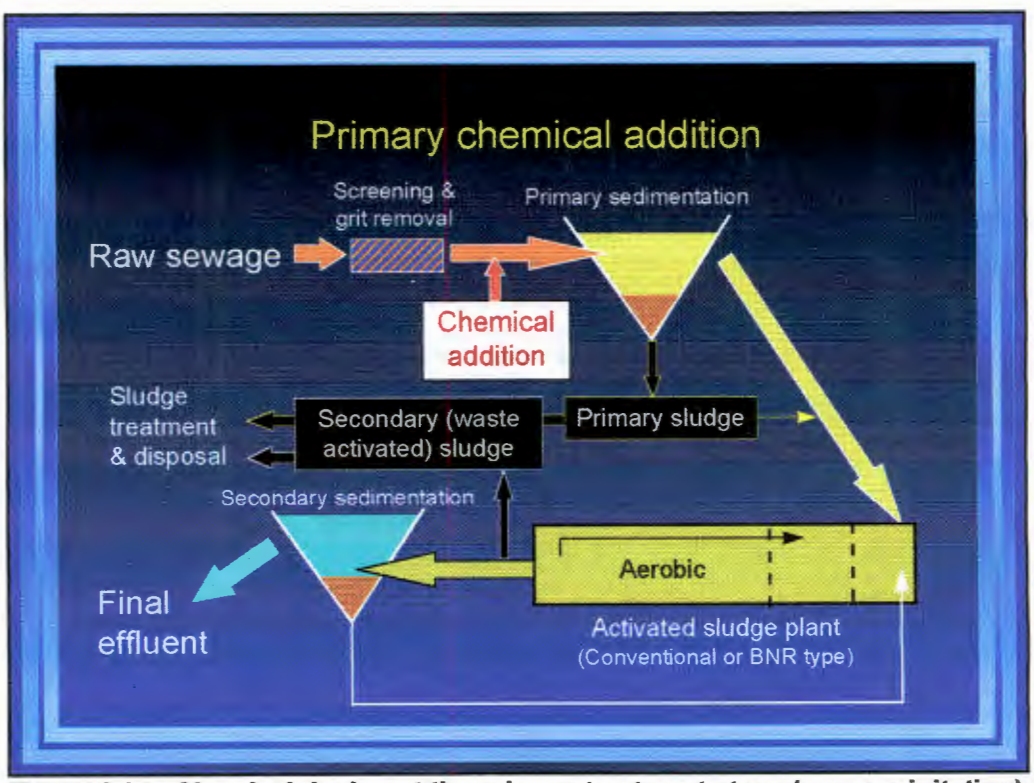


Figure 1.1a : Chemical dosing at the primary treatment stage (pre-precipitation).

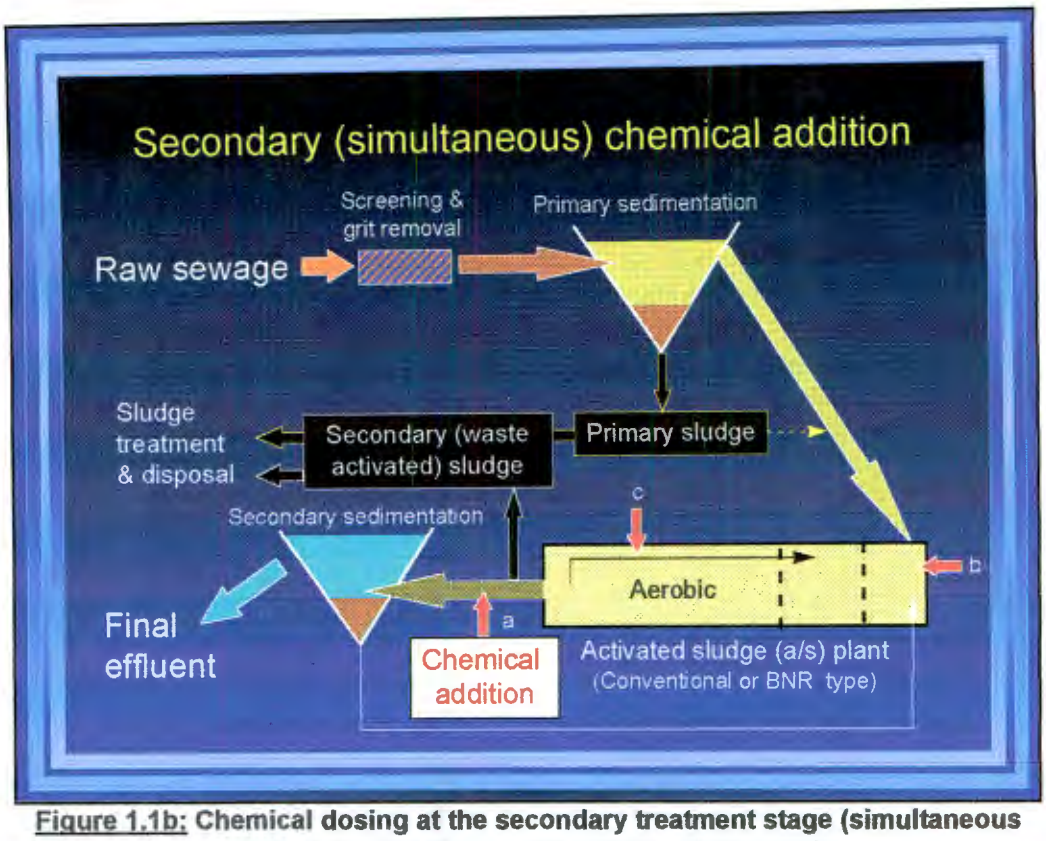


Figure 1.1b: Chemical dosing at the secondary treatment stage (simultaneous precipitation). Note: a,b,c are optional dosing points.

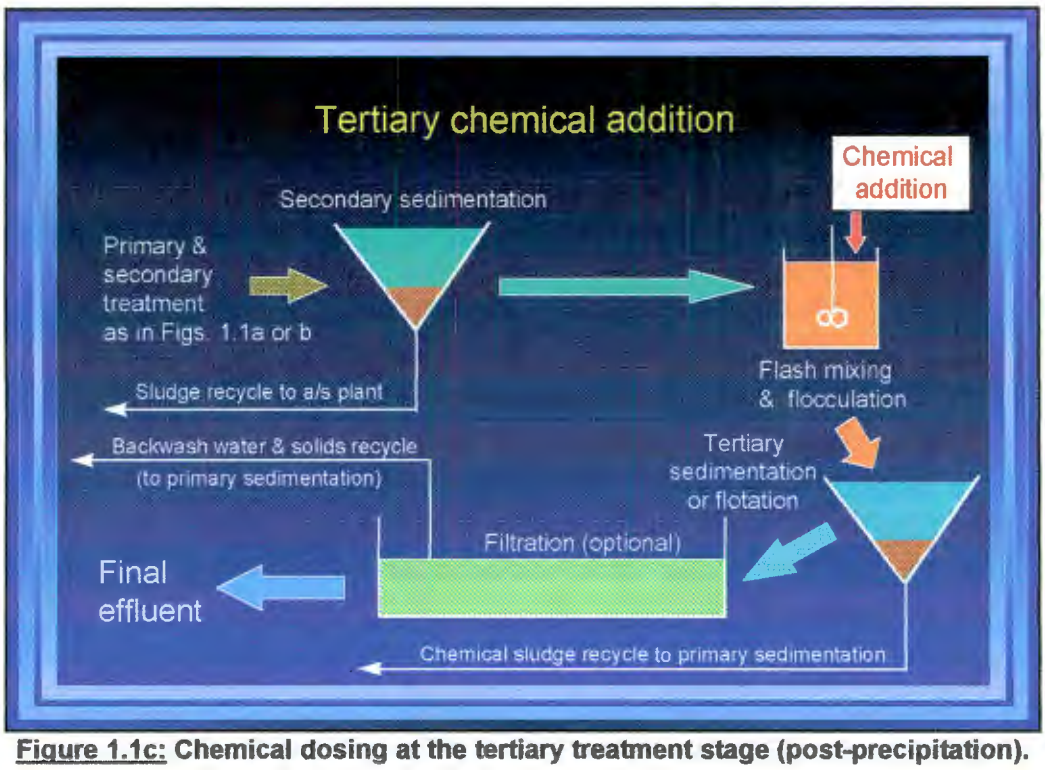


Figure 1.1c: Chemical dosing at the tertiary treatment stage (post-precipitation).

1.2.1 Iron salts

1.2.1.1 Oxidation state of iron and P precipitation

For chemical P removal, or a combination of chemical and biological removal, iron salts are widely used. Iron (III) chloride (ferric chloride) is the most common. In reviewing guidelines for chemical phosphate removal from municipal waste waters, Wiechers (1987) stated that both forms of iron, ferrous and ferric, combine with orthophosphate (ortho P) in a precipitating reaction, and with hydroxide in a competing reaction. The iron hydroxide is also important in the removal of phosphate, as result of slower exchange of hydroxyl ions for orthophosphate (ortho P) ions (Rabinowitz and Marais, 1980). From stoichiometry, ferric ions form $FePO_4$ (strengite) in the reaction with orthophosphate, while ferrous ions form $Fe_3(PO_4)_2.8H_2O$ (vivianite). However, both ferric and ferrous ions react with hydroxide to form amorphous iron hydroxide flocs which destabilise the negatively charged iron-phosphate colloids, enmesh them and provide an adsorption capability for ortho P and polyphosphate (poly P) such as pyrophosphate and tripolyphosphate which occur commonly in detergents as softeners (Wiechers, 1987). The stoichiometric *mass* ratio of Fe:P for $FePO_4$ (ferric) and $Fe_3(PO_4)_2$ (ferrous) is 1,8:1 and 2,7:1, respectively (Wiechers, 1987). Competition between hydroxyl ions and phosphate ions for the iron ions at the point of addition, the reaction of bicarbonate ions forming iron hydroxides, and the need to destabilise colloids (e.g. iron-phosphate, dispersed micro-organisms or influent organics), probably account for cases where a stoichiometric excess of ferric iron is required for phosphate precipitation (Jenkins *et al.*, 1971).

According to Yeoman *et al.* (1988), iron (II) (ferrous) salts may also be used. Aspegren (1995) described operation of a full-scale plant in Sweden with pre-precipitation in the primary treatment stage using ferrous sulphate. An example of the use of ferrous sulphate for simultaneous precipitation on small sewage works in Denmark is given by Olesen (1990). Similarly, both ferrous and ferric chloride are widely used in South Africa to supplement biological P removal in BNR plants, mainly by simultaneous precipitation (Leopold, 1996).

Singer (1972) noted that under anaerobic conditions in primary sludge (i.e. where ferrous iron was dosed into raw sewage before primary sedimentation), phosphate was precipitated as crystalline ferrous phosphate (vivianite) and little phosphate was released when this primary sludge was treated by anaerobic digestion. Similarly, Frossard et al. (1997), using X-ray diffraction, electron microscopy and ^{57}Fe Mössbauer spectroscopy, found direct evidence that most (67%) of the phosphate precipitated in anaerobically digested sludge[3] is the form of crystalline vivianite ($Fe_3(PO_4)_2.8H_2O$). Interestingly, by applying the same techniques to activated sludge receiving simultaneous addition of ferrous sulphate, Frossard *et al.* (1997) found that as much as 43% of the total phosphate in the sludge was also precipitated in the form of vivianite. They concluded that vivianite may be precipitated slowly and in anaerobic pockets in the activated sludge system; the balance of the iron in the sludge was expected to be in the form of Fe^{2+} or Fe^{3+} ions associated with organic compounds, as well as Fe^{3+} in the form of hydroxides[4,5]. However, Yeoman *et al.* (1988) assumed that under aerobic conditions ferrous salts mostly act as phosphate precipitants after oxidation to the iron (III) form. The reaction may be written as (Loewenthal *et al.*, 1986):

$$Fe^{2+} + \tfrac{1}{4}\, O_2 + H^+ \rightarrow Fe^{3+} + \tfrac{1}{2}\, H_2O$$

This oxidation reaction for ferrous iron to ferric iron requires a neutral or weakly alkaline pH and has a significant oxygen demand (0.15 g O_2/g Fe^{2+}) (Singer, 1970, quoted by Yeoman *et al.*, 1988). The half-time of the oxidation reaction is about 16 min, at pH 7.0, 2 mg/ℓ D.O. and 25 °C (Singer 1972).

---

[3] These sludges were derived from works with (pre-)precipitation using ferrous sulphate, followed by primary sedimentation.
[4] Frossard et al. (1997) used the term "oxy-hydroxides", probably meaning amorphous ferric hydroxides of the type FeOOH.
[5] Frossard et al. (1997) appear to have accepted that oxidation of ferrous ions to ferric ions is possible and likely in aerobic activated sludge sludge systems, but considered it unlikely that the sludge would contain ferric ions issued from the oxidation of vivianite *after* precipitation.

It is generally assumed that most Fe bound in activated sludge is in the oxidised state as ferric iron, probably as ferric hydroxide (Rasmussen and Nielsen, 1996). Using techniques that are commonly applied in soil science, Rasmussen and Nielsen (1996) were possibly the first to verify the oxidation state of Fe in activated sludge. Sludge samples were obtained from a Danish treatment plant with biological N and P removal in which P removal is also augmented chemically with ferrous sulphate. They found an average total iron content of ca. 63 mg Fe/ g dry solids (d.s.) for the activated sludge samples. By means of extraction techniques involving iron reduction to Fe(II) and determination of the latter using ferrozine, they showed that fresh sludge contained very little Fe(II); Fe(II) was also not detectable in the supernatant from fresh sludge. Fe(III) accounted for 70-90% of the total Fe in the sludge. Whether the Fe(III) in activated sludge is precipitated and trapped in crystalline or amorphous form, and to what extent it is organically bound, could not be determined by Rasmussen and Nielsen (1996). However, they did point out that extracellular polymeric substances are common in activated sludge and consist of humic substances, polysaccharides, proteins, and DNA, all of which (especially humic substances and polysaccharides) are known to bind metal ions. Reduction of Fe(III) to Fe(II) commenced immediately after initiation of an anaerobic stage. Almost all the Fe(II) formed by reduction remained in the floc matrix. The rate of Fe(II) accumulation was somewhat higher in short-term than in long-term anaerobic experiments, indicating that some form of substrate limitation (or depletion of easily available Fe pool) comes into effect. From unpublished data, Rasmussen and Nielsen (1996) concluded that the Fe reduction process was mainly biologically mediated. The rate of Fe(II) accumulation in anaerobically stored sludge was in the region of 0.78 to 1.29 mgFe/gVSS.h, or 0.014 to 0.023 meq/gVSS.h. Similarly, Nielsen (1996) reported *potential* Fe (III) reduction rates of 0.9 to 3.7 mgFe/gVSS.h (or 0.016 to 0.066 meq/gVSS.h) in the presence of excess lactate as external substrate, noting that these rates were approx. 20 to 30% higher than those found by Rasmussen and Nielsen (1996) in the absence of external substrate. By comparison, respiration rates for oxygen and nitrate are of the order of 0.5 to 1 meq/gVSS.h for activated sludge. However, the rate of iron reduction may be more comparable with other anaerobic processes such as fermentation or sulphate reduction (Rasmussen and Nielsen, 1996). Fe(III) reduction may nevertheless contribute to P release from chemical forms in the anaerobic zone of BEPR processes. However, on the basis of their observed Fe(III) reduction rates, and assuming an Fe:P ratio of 2.5:1, Rasmussen and Nielsen (1996) concluded that relatively slow P release rates of around 1 mgP/ℓ.h may be expected from this source. This corresponded with release rates observed on the full-scale plant during the first 1-4h *without* external substrate addition (sewage). From the investigation by Rasmussen and Nielsen (1996), it can be concluded that in aerobic activated sludge mixed liquor, iron exists principally in the ferric form and produces most of the phosphate precipitation/ adsorption reactions in this form. In activated sludge systems with unaerated zones (typical BNR plants), reduction of iron from ferric to the ferrous form may occur and this may contribute to the chemical release of P from precipitated forms. However, the rate of reduction appears to be slow in relation to biological P release in such systems. This together with the fact that re-oxidation will be expected in the aerobic zone (immediately followed by P precipitation) suggests Fe reduction is of secondary importance in the combined chemical-biological P removal mechanism in activated sludge systems.

Nielsen (1996) studied the role of iron in oxidation-reduction reactions in several Danish activated sludge plants with chemical dosing, usually in the form of ferrous sulphate. The total amount of iron in these systems was expected to be high and 65 to 190 mgFe/gVSS was reported. By means of HCl extraction, Nielsen (1996) found that the concentration of Fe(II) was always lowest in the aerobic/anoxic tank of a Biodenipho plant (10 to 15 mgFe/gVSS), with little difference noted during the aerobic/ anoxic cycle. In the return sludge and anaerobic tank, the Fe(II) concentration was a little higher (14 to 24 mg Fe/gVSS). Nielsen (1996) postulated that Fe(III) reduction occurs in activated sludge under anaerobic conditions as a result of Fe(III)-reducing bacteria (FeRB) using organic substrates (e.g. acetate, lactate, glucose) as source of electrons and energy. According to this postulate, either complete oxidation to CO_2 or incomplete oxidation to yield fermentation by-products (e.g. acetate) are possible. Nielsen (1996) suggested that acetate production by FeRB could be a source of acetate for consumption by phosphorus-accumulating organisms (PAO) (i.e.

poly P organisms) in the BEPR mechanism. However, from the observed rates of Fe(III) reduction in full-scale plants, Nielsen (1996) estimated that the rate of acetate production by FeRB would likely be 0.26 to 0.62 mg COD/(gVSS.h) or 0.75 to 2.0 mgCOD/(ℓ.h) in an anaerobic tank with 3 g VSS/ℓ. Since the hydraulic retention time in the anaerobic tank would typically be 1 to 2 h, the acetate from this source (< 4 mg COD/ℓ) would be relatively insignificant (equivalent to <0.4 mgP/ℓ additional biological P removal, based on the steady-state model of Wentzel *et al.*, 1990). Nevertheless, if the reduction of Fe(III) to Fe(II) resulted in dissociation of an iron-phosphate precipitate with an hypothetical Fe:P molar ratio of 2.5:1 (Luedecke *et al.*, 1989), then the above-mentioned observed changes in Fe(II) during the anaerobic-aerobic cycle could result in P release of up to approx. 10 mgP/ℓ in an anaerobic tank with 3 gVSS/ℓ. P release from this source would be of chemical origin (mediated through biological reduction of iron) and may be significant when interpreting data from combined chemical-biological P removal plants.

1.2.1.2 Effect of pH on precipitation with iron salts

According to Benedek *et al.* (1976) (quoted by Yeoman *et al.*, 1988), in an iron-ortho P system, removal of phosphate is independent of pH below an Fe:P molar ratio of 1.5:1; at ratios above this value, pH has an increasing influence. The optimum pH for phosphate precipitation with ferric iron is the range between pH 4.0 and 5.0, while that for ferrous iron is close to pH 8.0 (Wiechers, 1987). However, in practice wastewater treatment systems usually rely heavily on biological processes which have an optimum pH in the range ca. 6.8 to 8.0. Similarly, standards for discharge of treated effluent to rivers and lakes or dams also usually mandate a pH range close to neutral. Furthermore, special corrosion-resistant construction materials would be required for reactors to tolerate a pH as low as 4.0, and pH correction to a neutral pH would incur major additional chemical costs (e.g. lime or soda ash). It is therefore seldom practical to operate a wastewater treatment process (or a part of the process) in the optimal pH range for ferric phosphate precipitation. Fortunately, the implication is not serious in practical terms since the low solubility products of ferric phosphate makes it chemically possible to achieve low effluent P concentrations (ca. 0.1 to 1 mgP/ℓ) at near-neutral pH with simultaneous iron dosing (Luedecke *et al.*, 1989). This aspect will be addressed further in the literature review related to modelling combined chemical- biological P removal systems (Chapter 7, section 7.1).

1.2.1.3 Observations with simultaneous iron dosing

Wuhrmann (1968) conducted a number of valuable pilot experiments involving the addition of ferric chloride to the aeration basin of an activated sludge plant (reviewed by Jenkins *et al.*, 1971). Effluent total P concentrations were seldom less than 0.5 mgP/ℓ at 30 mg/ℓ as Fe(III) (Fe:P mole ratio = 3.1:1). Wuhrmann (1968) also reported that ferric chloride dosing caused the virtual disappearance of protozoa from the activated sludge culture. The poor phosphate removal observed was largely attributable to the failure of the secondary sedimentation process to remove fine phosphate-containing particles. It was not clear to Wuhrmann (1968) whether the turbid effluents obtained were due to poorly flocculated ferric-hydroxy-phosphate particles or as a result of dispersed activated sludge particles due to the absence of protozoa. Wuhrmann (1968) obtained better phosphate removal and less turbid effluent in tertiary chemical treatment experiments but commented on the poor settling and dewatering properties of the tertiary sludge (Jenkins *et al.*, 1971).

In the late 1960s and 1970s concern over eutrophication, particularly in the Great Lakes region of North America, led to widespread implementation of simultaneous chemical dosing (mainly with iron salts) for P removal in the USA, Canada and parts of Europe (e.g. Boyko and Rupke, 1973; Stepko and Shannon, 1974; Viitasaari, 1976; Sutton, *et al.*, 1978; Black, 1979; Rensink *et al.*, 1979; D'Elia and Isolati, 1992). However, most of these plants were high-rate (short sludge age) or conventional (completely aerobic) activated sludge plants which did not make provision for BEPR.

Therefore, the possible interaction between biological and chemical P removal mechanisms were hardly considered. BEPR process designs began to emerge in South Africa in the late 1970s and the first new BEPR plant in North America was built in Kelowna (BC, Canada) in 1980 (Barnard, 1995).

Rabinowitz and Marais (1980) were possibly the first to investigate the effect of simultaneous addition of ferric chloride and ferrous sulphate to modified activated sludge systems incorporating BEPR in the 3-stage Phoredox or UCT configurations. They drew several important conclusions:

- Chemical addition enhanced the P removal in the test systems. The iron phosphate chemical removal mechanism appeared to operate independently of the biological removal mechanism. This conclusion was drawn by comparing the observed system P removal with the theoretical P removal potential (i.e. mathematical model prediction for biological removal plus an apparent stoichiometric chemical precipitation of $FePO_4$ using ferric chloride).
- Chemical P removal was strongly pH dependent. For both $FeSO_4$ and $FeCl_3$ addition, if the process pH fell below 7.0, the P removal efficiency decreased, the effluent became yellow-green in colour and turbidity increased. At a process pH $\geq$ 7.2, the P removal efficiency increased to a maximum, the effluent was virtually colourless and the turbidity low.
- Using $FeSO_4$ addition at process pH $\geq$ 7.2, an estimated stoichiometric chemical removal efficiency of 80% was achieved. Using $FeCl_3$ addition, an estimated stoichiometric removal efficiency of 100% was achieved. There were indications that when the effluent phosphorus concentration fell to <1.5 mgP/ℓ, the removal efficiency decreased (i.e. $Fe_{dose}/P_{removal}$ ratio increased). Consequently, for low effluent P concentrations, the iron dose needed would be greater than the stoichiometric amount, in relation to the P removal required.
- Simultaneous chemical addition exhibited a "persistence effect" as became evident from P removal behaviour under cyclic loading conditions, as well as continued P removal in excess of calculated biological P removal potential for several days after cessation of dosing. It was proposed that this was due to the accumulation of ferric-hydroxide precipitate in the sludge mass which leads to phosphate removal by an ion exchange effect between hydroxide and phosphate ions.
- The point of iron dosing did not appear to have any significant effect on the system chemical P removal performance.
- "Iron leakage" into the effluent was tested when dosing $FeCl_3$, but effluent iron concentrations were consistently low (<0.1 mg Fe/ℓ). It was concluded that virtually all the added Fe was adsorbed or precipitated in the sludge mass.

Lötter (1991) reported satisfactory plant performance (effluent <1 mgP/ℓ as ortho P) at Alexandra Works (Johannesburg) with ferrous sulphate dosed in the **mass** ratio of 2.1:1 to 2.4:1 for $Fe:P_{removed}$. At Northern Works (Johannesburg), satisfactory performance was achieved with one module dosed with ferric sulphate at a **mass** ratio of approximately 2:1 for $Fe:P_{removed}$ [6]. However, Lötter (1991) also reported that partial inhibition of the biological P removal process make it difficult to a control simultaneous iron dosing where BEPR is expected to make a major contribution to the system P removal performance. This aspect will be discussed further in section 1.4 below.

Luedecke *et al.* (1989) developed a chemical model of ferric phosphate precipitation in activated sludge systems which described ferric hydroxy-phosphate precipitation either alone or together with ferric hydroxide. The model is based on equilibrium chemistry and additionally includes a description of adsorption of phosphate ions on ferric phosphate and ferric hydroxide precipitates. This model is reviewed in detail in Chapter 7. Its application to combined biological-chemical P removal activated sludge systems is limited by the fact that it takes no account of the biological processes for phosphate. In order to set up a combined model, the basis for dividing the available phosphorus between the biological and chemical P removal processes needs to be carefully examined. Such a combined chemical-biological P removal model has been proposed by Briggs

[6] A mass ratio (Fe:P) of 2:1 corresponds to a molar ratio of 0.55:1.

(1996), based partly on the work of Luedecke *et al.*, 1989). Activated Sludge Model No. 2 (IAWQ, 1995) also makes provision for simultaneous chemical precipitation in biological nutrient removal systems. However, there are major differences in the modelling approach followed by Briggs (1996) compared to that used in the IAWQ model. These differences will be examined in Chapter 7.

1.2.2 Alum and poly-aluminium chloride

Aluminium sulphate is used extensively for phosphate precipitation, particularly in Scandinavian countries and in the USA (Ulmgren, 1975; Klute and Hahn, 1992; Morales *et al.*, 1991). The chemical principally used is hydrated aluminium sulphate (or alum) with the approximate formula of $Al_2(SO_4)_3.14H_2O$ (Wiechers, 1987). According to Wiechers (1987), two competing reactions are involved when alum is dosed into phosphate-containing waters. Neglecting reactions between condensed and organic phosphates, which are also involved, there is mainly competition between the formation of aluminium hydroxides ($Al(OH)_3$ ideally) and aluminium phosphate ($AlPO_4$ ideally). Ideally, equations for the formation of $Al(OH)_3$ and $AlPO_4$ may be written as:

$$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+$$

$$Al^{3+} + PO_4^{3-} \rightarrow AlPO_4$$

However, these equations are probably an over-simplification, as a more detailed review of the literature (Chapter 7, section 7.1) will reveal. For example, numerous other hydrolysis products (ion pairs) of aluminium may form (Briggs, 1996), depending mainly on pH. Similarly, several different formulae for an aluminium-hydroxy-phosphate precipitate have been proposed, depending on experimental conditions.

From an examination of the literature, Power *et al.* (1992) concluded that although a mechanism of adsorption/ion exchange of phosphate ions with aluminium hydroxide flocs has been proposed, there is evidence for direct precipitation of insoluble aluminium phosphates. Disagreement exists over the stoichiometry of aluminium-phosphate reactions. The stoichiometric molar ratio of Al:P of 1:1 in $AlPO_4$ is never achieved in practice, and the actual ratio between aluminium dosed and P removed varies between 2:1 and 3:1 (Wiechers, 1987). This suggests that one or more of the hydrolysis products of Al^{3+} (e.g. $Al(OH)_2^+$, $Al_2(OH)_2^{4+}$) are involved in the precipitation of phosphate (Power *et al.*, 1992). According to Jenkins *et al.* (1971), the formation of aluminium phosphate is thermodynamically and kinetically favoured over hydroxide formation. However, at low phosphate concentrations (<10 mgP/ℓ), the competition between hydroxide and phosphate is more significant (Stumm and Morgan, 1970, quoted by Yeoman *et al.*, 1988). Hence, once formed, the precipitate probably has an amorphous composition intermediate between crystalline aluminium phosphate and hydroxide solids. The precipitation reactions are pH-dependent, with the optimum pH in the range 5.5 to 6.5, depending on the composition of the wastewater (Wiechers, 1987).

The flocs resulting from aluminium salts are "lighter" (less dense) and slower to form than those from iron salts. D'Elia and Isolati (1992) reported that iron salts readily lead to the formation of well developed flocs with good settling characteristics (low SVI, due to a "weighing down" effect of the iron ions) but increased sludge production. On the other hand, the advantage of aluminium compounds is shown in a higher efficiency in the neutralisation of surface charges and hence in coagulation-flocculation processes (e.g. removal of turbidity) (D'Elia and Isolati, 1992).

Power *et al.* (1992) investigated the use of waste alum sludges (from water treatment works) for chemical phosphate removal in an activated sludge system at laboratory scale. The system selected for the experiment was of a modified Ludzack-Ettinger configuration with a large (70%) anoxic mass fraction in an attempt to promote filamentous bulking. The alum sludges were found

to have an ash content (or inorganic suspended solids, ISS[7]) of 30 to 47%, and a COD/VSS ratio of 0.9 to 1.2. The alum sludge dosage used was 17 to 49 mg ISS/ℓ based on influent flow. Since these alum sludges originated from plants treating "soft" waters (low TDS, low alkalinity), the mass of inorganic precipitates such as calcium carbonate, magnesium carbonate and calcium sulphate in the resultant sludge was considered negligible. Hence, after ashing, virtually all the ISS was considered to be aluminium oxide (Al_2O_3). On this basis, and converting stoichiometrically from the molecular weight of Al_2O_3, the aluminium dosage to the experimental reactors was expressed as approximately 53% of the ISS, or 9 to 26 mg/ℓ as Al. This would be equivalent to 99 to 286 mg/ℓ as "fresh" alum ($Al_2(SO_4)_3.14H_2O$). Phosphate removal was measured by difference between parallel control and experimental systems, with alum sludge dosed into the latter. Biological P removal was discouraged (though not eliminated) by dosing nitrate into the anoxic reactor to prevent it becoming anaerobic. Considerable periods (100 days or more, at a sludge age of 20d) lapsed before an approximate steady state was observed in terms of the additional P removed by the test system relative to the control. Neglecting experimental periods when the systems were considered to be far from steady-state, linear regression data suggested that the additional (chemical) P removal due to alum sludge addition amounted to 0.18 mgP/mg ISS dosed (equivalent to 0.34 mgP/ mg Al dosed). If the stoichiometry of AlPO4 precipitation is considered (1.15 mgP/mg Al), then just under one third of the stoichiometric chemical P removal was observed in the experimental system with waste alum sludge. Steady-state VSS in the test reactor receiving alum sludge increased in direct proportion to the additional VSS dosed as alum sludge, indicating that the water works sludge is unbiodegradable. A marked improvement in DSVI was noted for the test system receiving alum sludge (ca. 100 mℓ/g compared with 200 to 250 mℓ/g in the control system), presumably due in part to the alum sludge exerting a coagulating effect in the mixed liquor, and partly due to "weighing down" (density) effect exerted by alum sludge particles becoming enmeshed in the sludge. However, the alum sludge tended to increase the turbidity and COD of the system effluent, with calculations implying that as much as 50% of the alum sludge COD escaped with the effluent as unbiodegradable soluble COD. Dewaterability of the sludge (as tested by specific resistance to filtration) from the test and control systems was very similar, although tending to be slightly better in the test system, which may have been related to the lower DSVI. Interestingly, the alum sludge alone (prior to dosing into the activated sludge system) dewatered much more poorly than the activated sludge alone. Similarly, a simple mixture of the two sludges produced a sludge with the dewatering characteristics of the constituent sludges, depending on their relative mixing ratio. Hence, the improved dewaterability of the waste alum sludge after treatment in the activated sludge system was in some way mediated by the biological process, or possibly by a "washing" effect via the reactor-clarifier recycle.

Poly-aluminium chloride (PAC), sometimes called polyaluminium hydroxy-chloride, has also been tested for phosphate removal in wastewater treatment. According to Hahn (1992), "aluminium polymers" are more readily available for technical processes than pre-polymerised iron species. The advantage of pre-polymerised polynuclear hydroxo species such as PAC is that they are more efficient in destabilising colloids (therefore probably better for coagulation of organic matter) and not very dependent on mixing intensity compared to non-hydrolysed metal salts (e.g. alum). When dosed into water, the unhydrolysed metal salts need to hydrolyse (form metal hydroxides) *in situ* before exerting coagulating/precipitating properties. These metal salts therefore become less efficient with decreasing mixing intensity because optimal hydroxide formation requires rapid dilution of the metal ion before a pH change occurs (Hahn, 1992). D'Elia and Isolati (1992) studied PAC in tandem with ferric chloride for simultaneous phosphate precipitation in a seasonally overloaded conventional activated sludge plant. Ferric chloride (50 mg/ℓ) in the influent to an aeration basin, along with 30 mg/ℓ PAC in the return sludge, gave phosphorus reductions of approximately 85%, compared to 50 to 70% phosphorus reduction for 120 mg/ℓ ferric chloride alone for the same period in a previous year for the same plant. This suggested that the PAC+$FeCl_3$ system was more efficient in simultaneous precipitation.

[7] %ISS = (1-VSS/TSS) x 100

1.2.3 Lime/ calcium salts

The addition of lime (or other calcium compounds) for simultaneous P precipitation in activated sludge systems has been proposed (Jenkins *et al.*, 1971). Phosphate precipitation with calcium results in the formation of apatites (e.g. $CaHPO_4$; $Ca_4H(PO_4)_3$; $Ca_3(PO_4)_2$) or hydroxyapatite ($Ca(PO_4)OH$) (Arvin, 1979). However, precipitation with lime or calcium salts is probably not as cost effective as the use of iron or aluminium salts (Arvin, 1985). One of the draw-backs of using lime or calcium salts is that P precipitation occurs at high pH (ca. ≥9), which would be outside of the optimal pH range for most biological processes. Moreover, relatively high doses of lime are required to achieve the necessary pH for calcium phosphate precipitation. According to Aspegren (1995), at pH 8.6 redissolution of calcium phosphate precipitate occurs at phosphate concentrations of <3 mgP/ℓ, while at pH 7.0, redissolution occurs at <90 mg/ℓ (approximately). Special effluent discharge standards which restrict phosphorus usually call for maximum concentrations in the region of 0.5 to 2 mgP/ℓ. For these reasons, lime dosing was not considered for this investigation.

1.3 ADVANTAGES AND DISADVANTAGES OF SIMULTANEOUS PRECIPITATION

As pointed out in section 1.2 above, chemical phosphate precipitation can be by pre-precipitation, simultaneous precipitation or post-precipitation (Yeoman *et al.*, 1988). According to D'Elia and Isolati (1992), there is demand on the part of treatment plant managers for a simple and flexible technology that combines nitrification, denitrification, and simultaneous phosphate precipitation (or "co-precipitation"). Wiechers (1987) pointed out that simultaneous phosphate precipitation offers the following advantages:

- ease of operation (flow proportional dosing not necessary due to the retention of precipitate in the biomass, and continual recycling from the secondary clarifiers back into the process);
- flexibility to changing conditions (treatment costs are largely a function of influent characteristics and final effluent phosphate concentrations, without large capital costs for new tertiary solids separation as with post-precipitation);
- relatively small additional solids production;
- improvements in sludge settleability and dewaterability;
- low effluent phosphate levels are possible, and improved COD and suspended solids removal give a higher quality final effluent;
- chemicals can assist in controlling activated sludge bulking and foaming.

However, there may be certain disadvantages associated with chemical precipitation, and simultaneous precipitation in particular. These include the following:

1.3.1 Increased dissolved solids load on the receiving water

An unavoidable negative side-effect of chemical dosing is that chemical dosing always results in an increase in the total dissolved solids (salinity) content of the treated effluent, mainly in the form of either chloride or sulphate. Depending on the nature of the receiving water and constraints posed by location of the treatment works in the catchment, this may or may not be an important consideration. In either event, it is preferable from a water quality point of view to minimise the chemical dose required to meet the required effluent phosphate standard. This provides further incentive for optimising biological P removal processes and limiting chemical dosing as far as possible.

1.3.2 Sludge production

Increased sludge production is a likely disadvantage resulting from chemical dosing in waste water treatment (Henze and Harremoes, 1992). Schmidtke (1985) conducted a survey of 15 wastewater treatment plants in Ontario (Canada) before and after phosphorus removal by the installation of chemical precipitation systems. For conventional activated sludge plants (probably high rate, or short sludge age plants which predominated in North America at that time), Schmidtke (1985) found an average sludge production rate (for primary + waste activated sludge) of 179 kg dry solids per Mℓ of sewage treated. After inclusion of simultaneous ferric iron precipitation, the same plants showed an average sludge production rate (raw + waste activated + chemical sludge) of 217 kg dry solids/ Mℓ treated, an increase of 26%. The average solids volume increased by 35%. There appears to be a paucity of similar data for BNR plants, which usually operate at intermediate to long sludge ages, but an increase in sludge production in proportion to chemical dose may be expected.

1.3.3 pH and alkalinity effects

A further disadvantage of simultaneous chemical dosing into activated sludge systems is that care must be taken not to inhibit the biological processes. Direct toxicity to the biological reactions at typical doses for typical domestic/ mixed domestic-industrial wastewaters has not been reported. According to Arvin (1985), the metal dosage needed for simultaneous P precipitation is small. There are no reports indicating that addition of small or moderate amounts of iron or aluminium salts inhibit biological activity at normal pH values close to 7 (Arvin, 1985). The most likely negative effect of chemical addition on biological processes is through pH depression, with nitrification (and hence denitrification) being particularly sensitive. Most chemical salts dosed are acidic, and the iron salts usually more so. According to data provided by suppliers of chemicals in South Africa, alum has a pH of approximately 2 to 3, while ferric chloride and ferrous-ferric chloride blend have a pH of <1. The free acid content is determined by the production process and may vary between suppliers. Ferric chloride or ferrous-ferric chloride blend sold by one major supplier in South Africa has a free acid content of <1% m/m and usually ≤ 0.5% m/m as HCl (Reynolds, 1996).

Apart from the acidity of the precipitant dosed, the removal of hydroxides and phosphates from the aqueous phase due to the precipitation reactions results in a loss of alkalinity. For alum, Power *et al.* (1992) gave the alkalinity loss as 0.55 mg/ℓ as $CaCO_3$ per mg/ℓ alum dosed. According to Loewenthal *et al.* (1986), the theoretical alkalinity loss due to metal hydroxide precipitation is: 0.253 mg/ℓ as $CaCO_3$ per mg/ℓ as $Al_2(SO_4)_3.14H_2O$ (or 0.44 mg/ℓ as $CaCO_3$ per mg/ℓ as $Al_2(SO_4)_3$) for aluminium sulphate (alum); and 0.92 mg/ℓ as $CaCO_3$ per mg/ℓ as ferric chloride (or 2.67 mg/ℓ as $CaCO_3$ per mg/ℓ as Fe). In the case of ferrous salts, the oxidation of ferrous ions to ferric ions results in a *gain* in alkalinity of 0.89 mg/ℓ as $CaCO_3$ per mg/ℓ as Fe^{2+} (Loewenthal *et al.*, 1986). In turn, the ferric ions formed result in a loss of alkalinity due to hydroxide formation (see above). Assuming a ferrous-ferric blend contains 60% ferrous iron and 40% ferric iron, the net theoretical loss in alkalinity will be 2.14 mg/ℓ as $CaCO_3$ per mg/ℓ as Fe, based on the information given by Loewenthal *et al.* (1986).

The simultaneous precipitation experiments of Wuhrmann (1968) (reviewed by Jenkins *et al.*, 1971) using ferric chloride (see above) tended to produce turbid effluents which may have been partly due to the inhibition of protozoa which play an important role in "scavenging" free bacteria from activated sludge flocs to produce good settling sludges. Barth and Ettinger (1967) also noted that turbid effluents resulted from addition of ferric chloride (15 mg/ℓ as Fe) to a pilot plant activated sludge aeration basin. This was ascribed to a drop in pH to 6.0 to 6.2 caused by ferric chloride addition, but no causative mechanism was suggested. Eberhardt and Nesbitt (1968) added alum (at Al:P molar ratios as high as 2.4:1) to the aeration basin of a laboratory-scale high

rate activated sludge plant. They also found that this resulted in effluent turbidity and poor total phosphate removal. Their reactors operated in the pH range 5.5 to 6.5, which is low considering that the optimum for activated sludge processes is usually in the neutral to weakly alkaline range (pH 7.0 to 7.6), particularly where nitrification is required.

The loss of alkalinity upon chemical dosing may necessitate alkalinity supplementation (usually in the form of lime dosing) in areas of low alkalinity water or wastewater, particularly where simultaneous chemical addition is to be applied. For example, Bliss *et al.* (1994) found that spent pickle liquor (an acidic waste product containing ferrous iron) inhibited nitrification in an activated sludge plant. This was found to be due to pH depression to <6.0 as a result of the low alkalinity sewage being treated. Lime addition corrected the pH and restored nitrification. Minimum residual total alkalinity in the treated effluent of around 75 mg/ℓ as $CaCO_3$ proved suitable for sustaining nitrification (Bliss *et al.*, 1994). WRC (1984) recommended a minimum alkalinity in the region of 40 to 50 mg/ℓ as $CaCO_3$ to keep the pH of the system above 7.0. Residual alkalinity of this order is generally also required to minimise corrosion of concrete structures.

1.3.4 Inhibition of biological P removal

Evidence has emerged that simultaneous dosing of metal salts into BNR activated sludge plants with BEPR capability results in partial inhibition of the BEPR mechanism. This evidence is reviewed in section 1.4 below.

1.4 EFFECT OF SIMULTANEOUS CHEMICAL DOSING INTO FULL-SCALE BNR PLANTS

In previous sections it has been pointed out that for reasons both of cost and water quality, especially where a large capital investment in BNR technology has already been made and simultaneous supplemental chemical dosing is implemented, optimal use of chemicals must be made by minimising the impact on biological P removal. In South Africa anecdotal evidence suggested that sustained iron dosing to an activated sludge plant diminishes the plant's capacity to remove phosphate, necessitating higher and higher doses (Lötter, 1991). For this reason, Lötter (1991) carried out a number of batch tests with ferric chloride, ferric sulphate and ferrous sulphate as simultaneous precipitants in mixed liquor from BNR plants in the Johannesburg area. From these batch tests and observations made at full-scale, including the results of fractionation studies reported more fully by de Haas and Greben (1991), Lötter (1991) concluded that:

- Continuous iron dosing to an activated sludge plant appeared to produce a "progressive inhibitory effect .... on the biological as well as the chemical process" (p620);
- The results of fractionation studies on Northern Works "demonstrated clearly that polyphosphate storage is inhibited by the addition of iron salts. The exact mechanism involved here requires further study. Although the results obtained during this study cannot be considered unequivocal, they provide enough evidence to suggest that further study into the mechanism of combined chemical and biological phosphate removal is imperative if these two processes are to optimised" (p 619);
- Ferric phosphate precipitation is inhibited by "prior iron treatment" (p 614), as shown by laboratory batch tests, and to some extent borne out by performance of two full-scale plants;
- From full-scale data, a beneficial effect was reportedly produced by reducing iron dosing for a short time. Although the underlying mechanisms of this effect were unclear, it was hypothesised that ferric phosphate build-up in the sludge inhibits the precipitation process. This was perceived to pose operational problems since legislation governing effluent quality does not allow sufficient latitude for a non-complying effluent to be discharged while the sludge "recovers its precipitation propensity" (p 620);

- The addition of iron to an area of high phosphate concentration (e.g. anaerobic zone) "clearly had a beneficial effect on the precipitation process. The effect of this on the biological process still has to be determined" (p 620);
- In view of the apparent inhibitory effect of iron dosing on the chemical and biological processes, addition of iron salts in the primary treatment stage (prior to primary sedimentation or sludge fermentation) was advocated for further investigation.

The work of Lötter (1991) merits comment. Firstly, considering that the average influent total P to the Johannesburg Works would be approximately 16 mgP/ℓ and that around 75% removal should be possible by biological means, approximately 4 mgP/ℓ removal by chemical means would be required. This ties up with full-scale data presented by Lötter (1991) where the iron dose at Northern Works in early 1989 was 8 mg Fe/ℓ, based on inflow. However, in laboratory-scale batch tests, Lötter (1991) added relatively high concentrations of phosphate (50 mgP/ℓ) to the mixed liquor samples[8]. This was followed by 100 mg Fe/ℓ of the selected iron precipitant and aeration for 2 hours. To investigate the effect of sustained chemical dosing, the same phosphate precipitation regime was repeated in batch tests on mixed liquor already treated with iron (Lötter, 1991). The results indicated that in the first batch test, chemical P removal was good with all three iron salts, although the ferrous salt showed a delayed reaction in the first hour (ascribed to the oxidation of ferrous ions to ferric ions preceding P precipitation). However, in the second batch test, repeat exposure to the chemicals gave P removal which was weakened by approximately 40%, 25% and 12% for ferric sulphate, ferric chloride and ferrous sulphate respectively *but only by comparison with controls which had been aerated without chemicals in the first test*. On the other hand, Lötter (1991) did not explain why the P removal was virtually identical in the first and second batches on the same mixed liquor samples dosed with chemicals. By interpolation of the published graphs, the reported removals for the test reactors were, respectively:

- Ferric sulphate: 52 mgP/ℓ (batch test 1) and 50 mgP/ℓ (batch test 2);
- Ferric chloride: 50 mgP/ℓ (batch test 1) and 50 mgP/ℓ(batch test 2;
- Ferrous sulphate: 55 mgP/ℓ (batch test 1) and 57 mgP/ℓ (batch test 2).

In the control reactors, the removals were:

- Batch test 1: 11 mgP/ℓ and Batch test 2 (ferric sulphate): 77 mgP/ℓ;
- Batch test 1: 11 mgP/ℓ and Batch test 2 (ferric chloride): 66 mgP/ℓ;
- Batch test 1: 12 mgP/ℓ and Batch test 2 (ferrous sulphate): 69 mgP/ℓ.

Lötter (1991) assumed that P removal under the experimental conditions of the (aerobic) batch tests described above was almost exclusively by chemical precipitation. She concluded that the results "appear to confirm observations by plant operators that continuous iron salt addition results in reduced chemical precipitation efficiency, which in turn leads to higher doses" (Lötter, 1991, p614). An alternative explanation of these results may be that aeration of the control mixed liquor for two hours in the first batch test produced conditions for improved phosphate precipitation relative to the test mixed liquor in the second batch test. For example, aeration may have stripped out dissolved CO_2 which accumulated from mixed liquor storage prior to the experiment, thereby reducing the alkalinity of the mixed liquor, which in turn could have improved P-precipitation. Furthermore, it is possible that the biological mechanisms of activated sludge are more important in their influence on the efficiency of chemical P-precipitation than accounted for by Lötter (1991).

Apart from a decrease in chemical precipitation efficiency as a result of continuous iron dosing (see above), Lötter (1991) postulated that the biological mechanism is also inhibited by iron dosing. This postulate was based on the results of fractionation studies (see 1.5 below). However,

[8] The point of sampling for the mixed liquor was not reported. The mixed liquor was merely reported to be "denitrifying" or "nitrifying" under the laboratory batch test conditions.

it is surprising to find that Lötter (1991) discarded results from anaerobic batch tests in the presence of acetate. The results from only one anaerobic batch test experiment were described. These results were discarded by Lötter (1991) because the control mixed liquor (without iron added) appeared to release less P than mixed liquor to which iron had been added in the laboratory, followed by two hours aeration prior to the anaerobic P release test. These experiments were poorly described in that the history of the mixed liquor sample was not given, the rationale behind the addition of iron in the batch tests was not explained (e.g. whether it could be considered representative of the long-term effects noted on the full-scale plants with continuous dosing), and the relevant graph (Lötter, 1991, Fig. 3) had phosphate release expressed on a percentage scale without indication of the basis for this scale.

Lötter (1991) also presented evidence from monitoring of full-scale plants which indirectly appeared to support the hypothesis that chemical addition negatively affects the biological P removal mechanism. For example, with ferric sulphate dosing (in approximately equal mass relative to the dissolved phosphate present) to the return sludge lines of parallel modules at Northern Works (Johannesburg), it was observed that P removal was weaker and more erratic in a module with the Johannesburg (pre-anoxic zone) configuration, compared to the older 5-stage Phoredox configuration. This was contrary to expectations of better biological P removal performance with the Johannesburg configuration (Osborne *et al.*, 1986; 1989; Pitman, 1991), and was taken by Lötter (1991) to be as a result of chemical dosing, without detailed explanation. Similarly, ferric chloride dosing at Olifantsvlei Works was successful over a period of approximately 2½ years after which it apparently became increasingly subject to upsets in terms of the effluent failing to comply with the 1 mgP/ℓ ortho P standard. The dose was increased to an Fe:P mass ratio of >1.8:1 (up to 3:1), reportedly without success. However, all the possible reasons for the plant failure were not discussed. Some points mentioned (but not elaborated on) by Lötter (1991) were :

- that the load to the plant increased prior to one period of unsatisfactory compliance;
- cessation of dosing "for a few days" produced a recovery. However, on the principal occasion in this context, the recovery in effluent P concentrations was so dramatic from 6 mgP/ℓ to <0.5 mgP/ℓ as to be very remarkable.

Supporting data, such as nitrate recycles to the anaerobic zone, influent load and flow, were not given by Lötter (1991). According to Lötter and Pitman (1992, cited by Boyd and Lötter, 1993), success at Olifantsvlei was subsequently achieved with a ferrous/ferric chloride blend and refined dosing control.

In conclusion, from a re-interpretation of the data of Lötter (1991), a degree of uncertainty exists over the true extent to which the biological mechanism is inhibited by continuous simultaneous chemical addition. Lötter's postulate that such inhibition can arise appeared to be heavily based on the fractionation studies, which will be examined in more detail below (section 1.5). Moreover, Lötter (1991) postulated that chemical precipitation efficiency itself is reduced by repetitive chemical dosing, but this postulate was heavily based on batch tests with only two repeat steps of chemical addition, and at concentrations (of both added phosphate and iron) which were much higher than those typically encountered in full-scale BEPR plants. Nevertheless, Lötter (1991) did note that her results could not be considered unequivocal and advocated further study into the mechanism of combined chemical and biological phosphate removal.

Boyd and Lötter (1993) conducted further studies into combined chemical-biological P removal under conditions of simultaneous chemical addition. They postulated that inhibition of the BEPR mechanism by iron salts is caused by ferric hydroxide precipitate "using up" hydroxyl ions necessary for the hydroxyl mediated transport process for phosphate across bacterial cell membranes. To investigate this hypothesis, Boyd and Lötter (1993) operated two pilot plants of unspecified size at a 14d sludge age which were fed settled/ fermented sewage from the Northern Works balancing tank (Johannesburg). After the operation of the pilot plants had stabilised, ferrous

sulphate was dosed to the anaerobic reactor of one pilot plant while the other served as control. The iron dose was given as a ratio of 0.5:1 (Fe:P), but without stating whether this was a mass ratio or a molar ratio. Samples of mixed liquor were subjected to fractionation according to de Haas (1991) as well as microbiological tests on enrichment culture isolates from each of the aerobic reactors. According to Boyd and Lötter (1993), the experimental reactor (iron dosed) gave effluent ortho P concentrations of 1.1 (± 0.3) mgP/ℓ, while the control reactor performed *better* with 0.7 (± 0.3) mgP/ℓ in the effluent. However, the experimental results suggested that the pilot plants operated with stable, low effluent phosphate concentrations in both units for seven sludge ages, after which an "unexplained decrease in biomass ... led to destabilisation of the BEPR process in both cases" (Boyd and Lötter, 1993, p 90). Boyd and Lötter (1993) measured intracellular polyphosphate (IPP) concentrations by an unspecified method[9]. Interpolating from the graphical results of Boyd and Lötter (1993), over the first seven sludge ages, the aerobic IPP concentrations averaged about 45 (± 23) mgP/gVSS in the control unit and 26 (± 10) mgP/gVSS in the experimental unit. Unfortunately phosphate recoveries and a breakdown of the fractionation results were not given, making interpretation difficult. During the period corresponding to between seven and nine sludge ages, the IPP plummeted to <10 mgP/gVSS in both units, recovering gradually to ca. 52 mgP/gVSS (control) and 32 mgP/gVSS (experimental) by the time a period corresponding to eighteen sludge ages had passed (end of trial). Boyd and Lötter (1993) explained these results on the basis that the biological mechanism was partially inhibited by iron salt dosing. This explanation was supported by microscopic investigations indicating that the cells from the experimental unit were smaller and "less full" of polyphosphate as viewed with the metachromatic (Neisser) stain. Enrichment cultures suggested that there was no difference in the ability of *Acinetobacter* isolates from the two units to synthesise and store polyphosphate (poly P).

The work of Boyd and Lötter (1993) appeared to confirm the conclusion of Lötter (1991) that biological P removal is inhibited by continuous simultaneous chemical (iron) dosing. Similarly, from fractionation studies, Röske and Schönborn (1994a) concluded that in cases with addition of (iron) precipitants to an anaerobic-aerobic system, "the biological P-elimination by bacteria is substantially reduced" (p 1109). Röske and Schönborn (1994b) found that the rate of P release (to the supernatant) under anaerobic conditions is lower in systems with simultaneous addition of ferric ions. Such conclusions are fundamentally important to the design and operation of biological P removal plants which incorporate (or have come to be reliant upon) simultaneous chemical addition in order to consistently achieve the required phosphate discharge standard. The successful use of biological P removal requires investment in such additional process components as anaerobic (and possibly pre-anoxic) zones, suitable mixers, recycles and primary sludge fermenter-thickening facilities. These components can add substantially to the capital cost of a BNR plant and such capital investment could be largely wasted if simultaneous chemical addition leads to a "progressive" inhibition of the biological P removal mechanism or the plants overall propensity to remove phosphate, as suggested by Lötter (1991), Boyd and Lötter (1993) and Röske and Schönborn (1994a). With the trend toward consulting engineers being asked to provide design guarantees in terms of project performance specifications, uncertainty over the viability of combined chemical-biological P removal in BEPR designs could lead to simultaneous precipitation being disfavoured for full-scale applications in spite of its potential to allow for more economical use of reactors and clarifiers. It is therefore imperative that the impact of simultaneous chemical addition on the biological P removal mechanism be investigated further, particularly with a view to addressing possible outstanding questions arising from re-interpretation of earlier work. The principle aim of this study was to conduct such an investigation. The objective was set of attempting to define conditions under which inhibition of the biological P removal mechanism in the presence of chemical addition may be observed. Clearly, this objective would require the chemically-precipitated phosphate content of the mixed liquor to be measured as distinct from the biologically-stored phosphate (or poly P) pool. A method for chemical fractionation of the phosphate compounds of activated sludge would therefore be essential.

[9] de Haas (1991) was cited but presented two possible methods in this respect.

1.5 CHEMICAL FRACTIONATION STUDIES

It is possible to study the composition of phosphate compounds stored or bound in samples of widespread origin (e.g. soils, sediments and sludges or other forms biomass, including that of animal, plant, fungal and bacterial origin) by means of chemical extraction. Such techniques are generally termed fractionation methods. Many different chemical solutions and extraction techniques have been used in a variety of fractionation techniques. Some of these, particularly in so far as they relate to phosphate compounds of biological origin (notably polyphosphates and nucleic acids), have been reviewed by Kulaev (1979). De Haas (1989b) reviewed fractionation methods which have been applied to activated sludge from wastewater treatment plants and found that such methods may offer a useful tool for quantifying the P compounds which appear to be stored via chemical versus biological P removal mechanisms. However, de Haas (1989b) also pointed out certain weaknesses of the available chemical fractionation methods when applied to activated sludge.

Lötter (1991) presented chemical fractionation data extracted from de Haas (1989b) and de Haas and Greben (1991) which suggested that chemical dosing may have been responsible for a reduction of the observed poly P content of the mixed liquor during chemical dosing, compared to that before or after dosing in one of the modules at Northern Works. The ortho P content of the module dosed with iron increased in opposition to a decrease in poly P content. Yet in mass terms, during the period prior to the commencement of iron dosing, the same module gave an ortho P content which was almost as high (32 mgP/gVSS) as that after two months of iron dosing (37 mgP/g VSS). One of the weaknesses of these results was that the two modules were not subjected to parallel fractionations on the same day. Part of the reason for this was that the fractionation procedures (de Haas, 1989b) tended to be too tedious for fractionation of more than one mixed liquor sample on the same day. Moreover, storage of mixed liquor samples by freezing prior to fractionation proved to be unreliable (de Haas and Dubery, 1989; Blonda *et al.*, 1994).

De Haas (1989b) also drew attention to other limitations of the fractionation procedure used. Batch tests indicated that after dosing of relatively small amounts of phosphate and to mixed liquor from a BEPR plant, a disproportionately large increase in the ortho P content of the sludge resulted, compared to the control. Surprisingly, most of this additional ortho P was extracted in a dilute alkaline fraction, and not in the acid fraction. The poly P fraction had decreased, relative to the control. For example, in one experiment described by de Haas (1989b), 2.3 mgP/gVSS (or 5.8 mgP/ℓ) as ortho P and 4.1 mgFe/gVSS (10.2 mg Fe/ℓ) as ferric sulphate were added *in vitro* to mixed liquor from a full-scale BEPR activated sludge plant not dosed with chemicals. The total P content of the mixed liquor before *in vitro* addition of P and iron was 55.30 mgP/gVSS, of which 14.0 mgP/gVSS was ortho P considered to be of chemical origin (72% extracted in the perchloric acid (PCA) step and the remainder in the subsequent alkaline steps), and 31.8 mgP/gVSS was poly P of biological origin. After *in vitro* addition of P and iron (see above) and pH correction, the mixed liquor total P content had increased (as expected) by approximately 2.5 mgP/gVSS. However, the ortho P content had increased to 29.3 mgP/gVSS, representing an increase in the "chemical" P fraction(s) which was about six-fold greater than the ortho P added *in vitro*. Furthermore, the fractionation of the ortho P between the respective fractions had shifted in favour of the alkaline fractions (45% extracted in the PCA acid step and the remainder in the subsequent alkaline steps). The poly P fractions decreased to 20.0 mgP/gVSS, thereby accounting for most of the increase in the ortho P fractions which could not be accounted for on the basis of ortho P added *in vitro*.

A similar batch experiment with *in vitro* ferrous sulphate addition did not produce the same result (de Haas, 1989b). The added P could be accounted for more closely by the increase in the ortho P of the PCA extract, but an over-recovery was still noted. Compared to the control, small shifts in other phosphate fractions also occurred: some ortho P shifted from the alkaline extracts to the perchloric acid extract, and a form of complex P appeared in the supernatant.

These fractionation results could not be satisfactorily explained (de Haas, 1989b; de Haas and Greben, 1991). It was speculated (de Haas, 1989b) that complexes between iron, phosphate and biomass components (e.g. carbohydrates or proteins) may form upon chemical addition. Such complexes could explain extraction of phosphate under alkaline rather than acidic conditions. Proteins tend to precipitate in ice cold acid solutions but dissolve more readily in alkaline solutions at room temperature (Munro and Fleck, 1966). Similarly, Gehr and Henry (1983) found that extracellular "biopolymer" could be stripped from mixed liquor solids by chemical (and physical) means in the presence of 0.04 M dibasic potassium phosphate (K_2HPO_4) which has an alkaline equivalence point of pH 9.75 (from graphical technique described by Loewenthal and Marais, 1976). It was further suggested by de Haas (1989b) that rapid enzyme-catalysed hydrolysis of polyphosphate closely linked to the cell membrane(s) may have been triggered by membrane disruption caused particularly by a batch dose of reactive iron, notably as ferric ions. Typically, the sample handling (de Haas, 1989b) would have include ca. 5 min. on the bench after adding phosphate, iron and correcting pH to allow the phosphate precipitation to proceed. This would have been followed by the time required to remove the supernatant by centrifugation, wash the sludge by re-suspension in saline, followed by repeat centrifugation and finally commencement of PCA extraction, which at pH<1 and 0°C, would have stopped enzyme activity. Hence, a delay of up to 30 min. at room temperature in sample handling prior to the start of the PCA step may have occurred and would have been sufficient to allow significant enzymatic hydrolysis of poly P.

Given the above uncertainties, the work of Lötter (1991), de Haas and Greben (1991) and Boyd and Lötter (1993) cannot be regarded as indicating conclusively that simultaneous chemical dosing inhibits the biological P removal mechanism. De Haas (1989b) concluded that it is not possible to tailor a crude chemical fractionation procedure to suit *specifically* the extraction of poly P separately from chemical P precipitates in a complex medium such as activated sludge. The need for development of more powerful analytical techniques to determine the nature, chain-length and masses of stored poly P from activated sludge was highlighted, as was the need to carry out further fundamental research into the interaction between biological and chemical P removal mechanisms. Nevertheless, chemical fractionation procedures of the type used by de Haas (1989b) do makes it possible to obtain *broad classification and measurement* of chemical versus biologically accumulated forms of P in activated sludge.

Witt, Grabowski and Hahn (1994) studied the interactions between biological and physico-chemical mechanisms in biological phosphate removal, and posed the following questions:

- what is the relative importance of the biological and physico-chemical mechanisms in modified activated sludge systems?
- do the relative organic and inorganic sewage characteristics significantly influence the biological and physico-chemical mechanisms?
- which cations are involved in the biological and physico-chemical processes?
- are there any parameters appropriate for specifically characterising the biological phosphate elimination capacity in the above context?

In attempting to gain answers to the above questions, Witt *et al.* (1994) used a chemical fractionation procedure developed by Psenner *et al.* (1984) for lake sediments and applied it to activated sludge. This procedure is summarised in Table 1.1.

Witt *et al.* (1994) ran a laboratory-scale (Q= 24 ℓ/d) Phoredox plant which was fed raw sewage to which 100 mg/ℓ COD as Na-acetate had been added. The raw sewage was "soft", containing 15 mg Ca/ℓ and 11 mg Mg/ℓ. Phosphate was not added to the sewage. After a three month period of adaptation, P-removal from around 13 mg/ℓ in the influent down to between 0.2 and 1.9 mgP/ℓ in the effluent was achieved. As a representative result, the activated sludge mixed liquor total phosphorus was 37 mgP/gMLSS. Of this, about 23% was considered to be physico-chemically bound phosphorus since it was SRP extracted in the bicarbonate-dithionite and NaOH steps. About 75% was considered to be of biological origin (assumed poly P) extracted as NRP in the NaOH solution. Importantly, the NRP fraction in the bicarbonate-dithionite extract (which could

include polyphosphates complexed with Ca and Fe) was significantly smaller (about one sixth) than that of the NaOH extract (which should include most of the poly P stabilised with Mg and K, according to the interpretation of Witt *et al.*, 1994). Due to the low effluent P concentrations, only 2% of the mixed liquor TP was in the so-called soluble fraction (i.e. SRP and NRP in the supernatant). The recovery of mixed liquor total phosphate by summation of the various fractions was not stated, but appeared to be about 84% from the graphical results presented by Witt *et al.* (1994).

Witt *et al.* (1994) found that as the acetate content of the feed increased from 19 to 100 mg/ℓ as COD, the physico-chemically bound fractions decreased in absolute terms while the biological fractions increased. The net effect was still that the mixed liquor TP increased with increasing acetate fed, as expected. Unfortunately, Witt *et al.* (1994) did not report a control system to determine whether background fluctuations in the influent cation composition could have explained changes in the supposed physico-chemical fractions. Nevertheless from the data available, Witt *et al.* (1994) suggested that the chemical and biological mechanisms are antagonistic (i.e. competitive). By inference, in the absence of added metal ions, the biological mechanism maybe expected to dominate.

Table 1.1: Modified Psenner fractionation procedure as applied to activated sludge by Uhlmann *et al.* (1990) and Witt *et al.* (1994).

Definitions:

- SRP (Soluble Reactive Phosphorus) = DRP (Dissolved Reactive Phosphorus) = ortho P
- TP = Total Phosphorus
- NRP = Non-Reactive Phosphorus = TP - SRP

Fractionation step/ Conditions	Fractions	Interpretations
1. Phase Separation. Centrifugation, 10 min. 3000 rpm	PS- SRP	• Soluble ortho P • Soluble poly P • Soluble organic phosphates
2. Cold Water extraction Distilled water 10 min., 20°C	CW-SRP CW-NRP	• Slightly adsorbed ortho P • Slightly adsorbed poly P • Slightly adsorbed organic P
3. Bicarbonate-Dithionite extraction* : • 0.1M $NaHCO_3$/ $Na_2S_2O_4$, 30min., 40 °C	BD- SRP BD- NRP	Redox sensitive phosphates • chemical: $FePO_4$ in part Ca-P • adsorbed: $Fe(OH)_3$...P; $Mn(OH)_4$...P • poly P with Fe and Ca
4. NaOH extraction: • 1M NaOH, 17h, 20 °C	NaOH- SRP NaOH- NRP	• Chemical: Al and Fe phosphates • Poly P
5. HCl extraction: • 0.5 M HCl, 17h, 20°C	HCl-SRP HCl-NRP	• Chemical: Ca and Mg phosphates, Al and Fe phosphates (residues) • Weakly soluble biologically bound phosphates; • Poly P and organic phosphates

Summary classification	Fractions
soluble P	2 fractions: PS-SRP + PS-NRP
biologically bound P	4 fractions: CW-NRP + BD-NRP + NaOH-NRP + HCl-NRP
chemically bound P	4 fractions: CW-SRP + BD-SRP + NaOH-SRP + HCl-SRP

* : Dithionite is a strong reducing agent

With respect to the cations associated with the P-removal mechanisms, Witt *et al.* (1994) confirmed the findings of others (Comeau *et al.*, 1986; Wentzel *et al.*, 1986; Gerber *et al.*, 1987; van Groenestijn, 1988) that uptake and release patterns of Mg^{2+} and K^+ ions parallel that of ortho-

P in biological- removal systems, due to charge neutralisation of poly P by magnesium ions and proposed transport mechanisms across the cell membrane for potassium and ortho P ions. The importance of magnesium in the BEPR mechanism was also highlighted in a study by Lindrea *et al.* (1994) in which influent Mg limitation was identified as a likely cause of seasonal deterioration in P removal by a full-scale plant in Australia.

It is worth noting that during batch experiments, Witt *et al.* (1994) were able to show that most of the anaerobic P release (increase in soluble supernatant SRP) was associated with a decrease in the NaOH-NRP fraction (i.e. poly P fraction). However, the BD-SRP and NaOH-SRP fractions did show detectable increases too, suggesting that some 'entrainment' of phosphate in chemical precipitates did occur. The BD-NRB fraction (viz. proposed Ca or Fe-bound poly P) showed a decrease during the anaerobic period. It is surprising that these changes in the physical-chemical fractions, although relatively small, were reversible during the aerobic period and Witt *et al.* (1994) did not attempt to explain the mechanism by which the chemical and biological fractions interact. However, they concluded that:

- anaerobic breakdown of NRP (mainly poly P) fractions is not only connected with P release to the soluble phase, but to a lesser degree also with an increase in the particulate (or sludge-bound) SRP fractions (proposed to be chemically bound); and
- aerobic increase in the NRB fractions is caused not only by a transition from the soluble phase into the particulate phase (or sludge), but also by transfers within the particulate phase from the SRP fractions.

Röske and Schönborn (1994a) applied the modified Psenner fractionation procedure to activated sludge samples from bench-scale and full-scale plants. A two-stage bench-scale (anaerobic-aerobic) process was operated at a short sludge age (6d) to inhibit nitrification. Average influent COD was 610 mg/ℓ. An average P removal of >90% was achieved, from ca. 11.2 mg/ℓ TP in the influent to 0.9 mg/ℓ TP in the effluent. Ignoring the soluble (supernatant) phase, the mixed liquor typically contained about 27 mg P/g MLSS. Of this, around 24% was extracted into the bicarbonate-dithionite (BD) fraction and 66 % into the NaOH fraction. NMR spectroscopy confirmed that poly P was present in the NaOH extract. The BD fraction was interpreted as containing phosphate which is solubilised under strictly reducing conditions, namely, from Fe-phosphate or Fe-hydroxide complexes (extracted as SRP), or Fe-poly P complexes (as NRP). About two-thirds of the TP in the BD extract was in the form of SRP, and by difference, the other one-third was NRB. Röske and Schönborn (1994a) pointed to the low influent iron concentration (ave. 0.2 mg Fe/ℓ) as the reason for only a small proportion of the phosphate being bound in complexes extracted in the BD fraction. On the other hand, with such low iron concentrations in the influent, it was surprising that as much as 24% of the mixed liquor TP occurred in the form of (supposed) iron complexes . Furthermore, no removal of iron across the system was noted (influent = effluent = 0.2 mg Fe/ℓ). Cation analysis of the fractions from the bench-scale plant were found by Röske and Schönborn (1994a) to contain principally calcium in the BD, HCl and NaOH extracts, in that order of decreasing concentration. This suggested that chemical precipitation of calcium phosphate (apatite or hydroxyapatite) had occurred in the system. This was supported by the comparatively high pH (7.9) and an average removal of 6 mg Ca/ℓ normally measured in the bench-scale plant by Röske and Schönborn (1994a).

Röske and Schönborn (1994a) compared the results from their bench-scale plant to two full-scale activated sludge plants: Berlin-Münchehofe, in which iron was dosed for chemical P removal, and Berlin-Marienfelde, which is operated for biological P removal supplemented by simultaneous precipitation using a mixture of aluminium and iron salts. Röske and Schönborn (1994a) found that for the Münchehofe sludge, most (65%) of the mixed liquor phosphate was extracted in the BD fraction, with only ca. 30% in NaOH extract. By contrast, the mixed liquor phosphate from fractionated in a manner similar to the bench-scale plant, with about 15% of the TP extracted in the BD fraction and 72 % in the NaOH fraction. In the case of Marienfelde, iron was predominantly extracted in the BD fraction (70%) and to a lesser degree in the HCl fraction (20%); most of the aluminium (75%) was extracted in the NaOH fraction, with the remainder mainly in the HCl

extract. Unfortunately Röske and Schönborn (1994a) did not report the percentage recovery of mixed liquor Total P and cations in the fractionation procedure. Nevertheless, their results suggest that the modified Psenner fractionation procedure was able to distinguish the degree of biological P removal from chemical P removal in activated sludge systems with simultaneous chemical addition. Although comparisons between Test and Control systems operated in parallel were not made, the comparison between bench-scale (biological) and full-scale (combined chemical-biological) systems suggested that the P fractions of biological origin "substantially smaller" (p1109) in the presence of simultaneous chemical dosing (Röske and Schönborn, 1994a). To assist with interpretation of the fractionation data in such cases, it appears that knowledge of the extent of "background" chemical P fixation in the activated sludge without chemical dosing would be useful.

Röske and Schönborn (1994b) carried out further work with chemical dosing to a bench-scale plant to investigate this aspect in more detail.

Using activated sludge cultivated in a bench-scale system, Röske and Schönborn (1994b) confirmed by means of batch tests that potassium and magnesium ions are associated with biological uptake and release pattern of phosphate, while calcium did not correlate with this pattern. It is significant that for the same samples, Röske and Schönborn (1994b) also noted a very close correspondence between P and Ca distribution in the activated sludge flocs using scanning electron microscopy coupled with X-ray spectroscopy. They concluded that the granules with a high P and Ca content are physiologically inactive, and suggested that these may have been "Ca poly P" granules, although direct evidence of the nature of the phosphate component was not forthcoming.

In sequential experimental periods, Röske and Schönborn (1994b) added respectively 3 and 6 mg Fe/ℓ as ferric chloride (based on influent flow rate) to the aerobic reactor of a two-stage (anaerobic-aerobic) bench-scale system. Unfortunately, a full comparison of results before and after addition of precipitants was not presented by Röske and Schönborn (1994b). For example, it is not clear whether the systems were operated with "surplus" phosphate in the effluent, or under potentially P-limiting conditions in which the chemical and biological mechanisms would "compete" for available ortho P. Also, the extent (on a mass basis) of P release in the anaerobic reactor of the system was not reported, nor was the total P content of the mixed liquor before and during iron dosing given. This makes it difficult to interpret the fractionation results which were presented on a relative basis in the form of pie charts. Moreover, since additional phosphate was apparently not dosed into the sewage fed to the experimental system, the full P-removal potential (or effect of iron addition on that potential) may not have been tested. Röske and Schönborn (1994b) did report from batch experiments that the *rate* of P release and P uptake was inhibited with the addition of ferric chloride to the bench-scale plant from which the mixed liquor samples were taken. Compared to the period without addition of ferric iron, the addition of 3 mg Fe/ℓ caused the rate of P release to be inhibited by 50%, while the rate of uptake was inhibited by 30%. An increase in the ferric iron dose to 6 mg Fe/ℓ, resulted in approximately the same degree of inhibition of the P release rate, but the rate of P uptake was inhibited by a further 30%. Since the continuous flow system used was probably phosphate-limited (effluent dissolved P < 1 mg P/ℓ), Röske and Schönborn (1994b) were not able to fully extrapolate the results of the batch rate tests to their bench-scale plant. They did report that in the presence of Fe addition, "the release of P in the anaerobic tank" and the "*proportion* of poly P" (NaOH-NRB fraction) were not as high in the presence of iron addition as prior to that. Careful examination of the pie charts presented by Röske and Schönborn (1994b) suggests that the *mass* of poly P (NaOH-NRB fraction) *did not decrease with iron addition* and may even have increased by 5 to 10%, depending on the degree to which the system was operating at steady state. An increase in the BD-SRP fraction in the presence of iron addition was, however, clearly discerned (Röske and Schönborn, 1994b), confirming the likely extraction of Fe-P complexes in this step. The BD-NRB fraction, which could contain Ca-poly P or Fe-poly P complexes (Witt *et al.*, 1994), appeared to decrease (to a variable degree) in the presence of iron addition, which may be linked to the finding by Röske and Schönborn (1994b) that

calcium was much less prominent in X-ray spectra of sludge samples taken during iron dosing, compared to those without metal addition.

In summary, the results of Röske and Schönborn (1994a, b) still leave room for a certain amount of doubt over the actual extent of inhibition of the biological P removal mechanism in the presence of simultaneous chemical dosing. It seems clear, however, that chemical fractionation procedures of the type used by Röske and Schönborn (1994a, b) offer the possibility of crudely quantifying the chemical versus biological P fractions accumulated in activated sludge mixed liquor.

1.6 TYPES OF "POLY P" STORAGE

1.6.1 Microscopic studies

In experiments with pure cultures of *Acinetobacter lwoffi*, Halvorsan *et al.* (1987) found that two pools of poly P appeared in the cells of this organism, one cytoplasmic and one surface-associated (i.e. located close to the cell membrane, or in the periplasmic space between inner and outer bacterial cell membranes).

To obtain further information about fixation of phosphorus in the biomass of activated sludge, Streichan and Schön (1991) applied various microscope techniques to study several strains of *Acinetobacter* and one strain of *Moraxella*, all isolated from sewage plants exhibiting biological enhanced P removal (BEPR). Firstly, they found that pH control in the range 7.0 to 7.5 was essential to prevent chemical phosphate fixation in the bacterial pure (liquid) cultures. At pH >7.75, phosphate was precipitated from the growth medium and could be removed from the pelletised cells by washing in 0.01 M TRIS buffer (pH 7.5), indicating that only weak association between the biomass and precipitate[10]. Secondly, Streichan and Schön (1991) found by light microscopy (enhanced by DAPI fluorescence) that poly P granules could be located in the cytoplasm of the *Acinetobacter* strains as well as the *Moraxella* strain studied. On the other hand, unlike the *Acinetobacter* strains, in the *Moraxella* strain, poly P granules could also be located in the periplasm between the inner and outer cell membranes. This was confirmed by means of tests for metachromasy using toluidine blue. In such tests, there is a familiar shift in the absorption maximum for toluidine blue from around 635 nm to 548 nm in the presence of polyanions such as poly P. The *Moraxella* strain cell suspension caused the metachromatic shift without the need for cell disruption, whereas the *Acinetobacter* strains did so only after cell disruption through a French press at 6.6 bar, thereby releasing the cytoplasmic poly P into solution. It is worth noting that Halvorsan *et al.* (1987) had used the same technique to detect periplasmic poly P in their *Acinetobacter lwoffi* strain. Hence, although the identification of particular strains in pure culture which demonstrate the phenomenon may be complex, it seems reasonable to deduce that in activated sludge, poly P is located in *both* the cytoplasm *and* the periplasm of active cells. However, determination of the relative masses of these pools remains an analytical difficulty.

1.6.2 NMR studies

Hill, Benefield and Jing (1989) applied ^{31}P-NMR spectroscopy to activated sludge samples collected from a sequencing batch reactor (SBR) system set up to stimulate biological P removal. They made several important observations:

[10] Similar results were reported by Gerber *et al.* (1987), who found the precipitate to be magnesium ammonium precipitate (struvite). The occurrence of this precipitate was an artefact of the relatively high magnesium and ammonium ion concentrations in the liquid growth medium and the tendency for aeration and bacterial growth processes (CO_2 production) to raise the pH of the medium to ca. 8 or more, unless controlled by acid dosing.

- Using unruptured sludge cells actively exhibiting biological P removal, the poly P NMR signal was located at resonances of approx. -21 to -23 ppm, which is in agreement with the results of other authors (*inter alia* Florentz *et al.*, 1984; Hascoet *et al.*, 1985; Halvorsan *et al.*, 1987). However, this poly P signal was found to be absent in certain cases if no EDTA was added to the sample, compared to the same cells suspended in 0.1 M EDTA. Such an observation indicated that at least a portion of polyphosphate is located in the periplasmic space and is complexed to metal cations. Hill *et al.* (1989) quoted supporting evidence from Sianoudis *et al.* (1986) that frequently a signal is observed when poly-P complexes are dispersed by treatment with a metal ion chelator (EDTA).
- Activated sludge cells were taken from the end of the aerobic period of an acclimatised SBR system, disrupted by sonication and the supernatant collected after ultracentrifugation. The supernatant was suspended in 0.1 M EDTA but did not produce an NMR signal for poly P. This suggested that the poly P was attached to either the cell wall or the cytoplasmic membrane of the active cells and not released to the supernatant. The ruptured activated sludge cell suspension (not centrifuged) did produce a poly P NMR signal.
- The NMR signal ratio of poly P: inorganic (ortho) P for ruptured cell suspension was observed to change with time (several hours) after sonication. A number of resonances corresponding to pyrophosphate linkages were noted for the sonic ruptured cell suspensions. For this to occur, the cells must contain cell bound (or membrane bound) polyphosphatases in the same region as the bound poly P. In order to test whether the poly P degradation was enzyme catalysed, sonicated cells were brought to 100°C, which would denature enzymes present. For this sample, no decay of the poly P signal occurred over a 10 h period.
- Treatment of activated sludge samples with strong sodium hypochlorite solution resulted in two poly P resonance peaks being observed. The exact reason for the split signal was not determined, but it was hypothesised that apart from causing the cell membrane to be disrupted, the strongly alkaline environment of the hypochlorite solution may have removed multivalent metal cations (through precipitation as metal hydroxide) which had been complexed with poly P. Poly P located inside the cytoplasmic membrane then became visible but had been previously undetected in 0.1M EDTA cell suspensions due to the EDTA impermeability of the cytoplasmic membrane. This served as further evidence of both cytoplasmic and periplasmic poly P being present in activated sludge bacteria.

Hill *et al.* (1989) were unable to accurately quantify the cytoplasmic and periplasmic poly pools, due to limitations of the NMR methodology. Although no definite conclusions could be drawn, by separating and comparing spectra of cells and supernatant taken from the anaerobic period of their SBR system, they suggested it was possible that a portion of the inorganic phosphate generated through enzymatic degradation of the poly P located in the periplasm, participated in the transport of organic substrate across the cytoplasmic membrane. In summary, the work of Hill *et al.* (1989) is important in that it demonstrated the likely occurrence of periplasmic poly P in activated sludge cells, thereby validating supporting work on pure cultures of bacteria isolated from activated sludge. It also highlighted an important point, namely that metabolically active surface poly P, probably located in the periplasm between the inner and outer cell membranes, may be invisible by ^{31}P-NMR spectroscopy, depending on sample preparation (e.g. presence of EDTA). Florentz *et al.* (1984) and Hascoet *et al.* (1985) performed some of the first investigations of the biological P removal phenomenon by NMR Spectroscopy, and found a distinct poly P signal but did not report the use of EDTA in sample preparation. Halvorsan *et al.* (1987) drew attention to the importance of sample preparation (e.g. addition of EDTA, use of cell disruption or extraction techniques) prior to NMR Spectroscopy in order to make the metabolically active surface pool of poly P *Acinetobacter lwoffi* (isolated from a wastewater plant) visible by ^{31}P-NMR. Hence, it appears that the importance of poly P location in close association with membrane surfaces of active cells may have been overlooked in the past, especially where activated sludge samples were studied which had a high P content (e.g. 110 mgP/g MLSS - Florentz *et al.*, 1984) and in which cytoplasmic granules of poly P were obvious by electron microscopy.

In follow-up work, Jing, Benefield and Hill (1992) experimented with activated sludge cultured on synthetic sewage in sequencing batch reactors (SBRs) with either glucose or starch as substrate at

the same influent COD concentration. Both systems exhibited biological P removal , but the glucose-fed reactor (named the D-reactor) achieved better P removal than the starch-fed reactor (P reactor). The D- reactor activated sludge in the unruptured state and suspended in EDTA solution, exhibited an NMR signal for poly P. The same was *not* true of the P-reactor activated sludge when prepared freshly for the NMR investigation. Samples of these P-reactor activated sludge cells, which had been washed free of supernatant with 1 mM potassium nitrate, also produced only a very weak (inorganic) orthophosphate signal. However, over a period of several hours storage under anaerobic conditions in the NMR tube, the P-reactor cells produced an increasing orthophosphate signal, which implied that poly P located inside the cytoplasmic membrane and inaccessible to EDTA, was hydrolysing. Moreover, the supernatant from ruptured cells of the D-reactor did not produce an NMR signal for poly P, whereas that from the P-reactor *did.* The pellets of ruptured cells from both reactors did produce poly P NMR signals. On the basis of these results, as well as those from chemical fractionation patterns, Jing *et al.* (1992) concluded that the cells of the two systems demonstrated different storage patterns for poly P. In the D-reactor, transient phosphate (that which is subject to release and uptake in the biological P removal mechanism) is stored in the form of poly P located in the periplasm, outside the cytoplasmic membrane, probably in high molecular weight form and "visible" by NMR in the presence of EDTA. The enzyme which mediates its breakdown is cell bound (concluded by same technique as Hill *et al.*, 1989). No poly P exists in the mobile or unattached state in the cytoplasm. In the P-reactor, transient phosphate is stored primarily inside the cytoplasmic membrane, probably in low molecular weight form. A fraction of this material is cell bound (probably attached to the inside of the cytoplasmic membrane) and a fraction is mobile in the cytoplasm, but the fraction which mediates its degradation is membrane bound.

If the results of Hill *et al.* (1989) and Jing *et al.* (1992) are accepted, one may expect samples of activated sludge with an enhanced biological P removal capability to have a major fraction of their poly P stored outside the cytoplasmic membrane, probably in the periplasm between the inner and outer cytoplasmic membranes of Gram-negative bacteria. Fleit (1995) hypothesised functions for membrane-bound poly P structures in the context of biochemical models for biological excess P removal. The occurrence of periplasmic or membrane-bound poly P could also be of significance in the interaction between the biological and chemical P fixation, especially where multivalent metal salts are dosed to promote simultaneous chemical removal.

1.6.3 Fractionation studies

Lindrea *et al.* (1994) applied the fractionation method of Clark *et al.* (1986) to activated sludge samples from full-scale and laboratory-scale BEPR systems. In the majority of samples tested, P storage occurred mainly in the "long chain poly P" (LCP) fraction which was extracted with phenol-chloroform solvent. The other important fractions, namely, the "short chain poly P" (SCP) fraction extracted with cold trichloroacetic acid (TCA) / TCA-acetone solvent, and the "granular P" fraction extracted with phenol-chloroform solvent, were numerically smaller on a P/VSS basis and showed smaller changes during batch anaerobic-aerobic tests as well as full-scale plant monitoring. However, Lindrea *et al.* (1994) did not attempt to distinguish differing physiological roles for respective phosphorus fractions observed. Unfortunately, Lindrea *et al.* (1994) did not report fractionation results for sludge from the full-scale plant during a period when major deterioration in BEPR was recorded due to a suspected influent Mg limitation. However, laboratory-scale trials showed that under Mg limitation, calcium and potassium (to some degree) appear to replace magnesium ions in poly P charge stabilisation. A similar observation was made by van Groenestijn (1988) using a pure culture of *Acinetobacter.* During Mg limitation, both the SCP and LCP fractions were depressed relative to the control.

Müssig-Zufika, *et al.* (1994) compared various chemical fractionation methods with a view to isolating intact polyphosphate chains from activated sludges associated with biological P removal and a pure culture of *Acinetobacter* . The methods they tested were:

- Method 1 : Psenner *et al.* (1984) as modified by Uhlmann *et al.* (1990) (see Röske and Schönborn, 1994 above);
- Method 2 : Fitzgerald and Nelson (1966);
- Method 3 : Clark *et al.* (1986)
- Method 4 : Mino *et al.* (1985).

Method 4 involves extraction with cold 0.5 M perchloric acid (PCA) and is partly the method upon which the fractionation data of de Haas (1989b; 1991) was based.

Müssig-Zufika *et al.* (1994) tested the four fractionation methods on a pure culture of *Acinetobacter johnsonii* (isolated from a Berlin wastewater works). Although not specifically stated, pH control on the culture was probably applied and it is assumed the cells were collected during the logarithmic growth phase of the culture. Apparently working from the assumption that the true ortho P content of the pure culture cell biomass should be negligible, Müssig-Zufika *et al.* (1994) reported that, in the case of Method 4 (cold PCA extraction), 24% of the poly P was hydrolysed to ortho P. Methods 1 and 2 respectively gave approximately 5% and 10% poly P hydrolysis to ortho P, while Method 3 gave only 1%. They concluded from this that only the method of Clark *et al.* (1986) was acceptable for further investigation. However, they pointed out the limitation that the method of Clark *et al.* (1986) is unsuitable for Gram-positive organisms because it had been shown that this method failed to extract poly P from a culture of such organisms which appeared to contain poly P granules by electron microscopy. Müssig-Zufika *et al.* (1994) developed a new method partly by combining various steps of published procedures. Their modified method involved the formation of three fractions from the sludge pellet obtained after removal of the supernatant of the original sample:

- Fraction I - The combined extracts obtained in series from 2 mM EDTA (pH 7), followed by 2% trichloroacetic acid (TCA), followed by TCA-acetone (0.7% TCA in 67% acetone-water);
- Fraction II -The combined extract of two steps. In Step 1 the pellet was resuspended in 2 mM EDTA and the following reagents added (final concentrations estimated by interpretation of the procedure stated): methanol (12% v/v), chloroform (12% v/v), sodium hypochlorite (0.4 % m/v) and an unspecified amount of ammonium sulphate. The pH was adjusted to 7-8. This suspension was frozen overnight, thawed, centrifuged and the supernatant set aside. In Step 2 the pellet from Step 1 was extracted twice with the same EDTA-methanol-chloroform mixture as in Step 1, but without sodium hypochlorite added. The resulting extracts of Steps 1 and 2 were combined to give Fraction II;
- Fraction III - the pellet was resuspended in distilled water, frozen until needed for analysis, centrifuged and the supernatant taken. Any residue was discarded.

1.7 EVALUATION OF FRACTIONATION METHODS

Müssig-Zufika *et al.* (1994) used a novel analytical technique that allowed on-line detection of poly P after separation according to molecular weight by HPLC (using either an ion exchange column for poly P chain lengths of P1 to P4, or a gel column which separates high molecular weight poly P of >P45). Phosphate emerging from the column was determined by means of an automated vanado-molybdate colorimetric method, with post-column derivatisation (i.e. hydrolysis of poly P to ortho P) in the presence of 6.5% (ca. 1.4 M) nitric acid at 140 °C in an oven. According to Müssig-Zufika *et al.* (1994), organic phosphates are not hydrolysed under these conditions, since such compounds require the presence of an oxidising agent.

Critical appraisal of the work of Müssig-Zufika *et al.* (1994) hinges on the envisaged purpose of the fractionation procedure.

- The objective of Müssig-Zufika *et al.* (1994) was to attempt to isolate poly P from activated sludge or pure culture samples *in as intact a state as possible*. They did not report an objective of attempting to determine the relative importance of chemically precipitated

phosphate in the biological samples examined. Their work clearly met the stated objective since the presence of poly P with chain lengths largely in the range P5 to >P100 was demonstrated. It was of interest too that aerobic sludge from the full-scale works tested (Berlin-Ruhleben) contained only a modest amount of stored total P (around 22 mgP/g MLSS) and showed about equal quantities of poly P in the chain length range P5-P40 as in the range P70- >P100. On the other hand, the sample of aerobic sludge from a pilot-plant demonstrating stronger P removal (total P in sludge = 50 mgP/g MLSS) showed about 90% of the poly P in the higher molecular weight range (P70- >P100).

- With respect to organic P (by the analytical definition given above), Müssig-Zufika *et al.* (1994) found that the sludges from the full-scale plant contained about 10 mgP/g MLSS and the pilot plant sludges contained about 18 to 20 mgP/g MLSS. No comment on this difference was given. Müssig-Zufika *et al.* (1994) did not report the %VSS content of their sludges and this makes comparison of the organic P content difficult, particularly where the sludges contain large amounts of total P (i.e. have a low %VSS). On the basis of sludges with a total P content in the range 39 to 55 mgP/gMLSS from three full-scale plants in South Africa, de Haas (1989a,b) found a nucleic acid P content (based on determination of the pentose sugar content of RNA and DNA) of around 16 to 20 mgP/g VSS (10 to 15 mgP/g MLSS), which is in general agreement with the results of Müssig-Zufika *et al.* (1994) for Berlin-Ruhleben. For two pilot plants fed a synthetic sewage (with acetate or propionate as main substrate, similar to those of Müssig-Zufika *et al.*, 1994) and producing a sludge of about 150 to 180 mgP/ gMLSS, de Haas (1989a,b) found a nucleic acid P content of 9 to 12 mgP/g VSS (6 to 7 mgP/g MLSS). On the one hand, this suggests that where the sludges contain relatively large masses of poly P, the method of Müssig-Zufika *et al.* (1994) may have over-estimated the organic P content to a degree; on the other hand, de Haas (1989a,b) measured nucleic acid sugar directly and assumed other organic phosphates to be negligible.
- With respect to ortho P, Müssig-Zufika *et al.* (1994) reported 20-23% of the sludge total P as ortho P for sludges from the full-scale plant, and 2 to 5% as ortho P for their pilot plant. Amongst others, Wentzel *et al.* (1988) and de Haas (1989b) drew attention to the importance of pH control in pilot-plants fed relatively large amounts of fatty acids in order to prevent chemical precipitation. This point was not mentioned by Müssig-Zufika *et al.* (1994). De Haas (1989b, 1991) reported a range of 8 to 25% of the sludge total P as ortho P for eight samples of sludge from four different full-scale biological P removal plants in South Africa not receiving chemical supplements. The total P content of these sludges ranged from 42 to 76 mgP/ gVSS (27 to 55 mgP/g MLSS). The fractionation procedure used for these determinations included extraction into cold 0.5M PCA. These results do not support the finding by Müssig-Zufika *et al.* (1994) that most of the poly P extracted into cold PCA is hydrolysed to ortho P. It may be argued that this finding is only true for pure cultures. Yet the results of Müssig-Zufika *et al.* (1994) remain contradictory to those of a large number of other researchers who have used a fractionation procedure including cold 0.5M PCA extraction for extracting large quantities of poly P from activated sludge and pure cultures (inter alia Harold, 1962; 1963; Kulaev, 1979; Lötter, 1985; Murphy and Lötter, 1986; Mino and Matsuo, 1985; Mino *et al.*, 1985; Ohtake *et al.*, 1985; Mino *et al.*, 1987; Miya *et al.*, 1987; de Haas, 1989b, 1991; Appeldoorn *et al.*, 1992). The critical issue is whether Müssig-Zufika *et al.* (1994) applied pH control to their pure cultures (not stated). Several researchers (*inter alia* Gerber *et al.*, 1987; de Haas, 1989b, 1991; Streichan and Schön, 1991; Appeldoorn *et al.*, 1992) have reported the importance of pH control (to around neutral) in pure cultures of *Acinetobacter* to prevent the chemical precipitation of phosphate from the liquid growth medium. For a log phase batch culture of *Acinetobacter* 210A harvested after 9.5 h at pH 7.1, de Haas (unpublished) found 1.7 mgP/g dry weight ortho P extracted into cold PCA in the presence of 9 mgP/g dry wt poly P (determined both by 7 min. hydrolysis in 1M HCl at 96 °C and by difference between total P and nucleic acid P). The same culture, having reached stationary phase after 25 h at a pH of 9.1 (no pH control), gave a cold PCA extract with 27 mgP/ g dry wt as ortho P and 8 mgP/ g dry wt of poly P (by 7 min. hydrolysis). If the findings of Müssig-Zufika *et al.* (1994) concerning the lability of poly P to hydrolysis in cold 0.5 M PCA was correct, then it would not have been

possible to obtain such results. Similarly, Appeldoorn *et al.* (1992) were able to grow cultures of *Acinetobacter* (under pH controlled conditions) which contained up to about 20% of their total P content (or about 17 mgP/g dry wt) in the form of cold PCA -extractable poly P (or LPP, determined as the difference between total P and ortho P content of this extract). The ortho P content of these cold PCA extracts never exceeded 3 mgP/ g dry wt and the organic P content (determined by adsorption to powdered Norit A activated carbon) never exceeded 2-3 mgP/g dry wt (Appeldoorn *et al.*, 1992). Again, these results are not consistent with the results of Müssig-Zufika *et al.* (1994).

- It is entirely plausible that cold 0.5 M PCA does not extract poly P in an intact state. This conclusion was reached also by de Haas (1989b, 1991) from attempts to use gel chromatography to characterise the chain length of poly P extracted from activated sludge. De Haas (1989b, 1991) cautioned against ascribing particular metabolic functions to pools of poly P which are really defined by the methods of extraction from the sludge. However, random chemical hydrolysis of long poly P chains at a slow rate will tend initially to result mainly in shorter fragments, with the incidence of ortho P groups being cleaved off the ends of the chains increasing statistically as a function of time. According to Kulaev (1979), a number of enzymes have been isolated from micro-organisms which catalyse the sequential hydrolysis of poly P to shorter fragments, some proceeding only as far as pyrophosphate or tripolyphosphate; polyphosphatase is one enzyme which produces ortho P as the hydrolysis end product. However, enzyme activity seems unlikely at a pH of <1 in the PCA extract at 0°C. De Haas (1989b) investigated the rate of hydrolysis of Graham's salt (mainly linear poly P chains of variable chain length, according to Kulaev, 1979) in 0.5 M PCA at exactly 0°C. The results suggested that the half-life of the poly P to be of the order of 100 h or more, measured over a 72h period both in distilled water and a mixture of ions and proteins which attempted to mimic the presence of sludge. Blonda *et al.* (1994) carried out similar tests with poly P (purified in the form of >P75) and 2,3-diphosphoglyceric acid (DPGA), both at 100 mgP/ℓ concentration and reported that over a 90 minute period (sufficient for complete extraction of ortho P), no appreciable hydrolysis of either compound could be detected since the ortho P concentration of the solutions did not differ significantly in the presence of acid or without acid. A similar conclusion was reached over a 2h period for tripoly P in cold 0.5M PCA (4°C) by Kerdachi and Roberts (1985). These results do not support the conclusion of Müssig-Zufika *et al.* (1994) concerning poly P hydrolysis in cold PCA.
- Müssig-Zufika *et al.* (1994) recommended a fractionation procedure which used 2 mM EDTA, 2% TCA and 0.7% TCA in acetone-water as the extraction steps for ortho P complexes of the sludge. De Haas (1991) compared two fractionation procedures in which the first step (after preliminary removal of the supernatant and washing on the sludge pellet) was either: (A) 50 mM EDTA (five times) at room temperature followed by 1% (61 mM) TCA (three times) at 0°C; or (B) 0.5M PCA (four times) at 0°C. The two procedures were applied in parallel to the same activated sludge sample (total P = 75.5 mgP/g VSS; %VSS = 73.0) showing good biological P removal without chemical supplements. Neglecting possible interference from poly P, for Procedure A, the ortho P content of the sludge was found to be 21.9 mgP/g VSS, located mostly in the EDTA (12.7 mgP/g VSS) and TCA (6.9 mgP/g VSS) extracts. For Procedure B, the ortho P content was found to be 13.6 mgP/g VSS, located mainly in the PCA extract (11.3 mgP/g VSS). This appears to contradict the findings of Müssig-Zufika *et al.* (1994) which suggested that an EDTA-TCA based procedure would minimise hydrolysis of poly P and give a lower ortho P result.
- De Haas (1989b) discontinued the use of TCA-based fractionation procedures for activated sludge on the basis that 1 to 2% TCA (and even more so for 0.7% TCA in acetone-water solvent) at 0°C did not satisfactorily dissolve chemical precipitates of ferric (hydroxy) phosphate, calcium phosphates and magnesium ammonium phosphate. On the other hand, 0.5M PCA at 0°C gave >98% recovery of phosphate from the same chemical precipitates in three steps, and usually >80% recovery in the first one or two steps. The same conclusion was reached by Apeldoorn *et al.* (1992), both in the presence and absence of pasteurised sludge containing at least 60 mgP/g dry weight. Kerdachi and Roberts (1985) reported similar results and drew attention to the fact that metal perchlorates are generally

concentration range 0.5 to 3 mg/L). Similarly, Rabinowitz and Marais (1980) reported that for modified activated sludge systems dosed simultaneously with either ferrous or ferric ions at 5 to 10 mgFe/ℓ (based on the influent), minimal iron "leakage" occurred from the systems with <0.1 mgFe/ℓ found in the effluent. It seems that the vast majority of metal removed becomes rapidly adsorbed onto, or associated with the sludge by physico-chemical interactions, although a second, slower phase may involve some biological activity. From the review by Brown and Lester (1979), there appears to be good evidence that bacterial cell flocs in pure cultures, as well as extracellular polymers from these cultures or from activated sludge, can adsorb large quantities of metal ions from solution. Activated sludge contains a wide variety of extracellular polymers which play an important role in flocculation. These polymers are mainly of a polysaccharide nature, although protein and nucleic acids from autolysis (cell death and lysis) may also be constituents of the polymer matrix. Many (but not all) of the extracellular polymers produced possess negatively charged groups; these give the sludge floc surfaces an overall negative charge. The quantity of bacterial extracellular polysaccharide in activated sludge is controlled by nutrients in the growth medium, the sludge age and the oxidation of these polymers by other bacterial species present (Brown and Lester, 1979).

According to Brown and Lester (1979), different metal adsorption sites appear to exist on neutral polysaccharides and anionic polysaccharides. Metal ions of different valencies or with different charges may also bind at different sites. Neutral polysaccharides may bind metal cations at the hydroxyl groups of hexose or pentose sugars, exchanging with hydrogen bonds from water molecules "bound" by the polymer. Where polymers are anionic, carboxyl groups may be the metal binding sites. This type of bond is largely ionic and is much stronger than the hydrogen bonding between neutral polysaccharides and metal cations. However there is some evidence to suggest that in activated sludge, the former type of complexation may occur to a greater degree than the latter as carboxyl groups on the sludge surfaces appear to be already occupied (Brown and Lester, 1979).

Gels can adsorb cations to a greater degree than polymers in solution. This may mean that "zoogleal" gels in activated sludge can adsorb cations more effectively than soluble polymers. Anions (e.g. phosphate) may be adsorbed in conjunction with cations, forming a lattice of ions in the floc matrix. If cations such as calcium and magnesium under normal conditions form part of the floc structure, other metal ions, including the heavy metal ions, may replace these alkaline earth metals in the sludge flocs (Brown and Lester, 1979).

According to Flynn (1984), the iron (III) hydroxide polymer may be hypothesised to consist of a sphere of 2-4 nm diameter, containing approximately one hundred Fe (III) ions, most likely having octahedral co-ordination with the approximate formula of $Fe(O,OH,H_20)_6$. These octahedra are condensed, probably by sharing edges or vertices.

Recognising its importance in simultaneous precipitation activated sludge processes in North America, He, Leppard, Paige and Snodgrass (1996) studied the effect of phosphate on the colloid structure of (ferric) iron hydroxide using transmission electron microscopy (TEM). Using a water-miscible melamine resin (Nanoplast) recently developed for use with aquatic colloids, these authors aimed to preserve and embed ferric hydroxy-phosphate particles with minimal particle aggregation artefacts. With this technique, primary particle sizes down to 1 nm were detected. The work of He *et al.* (1996), supported by that of Coombes *et al.* (1989), suggests that as ferric ions hydrolyse, initially aggregates of polycations form (e.g. $[Fe(OH)^{+}\text{-}O\text{-}]_n$), changing with time from chain-like linear aggregates into fractal aggregates formed from octahedral $Fe(O,OH,H_20)_6$ co-ordination complexes with cross-linking. These aggregates form the primary particles of ferric hydroxide which are nearly spherical in shape and 1-4 nm in diameter. The primary particles possess a very large surface area, estimated by He *et al.* (1996) to be of the order 260-500 m^2/g. An increase in the pH from 5 through 6-7 with a constant Fe concentration results in an increase in the OH/Fe ratio and produces more dense chain-like clusters, probably by reducing the density (repulsion) of positive charges on the polycation formed.

According to He *et al.* (1996), the three dimensional structure of newly formed ferric hydroxide should resemble a highly porous sponge made up of cross-linked chains. When iron salts are used in water or wastewater treatment, with the progress of hydrolysis, the iron hydroxide forms linear aggregates of colloidal polycations with a ramified cross-linked chain-like structure. As anions or negatively charged "contaminant" colloids make contact with these aggregates, they are immediately trapped on the extensive surface provided by the three-dimensional network of polycations; this step takes a few seconds to accomplish. Depending on the nature and concentration of the trapped micro-components, one of several mechanisms might follow: adsorption, ion exchange or surface complexation.

Phosphate incorporation into iron hydroxide has been studied by a number of different methods. It has been shown that phosphate (like arsenate) forms a bidentate bridging group in a complex of the type Fe-O-P-O-Fe (He *et al.*, 1996). For example, comparing electron micrographs of iron hydroxide colloid and iron hydroxy-phosphate, He *et al.* (1996) found that primary particle dimensions remained the same before and after phosphate incorporation, but the chain-like structure changed. At high magnification (200 000 x) it was observed that the large agglomerates were made of primary particles aggregated more tightly by phosphate. At low P/Fe ratio (0.2), a low proportion of agglomerates was observed, with most of the iron hydroxide colloid still possessing the chain-like structure. At high P/Fe ratio (2.0), the aggregation of primary particles is strongly affected, so as to minimise the formation of the chain-like structure of the iron hydroxide structure (He *et al.*, 1996). It is significant in this context that most observations with simultaneous phosphate precipitation processes show that to achieve high degree of P removal, an iron dose in excess of 1:1 Fe/P molar ratio (i.e. *low P/Fe of < 1:1)* must be achieved.

Using X-ray coupled TEM, He *et al.* (1996) also studied the incorporation of phosphate by iron hydroxide derived from mixed liquor of a full-scale (conventional) activated sludge plant dosed with pickle liquor as the iron source. Phosphate was found incorporated into iron hydroxide agglomerated into particles of average diameter 30-60 nm. Some particles were trapped by meshes of biological microfibrils; some were attached to other extracellular organics; and some adhered directly to the surface of biological cells. Contrary to the suggestion by Arvin (1985), calcium was not found to be incorporated into the P-Fe solids, nor was any calcium phosphate solid found. One of the reasons for this may be that the pH in most biological treatment systems does not rise sufficiently (e.g. to pH 9) to favour calcium phosphate precipitation, particularly in systems dosed with iron since the iron-phosphate reaction would compete strongly (He *et al.*, 1996).

On the basis particularly of the work of He *et al.* (1996), which showed a close association between iron hydroxide, precipitated phosphate and activated sludge biomass, and an appreciation of the large capacity for iron (hydroxide) adsorption to polymers of biological origin (notably extracellular polymers) which are abundant in activated sludge, it seems inevitable that the biological and chemical P removal mechanisms of such systems will be linked in some manner. However, the interaction of the two mechanisms and possible links between them have not been well researched.

1.10 CONCLUSIONS FROM REVIEW OF LITERATURE

To secure reliable compliance with low effluent phosphate standards in wastewater treatment, simultaneous chemical precipitation in modified activated sludge systems designed for biological nutrient removal offers several advantages. Considerable research has been conducted into the interaction between biological and chemical P removal mechanisms in such combined systems. Some findings have been that simultaneous dosing of metal salts at small to moderate dosages do not interfere with the biological processes. Largely anecdotal information from full-scale

applications, as well as the results of chemical fractionation techniques which broadly group the various forms of phosphate fixed in activated sludge, suggest that the biological P removal mechanism is inhibited by simultaneous dosing of metal salts. This would have severe implications for full-scale applications, particularly since the higher capital costs of biological P removal plants is usually justified largely on the basis of lower chemical consumption in comparison with conventional activated sludge plants which are completely reliant on chemical dosing for P removal. Many modified activated sludge plants world-wide continue to operate with simultaneous chemical addition, but there is a paucity of information in the literature on the extent to which the biological mechanism continues to be viable. Accordingly, a thorough investigation of the influence of simultaneous chemical addition on the biological P removal mechanism seems warranted.

1.11 MAIN OBJECTIVES OF THIS STUDY AND STRUCTURE OF THIS THESIS

1.11.1 Primary objective

The primary objective of this study was to determine the extent to which simultaneous chemical dosing using metal salts interferes with (or inhibits) the biological excess P removal phenomenon in modified activated sludge systems.

In order to obtain as much information as possible, there appeared to be scope for testing the simultaneous dosing of metal salts in pilot plants analogous to those used to establish so-called "enhanced cultures" (Wentzel *et al.*, 1988; 1991). The advantage of this approach was considered to be that systems strongly exhibiting the BEPR phenomenon could be operated over extended periods under conditions as close as possible to steady-state. By dosing chemicals into one of two such parallel systems, interaction between the chemical and biological mechanisms could be studied more closely than in samples from full-scale installations where a number of real operating variables tend to interfere with experimental programmes or confuse interpretation of the results. Accordingly, two parallel pilot plants (or large laboratory-scale plants) were set up at the outset of the research work. Initially, the development of (semi-) enhanced cultures in these units was studied. This developmental work is not described in detail here since it followed essentially the same pattern as that described by Wentzel *et al.* (1988). However, samples of the activated sludge cultures were taken from one of the units while set up in the early part of the research programme at the University of Cape Town (UCT). These samples, were amongst those used during method development described in **Chapter 2**.

In examining the interaction between chemical and biological P removal, one tool that seemed potentially useful was chemical fractionation of the phosphorus compounds accumulated in the activated sludge mixed liquor. This would allow direct examination of the respective forms of stored phosphorus. Accordingly, development of a suitable fractionation method became an important part of method development during the study and is described in detail in **Chapter 2**.

In order to meet the primary research objective, three different types of metal salt were dosed into the pilot plants: alum, ferric chloride and a blend of ca. 90% ferrous chloride with 10% ferric chloride. These represent the principle forms of metal ion available in South Africa for simultaneous precipitation. The results of these investigations at pilot scale are reported in **Chapters 3, 4 and 5** respectively. During the course of the research, it appeared that phosphate limitation played a key role in the interaction between the chemical and biological mechanisms. Phosphate limitation (i.e. producing low effluent P concentrations) was first studied during the ferrous-ferric chloride dosing periods in the pilot plants, and the results are described in **Chapter 5**. Subsequently, ferric chloride dosing was *re-investigated* in the pilot plants under conditions of P limitation and these results are described along with the other results for ferric chloride dosing in

Chapter 4. Alum dosing under P limiting conditions was not investigated at pilot scale but considerable full-scale experience with alum dosing had been built up for the activated sludge plant at Darvill Works (Pietermaritzburg, RSA). The latter are described in **Chapter 6**.

1.11.2 Secondary objectives

Four secondary objectives were included in the study. These included the following:

- On the basis of pilot scale studies, to conduct a full-scale plant trial at Darvill Works using one of the iron salts (viz. ferric chloride or ferrous-ferric chloride) for simultaneous P precipitation for the purposes of comparison with alum. The rationale was that alum had been used with reasonable success for a number of years at this Works, but most other activated sludge plants in South Africa were using one of the iron salts where simultaneous precipitation was being applied. This raised the question of whether it would be viable to switch Darvill Works to iron dosing. Moreover, the chemical costs for the iron salts appeared to be lower, which provided an economic incentive for the study. The results of the full-scale plant trial are described in **Chapter 6**.

- Extend the scope of the above-mentioned full-scale plant trial to include not only a study of the P removal performance of the activated sludge plant, but also an assessment of the sludge settleability in the presence of iron dosing, compared to alum. The literature suggested that iron dosing improves the settleability of activated sludge. Settleability was of key importance at Darvill Works for reasons related to problems with trade effluent with a high oil and grease content, and the fact that the activated sludge plant was operating close to its design limit. In order to evaluate settleability and secondary clarifier performance in a consistent manner, stress tests of the full-scale clarifiers were conducted in terms of flux theory and the results are described in **Chapter 6**.

- Evaluate the results of the pilot-scale studies in terms of existing mathematical models for simultaneous chemical P precipitation in activated sludge systems. This entailed a review of the theory of precipitation reactions and approach used to date in modelling these reactions. **Chapter 7** contains both the literature review of existing models as well as the results of an investigation into the application of one model (the IAWQ Activated Sludge Model No. 2) to experimental results of this study.

- Draw overall conclusions, propose an hypothesis of the nature of interaction between the chemical and biological P removal mechanisms in modified activated sludge systems, and make suggestions for further investigation. **Chapter 8** aims to meet this objective.

1.11.3 Experimental programme

Table 1.2 provides an overview of the experimental programme for the pilot plants. The distinguishing features of each "steady-state" period are given to identify the important changes that were made as the experiments progressed.

Similarly, Table 1.3 provides an overview of the full-scale plant trial.

Table 1.2: Experimental programme : pilot plants
Note: AN: anaerobic zone; AE1 : first aerobic zone.
metal dose : mg/ℓ elemental metal, based on influent

Date range	Experimental Periods	Metal dose #; R1 zone dosed	Mode of operation of pilot plants	Thesis Chapter relevant
Aug. 1993 to Sep. 1993 (at UCT)	Period 1 Fractionation method development	None	Samples taken from: • MUCT units at UCT (Wentzel *et al.*, 1993) • S_{bsi} units at UCT (described by WRC, 1984, Appendix 2)	Chapter 2
Sep. 1993 to Nov. 1993 (at UCT)	Period 2 First attempt at enhanced culture development in Control unit (R2) only - Detailed results for performance during this exploratory period not given	None	Samples taken for fractionation method development	Chapter 2
23/2/94 to 31/5/94	3.1.1 to 3.1.5	None	Enhanced culture development starting with seed activated sludge from Darvill Works • increasing acetate (50 to 250 mg/ℓ COD) • increasing P, K & Mg • no bicarbonate added • increasing acid addition for pH control	Chapter 3
1/6/94 to 20/7/94	3.1.6	Al 5 mg/ℓ AE1	First alum dosing period • 250 mg/ℓ acetate COD • no bicarbonate added • high acid dose	Chapter 3
27/7/94 to 19/8/94	-	None	New (semi) enhanced culture developed	Chapter 3
19/8/94 to 31/8/94	3.2.1	None	• Acetate addition pegged at 50 mg/ℓ COD • Bicarbonate addition commenced with 50 mg/ℓ as $CaCO_3$ • No acid addition	Chapter 3
1/9/94 to 7/11/94	3.2.2 & 3.2.3	Al 5 mg/ℓ AE1	Second alum dosing period commenced • Small acid dose included with dilute alum solution dosed (from Period 3.2.3 onwards) to prevent precipitation of metal hydroxide before dosing • Bicarbonate addition continued (increased to 100 mg/ℓ as $CaCO_3$ in Period 3.2.3)	Chapter 3

Table 1.2 continued

8/11/94 to 26/12/94	3.2.4	Al 5 mg/ℓ AN	• Alum dosing point moved to anaerobic zone • Bicarbonate addition continued (100 mg/ℓ as $CaCO_3$)	Chapter 3
27/12/94 to 9/1/95	3.2.5	Al 9 mg/ℓ AN	• Alum dose doubled • Bicarbonate addition increased to 150 mg/ℓ as $CaCO_3$	Chapter 3
10/1/95 to 23/1/95	3.2.6	Al 9 mg/ℓ AE1	• Alum dosing point moved to aerobic zone • Bicarbonate addition continued (150 mg/ℓ as $CaCO_3$)	Chapter 3
23/1/95 to 25/1/95	-	-	Pilot plants had to be relocated due to construction work at Darvill WWW	-
25/1/95 to 19/2/95	-	-	New (semi) enhanced culture developed • acetate addition increased from 50 to 150 mg/ℓ as COD with P,K & Mg to match • Bicarbonate addition throughout (150 mg/ℓ as $CaCO_3$)	Chapter 3
20/2/95 to 22/3/95	3.2.7	Al 9 mg/ℓ AE1	• Alum dosing commenced (high dose) • Bicarbonate dose continued (150 mg/ℓ as $CaCO_3$)	Chapter 3
23/3/95 to 25/4/95	3.2.8a & b	Al 9 mg/ℓ AE1	• Alum dose continued • *No bicarbonate addition*	Chapter 3
26/4/95 to 15/5/95	-	None	Alum dosing stopped Mixed liquor wasted from Test unit (R1), followed by transfer of waste mixed liquor from Control (R2) unit to R1	-
16/5/95 to 16/7/95	3.3.1	Fe (III) 10 mg/ℓ AE1	• Ferric chloride dosing commenced • Small acid dose with dilute ferric chloride solution • Bicarbonate added (100 mg/ℓ as $CaCO_3$)	Chapter 4
17/7/95 to 19/8/95	3.3.2	Fe (III) 20 mg/ℓ AE1	• Ferric chloride dose doubled • Settling problems begin to develop in R1	Chapter 4

Table 1.2 continued

20/8/95 to 29/8/95	-	Fe (III) 20 mg/ℓ AN	• Ferric chloride dosing point moved to anaerobic zone • Settling problems worsen in R1 (Fe dosed) • Mixed liquor of R1 discarded • R1 re-seeded with half the mixed liquor from R2 (Control)	Chapter 4
29/8/95 to 3/9/95	-	None	• No ferric dosing • Allowing for re-equilibration of mixed liquor	Chapter 4
3/9/95 to 7/9/95	-	Fe (III) 10 mg/ℓ AN	• Recommenced with lower dose of ferric chloride	Chapter 4
8/9/95 to 5/10/95	3.3.3	Fe (III) 10 mg/ℓ AN	• Settling problems re-emerge in R1	Chapter 4
6/10/95 to 23/10/95	3.3.4	Fe (III) 10 mg/ℓ AN	• Sludge age reduced from 20 d to 10 d in both units (R1 and R2) • Settling problems become manageable	Chapter 4
24/10/95 to 13/11/95	3.3.5	Fe (III) 20 mg/ℓ AN	• Ferric chloride dose doubled	Chapter 4
14/11/95 to 3/12/95	3.3.6	Fe (III) 20 mg/ℓ AE1	• Ferric chloride dosing point moved to aerobic zone	Chapter 4
3/12/95 to 12/12/95	-	None	Ferric chloride dosing stopped Mixed liquor wasted from Test unit (R1), followed by transfer of waste mixed liquor from Control (R2) unit to R1	-

Table 1.2 continued

13/12/95 to 13/1/96	3.4.1	Fe (II)-Fe(III) 19 mg/ℓ AE1	• Ferrous-ferric chloride dosing commenced (high dose) • Small acid dose with dilute ferrous-ferric chloride solution • Bicarbonate added (100 mg/ℓ as $CaCO_3$)	Chapter 5
15/1/96 to 17/2/96	3.4.2	Fe (II)-Fe(III) 10 mg/ℓ AE1	• Ferrous-ferric chloride dose halved	Chapter 5
18/2/96 to 18/3/96	3.4.3	Fe (II)-Fe(III) 10 mg/ℓ AN	• Ferrous-ferric chloride dosing point moved to anaerobic zone	Chapter 5
1/4/96 to 10/6/96	3.4.4	Fe (II)-Fe(III) 10 mg/ℓ AE1	• Phosphate addition to influent reduced	Chapter 5
11/6/96 to 26/7/96	3.5.1	Fe (II)-Fe(III) 10 mg/ℓ AE1	• Phosphate addition to influent eliminated • Acetate addition to influent reduced	Chapter 5
27/7/96 to 27/8/96	3.5.2	Fe (II)-Fe(III) 10 mg/ℓ AN	• Ferrous-ferric chloride dosing point moved to anaerobic zone	Chapter 5
28/8/96	Pilot plants shut down	-	-	-
Aug. 1996 to Nov. 1996	Full scale plant trial conducted (see also Table 1.3)	Fe(II)-Fe(III) approx. 6 mg/ℓ AE	• Full scale trial at Darvill WWW • Ferrous-ferric chloride dosing to aerobic zones of activated sludge plant	Chapter 6
Dec. 1996 to Feb. 1997	Full scale plant trial continued (see also Table 1.3)	Al approx. 3 mg/ℓ	• Full scale trial at Darvill WWW • Alum dosing to aerobic zones of activated sludge plant	Chapter 6
Mar. 1997 to June 1997	(Pilot plants in use for other research)	-	(Research not part of this study)	-
29/7/97 to 4/8/97	-	Fe(III) 10 mg/ℓ AE1	Both pilot plants re-seeded with activated sludge from Darvill WWW • 50 mg/ℓ acetate COD added • 100 mg/ℓ as $CaCO_3$ bicarbonate added • No phosphate addition	-

Table 1.2 continued

5/8/97 to 8/8/97	-	Fe(III) 10 mg/ℓ AE1	• Acetate increased to 75 mg/ℓ as COD added	-
9/8/97 to 10/8/97	-	Fe(III) 10 mg/ℓ AE1	• Acetate increased to 100 mg/ℓ as COD added	-
11/8/97 to 4/10/97	3.6.1	Fe(III) 10 mg/ℓ AE1	• 100 mg/ℓ acetate COD added • 100 mg/ℓ as $CaCO_3$ bicarbonate added • No phosphate addition	Chapter 4
5/10/97 to 7/12/97	3.6.2a	Fe(III) 10 mg/ℓ AE1	• 100 mg/ℓ acetate COD added • *No bicarbonate added* • No phosphate addition	Chapter 4
7/12/97 to 20/12/97	3.6.2b	Fe(III) 10 mg/ℓ AE1	• 100 mg/ℓ acetate COD added • No bicarbonate added • *Phosphate added (20 mg/ℓ as P)*	Chapter 4

Table 1.3 Experimental programme for full-scale plant

Date	Mode of chemical addition on full-scale activated sludge plant	Thesis Chapter
Sep. 1992 to May 1997	• Alum dosing • Historical data	Chapter 6
1/5/97 to 13/8/97	• Alum dosing • Detailed analysis of plant performance	Chapter 6
20/8/97 to 14/11/96	• Plant switched to ferrous-ferric chloride dosing • Detailed analysis of plant performance	Chapter 6
14/11/96 to 20/11/96	• Increased ferrous-ferric chloride dose	Chapter 6
1/12/96 to 28/2/97	• Plant switched back to alum dosing • Detailed analysis of plant performance	Chapter 6

REFERENCES

Appeldoorn, KJ, Boom, AJ, Korstee, JJ and Zehnder, AJB. (1992) Contribution of precipitated phosphates and acid-soluble polyphosphate to enhanced biological phosphate removal. *Water Res.,* 26, (7), 937-943.

Arvin, E. (1979) The influence of pH and calcium ions upon phosphorus transformations in biological wstewater treatment plants. *Prog. Water Tech.* 1, 19-40.

Arvin, E. (1985) Biological removal of phosphorus from wastewater. *CRC Crit. Rev. Environ. Control,* 15 (1), 25-64.

Aspegren, H. (1995) *Evaluation of a high loaded activated sludge process for biological phosphorus removal.* Ph.D. Thesis, Dept. of Water and Environmental Engineering, Lund University of Technology, Lund, Sweden.

Bark, K, Sponner, A, Kämpher, P, Grund, S and Dott, W. (1992) Differences in polyphosphate accumulation and phosphate adsorption by *Acinetobacter* isolates from wastewater producing polyphosphate: AMP phosphotransferase. *Water Res.,* 26 (10), 1379-1388.

Barnard, JL. (1974) Cut P and N without chemicals. *Water Wastes Eng.,* 11, 33-36

Barnard, JL. (1975) Biological nutrient removal without addition of chemicals. *Water Res.,* 9, 485-490.

Barnard, JL. (1976) A review of biological phosphorus removal in the activated sludge process. *Water SA,* 2, 136-144.

Barnard, JL. (1983) Background to biological phosphorus removal. *Water Sci. Technol.,* 15, (3/4), 1-13.

Barnard, JL. (1984) Activated primary tanks for phosphate removal. *Water SA,* 10, 121-126.

Barnard, JL. (1995) *Personal communication*. Reid Crowther, Burnaby, Vancouver, British Columbia, Canada.

Barth, EF and Ettinger, MB. (1967) Mineral controlled phosphorus removal in the activated sludge process. *Journal WPCF,* 39, 1362.

Bliss, PJ, Ostarcevic, ER and Potter, AA. (1994) Process optimization for simultaneous biological nitrification and chemical phosphorus removal. *Water Sci. Tech.,* 29 (12), 107-115.

Black, SA. (1979) Experience with phosphorus removal at existing Ontario municipal wastewater treatment plants (Chapter 13). *Phosphorus removal strategies for lakes.* Ann Arbor Sci. Publ., Ann Arbor, Michigan.

Blonda, M, Brunetti, A, Morrone, S, Ramadori, R and May, JW. (1994) Determination of orthophosphate in activated sludges from wastewater-treatment systems showing enhanced biological phosphate removal. *Water Res.,* 28 (1), 155-159.

Boyd, LA and Lötter, LH. (1993) The effect of chemical addition on biological phosphate removal. *Proceedings of the WISA Conference,* May 1993, Durban, 88-95.

Boyko, BI and Rupke, JWG (1973) Design considerations in the implementation of Ontario's phosphorus removal programme. Proceedings of Phosphorus Removal Design Seminar No.1, 28 - 29 May 1973, Environ. Prot. Serv., Environment Canada, Ottowa.

Briggs, TA. (1996) Dynamic modelling of chemical phosphorus removal inthe activated sluydge process. M. Eng. Thesis, Dept. of Civil Engineering, McMaster University, Hamilton, Ontario, Canada.

Brown, MJ and Lester, JN. (1979) Metal removal in activated sludge: the role of bacterial extracellular polymers. *Water Res.,* 13, 817-837.

Chutter, FM. (1990) Evaluation of the impact of the 1mgP/ℓ phosphate P standard on the water quality and trophic status of Hartebeespoort Dam. *Water Sewage and Effluent*, 10 (1), 29-33.

Clark, JE, Beegan, H and Wood, HG. (1986) Isolation of intact chains of polyphosphate from Propionobacterium shermanii grown on glucose or lactate. *J. Bact.,* 168 (3), 1212-1219.

Cloete, TE and Steyn, PL. (1988) A combined membrane filter immunofluorescent technique for the in situ identification and enumeration of *Acinetobacter* in activated sludge. *Water Res.,* 22, 961-969.

Cloete, TE, Steyn, PL and Buchan, L. (1985) An aut-ecological study of *Acinetobacter* in activated sludge. *Water Sci. Technol.,* 17 (11/12), 139-146.

Comeau, Y, Hall, KJ, Hancock, REW and Oldham, WK. (1986) Biochemical model for enhanced biological phosphorus removal. *Water Res.,* 20 (12), 1511-1521

Coombes, JM, Manceau, Calas, G, and Bottero, JY. (1989) Formation of ferric oxides from aqueous solutions: A polyhedral approach by X-ray adsorption spectroscopy: [I] Hydrolysis and foramtion of ferric gels. *Geochim. Cosmochim. Acta,* 53 , 583-594.

De Haas, DW and Dubery, IA. (1989) Unreliability of cold-stored samples for assessment of chemical precipitate in activated sludge. *Water SA,* 15 (4), 257-260.

De Haas, DW and Greben, HA. (1991) Phosphorus fractionation of activated sludges from modified Bardenpho processes with and without chemical precipitant supplementation. *Water Sci. Technol.* 23 (Kyoto), 623-633.

De Haas, DW, Borain, GP and Kerdachi, DA. (1991) Review of treatment performance at Hammarsdale Waste-water Works with special reference to alum dosing. *Water SA,* 19 (2), 93-106.

De Haas, DW. (1989a) Fractionation of bioaccumulated phosphorus compounds in activated sludge., *Water Sci. Tech.,* 21 (Brighton), 1721-1725.

De Haas, DW. (1989b) Chemical fractionation of activated sludge with special reference to enhanced biological phosphate removal. MSc. Thesis, Dept. of Biochemistry, Rand Afrikaans University, Johannesburg., November 1989.

De Haas, DW. (1991) Significance of fractionation methods in assessing the chemical form of phosphate accumulated by activated sludge and an *Acinetobacter* pure culture., *Water SA,* 17 (1), 1-10.

De Wet, FJ, Barnard, JL and Saayman, G. (1992) Baviaanspoort wastewater reclamation plant. *Wat. Sci. Technol.,* 25 (4-5), 169-175.

Deimena, MH, Habets, LHA, Scholten, J, Turkstra, E and Webers, HAAM. (1980) The accumulation of polyphosphate in *Acinetobacter* spp. *FEMS Microbiol. Lett.,* 9, 275-279.

Deinema, MH, van Loosdrecht, M and Scholten, A. (1985) Some of the physiological characteristics of *Acinetobacter* spp. accumulating large amounts of phosphate. *Water Sci. Technol.,* 17 (11/12), 119-125.

D'Elia, M and Isolati, A. (1992) Observed synergistic effects of aluminium and iron salts in nutrients removal. *Chemical water and wastewater treatment II: proceedings of the 5th Gothenburg Symposium, September 28-30, 1992, Nice, France.,* Klute, R and Hahn, HH (eds.), Springer-Verlag, New York, 389-400.

Dillon, PJ and Molot, LA. (1996) Long-term phosphorus budgets and an examination of the steady-state mass balance model for central Ontario lakes. *Water Res.* 20 (10), 2273-2280.

Eberhardt, WA and Nesbitt, JB. (1968) Chemical precipitation of phosphorus in a high-rate activated sludge system., *J WPCF,* 40, 1239.

Fitzgerald, GB and Nelson, TC. (1966) Extraction and enzymatic analysis for limiting or surplus phosphorus in algae. *J. Phycol.,* 2, 32-37.

Fleit, E. (1995) Intracellular pH regulation in biological excess phosphorus removal systems. *Water Res.,* 29 (7), 1787-1792.

Florentz, M, Granger, P and Hartemann P. (1984) Use of ^{31}P-NMR nuclear magnetic resonance spectroscopy and electron microscopy to study phosphorus metabolism of microorganisms in wastewaters. Appl. Environ. Microbiol. 47, 519-525.

Flynn, CM. (1984) Hydrolysis of inorganic iron (III) salts. *Chem. Rev.,* 84, 31-41.

Frossard, E, Bauer, JP and Lothe, F. (1997) Evidence of vivianite in $FeSO_4$-flocculated sludges. *Water Res.* 31 (10), 2449-2454.

Fuhs, GW and Chen, M. (1975) Micobiological basis of phosphate removal in the activated sludge process for the treatment of wastewater. *Microb. Ecol.,* 2, 119-138.

Gehr, R and Henry, JG. (1983) Removal of extracellular material: Techniques and Pitfalls. *Water Res.,* 17 (2), 1743-1748.

Gerber, A, de Villiers, RH, Mostert, ES and van Riet, CJJ. (1987) The phenomenon of simultaneous phosphate uptake and release, and its importance in biological nutrient removal. In: *Advances in Water Pollution Control: Biological phosphate removal from wastewaters.,* (Ramadori, R, ed.), Pergamon, Oxford, 123-134.

Government Gazette. (1984) Requirements for the purification of waste water or effluent., *Government Gazette,* 227 (991), 12-17.

Grobler, DC. (1988a) Impact of nonpoint source derived phosphorus loads on water quality in South African reservoirs. Proceedings of the Phosphorus Symposium, September 1988, Pretoria, South Africa. Organising Committee, SIRI, Private Bag X79, Pretoria 0001 South Africa, pp 219-223.

Grobler, DC. (1988b) Evaluation of the impact of phosphate control measures on eutrophication related water quality in sensitive catchments - Executive Summary. Dept. of Water Affairs, Private Bag X313 Pretoria 0001 South Africa, pp 1-12.

Hahn, HH. (1992) Chemical dosing control : physical and chemical boundary conditions. *Chemical water and wastewater treatment II: Proceedings of the 5th Gothenburg Symposium, September 28-30, 1992, Nice, France*. Klute, R and Hahn, HH (eds.). Springer-Verlag, New York, 152-163.

Halvorsan, HO, Suresh, N, Roberts, MF, Coccia, M and Chikarmane, HM. (1987) Metabolically active surface polyphosphate pool in *Acinetobacter lwoffi., In: Phosphate Metabolism and Cellular Regulation in Microorganisms,* (Torriani-Gorini, A, Rothman, H, Silver, S, Wright, A and Yagil, E, eds.). American Soc. for Microbiology, Washington DC, 220-224.

Harold, FM. (1962) Depletion and replenishment of the inorganic polyphosphate pool in *Neurospora crassa. J. Bacteriol.,* 86, 216-221.

Harold, FM. (1963) Accumulation of inorganic polyphosphate in *Aerobacter aerogenes*. 1. Relationship to growth and nucleic acid synthesis. *J. Bacteriol.,* 86, 216-221.

Hartwig, P and Seyfried, CF. (1991) The combined biological nitrogen and phosphorus removal - design and large-scale experiences. Internal report, Institut für Siedlungswasserwirtschaft und Abfalltechnik, University of Hannover, Germany.

Hascoet, MC, Florentz, M and Granger, P. (1985) Biochemical aspects of enhanced biological phosphorus removal from wastewater. *Water Sci. Technol.* 17 (11/12), 23-41.

He, QH, Leppard, G, Paige, CR and Snodgrass, WJ. (1996) Transmission electron microscopy of a phosphate effect on the colloid structure of iron hydroxide. *Water. Res.,* 30 (6), 1345-1352.

Healey, KJ, Kerdachi, DA and Borain, GP. (1989) The use of simultaneous precipitation to supplement biological treatment in a nutrient removal (activated) sludge process., *Proceedings of the WISA Conference, Cape Town, 28-30 March 1989.* (No page nos.)

Henze, M and Harremoes, P. (1992) Characterization of wastewater: the effect of chemical precipitation on the wastewater composition and its consequences for biological denitrification. *Chemical water and wastewater treatment II: proceedings of the 5th Gothenburg Symposium, September 28-30, 1992, Nice, France.,* (Klute, R and Hahn, HH, eds.). Springer-Verlag, New York, 299-311.

Hill, WE, Benefield, LD and Jing, SR. (1989) ^{31}P-NMR spectroscopy characterization of polyphosphates in activated sludge exhibiting enhanced phsophorus removal. *Water Res.,* 23 (9), 1177-1181.

IAWQ (1995) *Activated Sludge Model No. 2.* IAWQ Task Group on Mathematical Modelling for Design and Operation of Biological Nutrient Wastewater Treatment Processes. International Association on Water Quality, 1 Queen Anne's Gate, London.

IAWQ Nutrient Removal Tour to South Africa. (1993) Personal notes., DW de Haas.

Jenkins, D. Ferguson, JF and Menar, AB. (1971) Chemical processes for phosphate removal. *Water Res.,* 5, 369-389.

Jing, SR, Benefield, LD and Hill, WE. (1992) Observations relating to enhanced phosphorus removal in biological systems. *Water Res.,* 26 (2), 213-223.

Kavanaugh, RG and Randall, CW. (1994) Bacterial populations in a biological nutrient removal plant. *Water Res.,* 29 (7), 25-34.

Kerdachi, DA and Roberts, MR. (1983) Further developments in the understanding of phosphate removal at Umhlatuzana. *Water Sci. Technol.,* 15 (3/4), 269-281.

University of Cape Town

Kerdachi, DA and Roberts, MR. (1985) Further investigations into the modified STS procedure as used specifically to quantitatively assess 'metal phosphates' in activated sludge., *Proc. Int. Conf. Management Strategies for Phosphorus in the Environment.*, Lisbon, Selper, UK, 66-71.

Klute, R and Hahn, HH. (eds.) (1992) *Chemical water and wastewater treatment II: proceedings of the 5th Gothenburg Symposium, September 28-30, 1992, Nice, France.* Springer-Verlag, New York.

Kulaev, IS. (1979) *The Biochemistry of Polyphosphates.* Wiley, Chichester.

Lawson, EN and Tonhazy, NE. (1980) Changes in morphology and phosphate uptake patterns in *Acinetobacter calcoaceticus* strains. *Water SA,* 6, 105-112.

Leopold, P. (1996) Personal communication. *NCP Ultrafloc*, Johannesburg, South Africa.

Levin, GV, Topol, GJ and Tamay, AG. (1975) Operation of full-scale biological phosphorus removal plant. *Journal WPCF,* 47 (3), 577-590.

Lilley, ID, Kolbe FF and Hammond, FM. (1993) Considerations and cost implications in the design of wastewater treatment works. *Proceedings of the WISA Conference, May 1993, Durban*, 93-107.

Lindrea, KC, Pigdon, SP, Boyd, P and Lockwood, GA. (1994) Biomass characterization in a nitrification-denitrification biological enhanced phosphorus removal (NDBEPR) plant during start-up and subsequent periods pf good and poor phosphorus removal. *Water Sci. Technol.,* 29 (7), 91-100.

Loewenthal, RE and Marais GvR. (1976) *Carbonate Chemistry of Aquatic Systems, Vol. I: Theory and Application*. Ann Arbor Science, Ann Arbor, Michigan.

Loewenthal, RE Wiechers, HNS and Marais, GvR. (1986) *Softening and stabilization of municipal waters*. Water Research Commission, Pretoria.

Lötter, LH and Murphy, M. (1985) The identification of heterotrophic bacteria in an activated sludge plant with particular reference to polyphosphate accumulation. *Water SA,* 11, 179-184.

Lötter, LH. (1985) The role of bacterial phosphate metabolism in enhanced phosphorus removal from the activated sludge process. *Water Sci. Technol.,* 17 (11/12), 127-138.

Lötter, LH. (1991) Combined chemical and biological removal in activated sludge plants. *Water Sci. Technol.*, 23 (Kyoto), 611-621.

Luedecke, C, Hermanowicz, SH and Jenkins, D. (1989) Precipitation of ferrioc phosphate in activated sludge: a chemical model and its verification. *Water Sci. Technol.* 21 (Brighton), 325-327.

Manz, W, Wagner, M, Amann, R and Schleifer, K-H. (1994) In-situ characterization of the microbial consortia active in two wastewater treatment plants. *Water Res.,* 28 (8), 1715-1723.

Marais, GvR, Loewenthal, RE and Siebritz, IP. (1983) Observations supporting phosphate removal by biological excess uptake. A review. *Water Sci. Technol.,* 15, 15-42.

Mino, T, Arun, V, Tsuzuki, Y and Matsuo, T. (1987) Effect of phosphorus accumulation on acetate metabolism in the biological phosphorus removal process. *In: Advances in Water Pollution Control: Biological phosphate removal from wastewaters,* (Ramadori, R, ed.). Pergamon, Oxford, 27-38.

Mino, T, Kawakami, T and Matsuo, T. (1985) Location of phosphorus in activated sludge and function of intracellular polyphosphates in biological phosphorus removal process. *Water Sci. Technol.,* 17 (11/12), 93-106.

Mino, T. and Matsuo, T. (1985) Estimation of chemically precipitated phosphorus in activated sludges., *Newsletter of the Study Group on Phosphate Removal in Biological Sewage Treatment Processes (IAWPRC),* 2 (2), 21-28

Miya, A, Kitagawa, M and Tanaka, T. (1987) The behaviour of magnesium in biological phosphate removal. *In: Advances in Water Pollution Control: Biological phosphate removal from wastewaters,* (Ramadori, R, ed.). Pergamon, Oxford, 135-146.

Morales, LM, Daigger, G and Borberg, JR. (1991) Capability assessment of biological nutrient removal facilities. *Research Journal WPCF,* 63 (6), 900-909.

Munro, HN and Fleck, A (1966) The determination of nucleic acids. In: *Methods of Biochemical Analysis*. (Glick, D. ed.) Interscience, New York, 113-1785.

Murphy, M and Lötter, LH. (1986) The effect of acetate and succinate on polyphosphate formation and degradation in activated sludge with particular reference to *Acinetobacter calcoaceticus*. *Appl. Microbiol, Biotechnol.,* 24 , 512-517.

Müssig-Zufika, M, Kömmuller, A, Merkelbach, B and Jekel, M. (1994) Isolation and analysis of intact polyphosphate chains from activated sludges associated with biological phosphate removal., *Water Res.,* 28 (8), 1725-1733.

Nielsen, PH. (1996) The significance of microbial Fe(III) reduction in the activated sludge process. *Water Sci Technol.* 24 (5-6), 129-136.

Nutt, SG. (1985) The technical and economic feasibility of retrofitting existing municipal treatment plants in Canada for biological phosphorus removal. Part Two (Water Quality Research), Proceedings: Technology Transfer Conference No. 6, Toronto Hilton Harbour Castle, Toronto, 11-12 December 1985, Environmental Protection Service, Environment Canada, p 257- 284.

Ohtake, H, Takahashi, K, Tsuzuki, Y and Toda, K. (1985) Uptake and release of phosphate by pure culture of *Acinetobacter calcoaceticus*. *Water Res.,* 19, 1587-1594.

Olesen, NS. (1990) Nutrient removal in small wastewater treatment plants. *Water Sci. Technol.*, 22 (3/4), 211-216.

Osborne, DW, Lötter, LH, Pitman, AR and Nicholls, HA. (1986) *Enhancement of biological phosphate removal by altering feed composition*. Water Research Commission, Pretoria, WRC Report No. 137/1/86.

Osborne, DW, Lötter, LH, Pitman, AR and Nicholls, HA. (1989) *Two-year study on the enhancement of biological phosphate removal by altering process feed composition (plant and laboratory studies).* Water Research Commission, Pretoria, WRC Report No. 137/2/89.

Peter, A and Sarfert, F.(1991) Operation experiences with biological phosphorus removal at the sewage treatment plants of Berlin (West). *Water Sci. Technol.,* 24 (7), 133-148.

Pillay, M, Hudson, N, Furness, HD and Buckley, CA. (1993) Detergent phosphorus in South Africa: Impact on eutrophication with special reference to the Umgeni catchment. *Proceedings of the WISA Conference,* May 1993, Durban, 295-307.

University of Cape Town

Pillay, M. (1994) *Detergent phosphorus in South Africa: Impact on eutrophication with specific reference to the Umgeni catchment.* MSc Thesis, Dept. of Chemical Engineering, University of Natal, Durban, December, 1994.

Pitman, AR. (1991) Design considerations for nutrient removal activated sludge plants. *Water Sci. Technol.,* 23 (Kyoto), 781-790.

Power, SPB, Ekama, GA, Wentzel, MC and Marais, GvR. (1992) *Chemical phosphorus removal from municipal wastewater by the addition of waste alum sludge to the activated sludge system.* Research Report No. W66, University of Cape Town, Dept. of Civil Engineering, September 1992.

Psenner, R, Pucsko, R and Sager, M. (1984) 4. Fractionation of phosphorus in suspended matter and sediment. *Arch. Hydrobiol. Beih. Ergebn. Limnol.,* 30 , 98-103.

Rabinowitz, B and Marais, GvR. (1980) *Chemical and biological phosphorus removal in the activated sludge process.* Research Report No. W32, University of Cape Town, Dept. of Civil Engineering, March 1980.

Rasmussen, H and Nielsen, PH. (1996) Iron reduction in activated sludge measured with different extraction techniques. *Water Res.,* 30 (3), 551-558.

Rensink, JH, Leentvaar, J and Donker, HJ. (1979) Combined bulking sludge counteraction and phosphate removal by dosing with iron (II) sulphate. *H2O* (Rotterdam) , 12 (7), 150-153.

Reynolds, T. (1996) *Personal Communication.* NCP Ultrafloc, Johannesburg, South Africa.

Röske, I and Schönborn, C. (1994a) Interactions between chemical and advanced biological phosphorus elimination. *Water Res.,* 28 (5), 1103-1109.

Röske, I and Schönborn, C. (1994b) Influence of the addition of precipitants on the biological phosphorus elimination in a pilot plant. *Water Sci. Technol.,* 30 (6), 323-332.

Schmidtke, NW.(1985) Estimating sludge quantities at wastewater treatment plants using metal salts to precipitate phosphorus. *Proc. Int. Conf. Management Strategies for Phosphorus in the Environment.,* Lisbon, Selper, UK, 379-385.

Singer, PC. (1972) Anaerobic control of phosphate by ferrous iron. *Journal WPCF,* 44 (4), 663-669.

Stepko, WE and Shannon, EE. (1974) Phosphorus removal demonstration study using ferric chloride and alum at C.F.B. Uplands. Technology Development Report EPS 4-WP-74-05, Canada Environ. Prot. Serv., Environment Canada, Ottowa.

Streichan, M and Schön, G. (1991) Periplasmic and intracytoplasmic polyphosphate and easily washable phosphate in pure cultures of sewage bacteria. *Water Res.,* 25 (1), 9-13.

Sutton, PM, Murphy, KL and Jank, BE. (1978) Nitrification systems with integrated phosphorus precipitation. *Water Pollution Control,* 116 (4), 27-33.

Szpyrkowicz, L and Zilio-Grandi, F. (1995) Seasonal phosphorus removal in a Phostrip process - 1. Two years' plant performance. *Water Res.* 29 (10), 2318-2326.

Twinch, AJ (1986) The phosphorus status of sediments in a hypertrophic impoundment (Hartebeespoort Dam) : Implications for eutrophication management. *Hydrobiologica* 135, 23-34.

Uhlmann, D, Röske, I, Hupfer, M and Ohms, G. (1990) A simple method to distinguish polyphosphate and other phosphate fractions of activated sludge. *Water Res.,* 24 (11), 1355-1360.

Ulmgren, L. (1975) Swedish experiences in chemical treatment of wastewater. *Journal WPCF,* 47 (4), 696 to 703.

Van Groenestijn, JW. (1988) Accumulation and degradation of polyphosphate in *Acinetobacter* sp., PhD Thesis, Dept. of Microbiology, Agricultural University, Wageningen, The Netherlands, June 1988.

Vasiliadis, DA, Bayly, RC and May, JW. (1988) Genospecies of *Acinetobacter* isolated from activated sludge showing enhanced removal of phosphate during pilot-scale treatment of sewage. *Biotechnol. Lett.,* 10, 831-836.

Venter, SN, Lötter, LH and de Haas, DW. (1989) Potential shortcomings of the Analytical Profile Index system in the identification of activated sludge bacteria. *Water SA,* 15 (4), 265-267.

Viitasaari, M. (1976) *Reaction rates and factors affecting them at extended aeration- simultaneous precipitation of wastewater.* Publications of the National Res. Inst., no. 16, 105-140. National Board of Waters, Vesihallitus, Helsinki, Finland.

Wagner, M, Amann, R, Lemmer, H, Manz, W and Schleifer, K-H. (1994b) Probing activated sludge with fluorescently labelled rRNA targeted oligonucleotides. *Water Sci. Technol.,* 29 (7), 15-23.

Wagner, M, Assmus, B. Hartmann, A, Hultzler, P and Amann, R. (1994c) *In situ* analysis of microbial consortia in activated sludge using fluorsecentli labeled, rRNA-targeted oilgonucleotide probes and confocal scanning laser microscopy. *J. Microscopy* 176, 181-187.

Wagner, M, Erhart, R, manz, W, Amann, R, lemmer, H, Wedi, D and Shleifer, K-H. (1994a) Development of an rRNA-targeted oligonucleotide probe specific for the genus *Acinetobacter* and its application for in-situ monitoring in activated sludge. *Appl. Env. Microbiol.,* 60 (3), 792-800.

Walmsley, RD and Thornton, JA (1982) Applicability of phosphorus budget models to southern African man-made lakes. *Hydrobiologica*, 89, 237-245.

Walmsley, RD and Thornton, JA (1984) Evaluation of OECD-type phosphorus eutrophication models for predicting the trophic status of southern African man-made lakes. *South African Journal of Science*, 80, June 1984, 257-259.

Wedi, D and Wilderer, PA. (1994) Full scale investigations on enhanced biological phosphorus removal - P-release in the anaerobic reactor. *Water Sci. Technol.,* 29 (7), 156-156.

Wentzel, MC, Ekama, GA and Marais, GvR. (1992) Processes and modelling of nitrification denitrification biological excess phosphorus removal systems - a review. *Water Sci. Technol.,* 25 (6), 59-82.

Wentzel, MC, Ekama, GA, Dold, PL and Marais, GvR. (1990) Biological excess phosphorus removal - Steady state process design. *Water SA* 16 (1), 29 -48.

Wentzel, MC, Loewenthal, RE, Ekama, GA and Marais, GvR. (1988) Enhanced polyphosphate organism cultures in activated sludge systems - Part 1: Enhanced culture development. *Water SA,* 14 (2), 81-92.

Wentzel, MC, Lötter, LH, Ekama, GA, Loewenthal, RE and Marais, GvR. (1991) Evaluation of biochemical models for biological excess phosphorus removal. *Water Sci. Technol.,* 23 (Kyoto), 567-576.

Wentzel, MC, Lötter, LH, Loewenthal, RE and Marais, GvR. (1986) Metabolic behaviour of *Acinetobacter* spp. in enhanced biological phosphorus removal - a biochemical model. *Water SA,* 12, 209-224.

Wentzel, MC, Mbewe A, Izzett H, Ozinsky AE, Ekama GA and Marais GvR. (1993). Progress report to the Water Resarch Commission on the research contract "Consolidation of Activated Sludge Research", July 1993, Annexure B: *Dynamic Response of nitrification denitrification biological excess phosphorus removal plants* by Lakay MT, Wentzel MC Ekama GA and Marais GvR.

Wiechers, HNS (ed.). (1987) *Guidelines for chemical phosphate removal from municipal waste waters.* Collaborative publication compiled by staff of the Town Council of Boksburg, City Council of Pretoria, National Institute of Water Research and the Water Research Commission. Water Research Commission, Pretoria, January, 1987.

Wiechers, HNS and Heynicke, JCC (1986) Sources of phosphorus which give rise to eutrophication in South African waters. *Water SA* 12 (2), 99-102.

Witt, PC, Grabowski, F and Hahn, HH. (1994) Interactions between biological and physico-chemical mechanisms in biological phosphate elimination. *Water Sci. Technol.,* 30 (6), 271-279.

WRC (1984) *Theory, design and operation of nutrient removal activated sludge processes.* Ekama, GA, Marais, GvR, Siebritz, IP, Pitman, AR, Keay, GFP, Buchan, L, Gerber, A and Smollen, M (eds.). Water Research Commission, Pretoria.

Wuhrmann, K. (1968) Objective, technology and results of nitrogen and phosphorus removal processes., *Adv. Water Quality Improvement,* University of Texas Press, p21.

Yeoman, S, Steohenson, T, Lester, JN and Perry, R. (1988) The removal of phosphorus during wastewater treatment: a review. *Environmental Pollution,* 49 (1988), 183-233.

Yue, CM, Thadani, VB and Healy, GM. (1987) A demonstration study for biological phosphorus removal at Lakeview WPCP. Part B (Water Quality Research), Proceedings: Technology Transfer Conference, Royal York Hotel, Toronto, 30 November-1 December 1987, Ministry of the Environment, Canada, (no page nos.).

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting biological enhanced phosphate removal.

Chapter 2

Method development

DW de Haas

CHAPTER TWO

METHOD DEVELOPMENT

2.1 INTRODUCTION

In order to determine the possible effects of simultaneous chemical addition on the biological phosphorus (P) removal mechanism in activated sludge systems, it was recognised that suitable methods would be required to measure both the extent of P removal in such systems, and the degree to which P removal could be ascribed specifically to the biological mechanism, as opposed to the chemical mechanism. Pilot or laboratory-scale activated sludge systems are most suitable for such research, and were used here. It proved economical to build identical systems which were operated under identical conditions, with the exception that one unit (the Test unit) could be dosed with chemical precipitant (e.g. alum or iron salt), while the other served as the Control unit. Phosphate removal could then be measured in both units from the difference between influent and effluent total P. Phosphate removal from the Test unit would be attributable to the combined chemical-biological mechanisms, while that from Control would be due mainly to the biological mechanism. Cations naturally present in domestic sewage could make a minor contribution to the system P removal of the Control (Arvin, 1983, 1985; de Haas, 1989). Therefore, it was considered an advantage to have a phosphorus fractionation procedure which, when applied to activated sludge mixed liquor from both the Test and Control units, would be capable of broadly estimating the relative magnitudes of phosphate fractions bound chemically versus those stored biologically. Fractionation procedures used for this purpose have been reviewed in Chapter 1.

The aim of the work described in this chapter was to test one fractionation procedure (that based on cold perchloric acid) which has been extensively applied to activated sludge (*inter alia* de Haas, 1989; Blonda *et al.*, 1994), in an attempt to simplify it, where possible, as well as to validate it. Validation of the chemically-removed fractions could be attempted by means of batch tests in which known amounts of chemical precipitant and phosphate are added to samples of activated sludge from laboratory-scale units exhibiting enhanced biological P removal (e.g. the Control unit described above), followed by application of the fractionation procedure to determine recovery of chemically-bound phosphate from the sludge. Validation of the biological fractions could be attempted by comparing the fractionation results for the Control unit, under defined conditions, with the concentrations of biologically-stored polyphosphate (poly P) projected from a mathematical model (Wentzel *et al.*, 1992). Mathematical modelling is examined in greater detail in Chapter 7.

In addition to describing fractionation method development and testing as outlined above, this chapter discusses the methods used for routine measurement of parameters used to define performance of the pilot and full-scale plants described in Chapters 3 to 6.

2.2 TOTAL PHOSPHATE METHOD

Total phosphate (total P) is most commonly determined by either the vanadate-molybdate method or the molybdate-ascorbic acid method. With phosphate is added to the influent of laboratory or pilot-scale systems, the effluent P concentrations are usually >1 mgP/ℓ. Under these conditions, the vanadate method has the advantage of working in a higher concentration range, thereby reducing the number of dilutions required for analysis. On the other hand, the ascorbic acid method is more suitable where low total P concentrations (<1 mgP/ℓ) need to be determined. This section describes both methods, particularly in respect of their application to samples of activated sludge in the fractionation procedures described in section 2.4 below. Particular attention was paid to the concentrations of acid and persulphate

used in the digestion procedure, since both can influence the recovery of total P and/or produce interference in the subsequent colorimetric reactions (de Haas *et al.*, 1990).

2.2.1 Vanadate-molybdate method

The method for total P digestion used for a number of years in the Water Quality Engineering laboratory at UCT Dept. of Civil Engineering has been described by Burke *et al.* (1986). It involves digestion of the sample (20 mℓ) with sulphuric acid (5 mℓ of 0.11 M H_2SO_4) and potassium persulphate (5 mℓ of 3% m/v $K_2S_2O_8$) in a pressure cooker at 100 kPa for 30 minutes. This method gives final concentrations (after admixture with sample) of 0.018 M H_2SO_4 and 0.5% $K_2S_2O_8$. Whilst these concentrations may be adequate for waste water influent or effluent samples with a low solids content, incomplete digestion may occur when the method is applied to activated sludge mixed liquor samples. De Haas *et al.* (1990) found that the final concentrations of sulphuric acid (0.1 M) and persulphate (0.8% as ammonium persulphate) recommended in *Standard Methods* (1985) was the minimum that gave acceptable recovery of total P, compared to a magnesium nitrate fusion method. De Haas *et al.* (1990) recommended a higher final sulphuric acid concentration (1M) for complete total P recovery from mixed liquor. However, this necessitated larger dilutions (at least 20-fold) of the digest in order to avoid interference in the subsequent colorimetric orthophosphate determination. This aspect was further investigated for the purpose of this study.

As a point of departure, the vanadate-molybdate determination of orthophosphate (after total P digestion) was adopted since it offered the most suitable range for activated sludge phosphate concentrations (Burke *et al.*, 1986). An experiment was set up in which the final acid concentrations (prior to digestion) were 0.02 M (Burke *et al.*, 1986), 0.1 M (*Standard Methods*, 1985) and 1 M (de Haas *et al.*, 1990). The final persulphate concentration was fixed at 1% potassium persulphate (0.037 M) since this corresponded closely with 0.8% ammonium persulphate (0.035 M) in *Standard Methods* (1985). Standard curves were prepared from standard solutions of dipotassium hydrogen orthophosphate (K_2HPO_4) carried through the respective digestion regimes. The same sample of activated sludge mixed liquor (from a laboratory unit exhibiting enhanced biological P removal) was subjected to all three digestion regimes at dilutions of 6.66, 4 and 2-fold.

In order to establish a control procedure against which the persulphate digestion regimes could be tested, a carbonate fusion digestion procedure was used. This method had been the standard procedure for the total P digestion in the Water Quality Engineering Laboratory at UCT prior to the work of Burke *et al.* (1986). The carbonate fusion procedure is described in detail by Rabinowitz and Marais (1980). In summary, it involves the following steps:

- Mixed liquor (5 mℓ) plus distilled water (20 mℓ) were placed in a platinum crucible and evaporated to dryness by gentle heating over a boiling water bath;
- Sodium carbonate (½ teaspoon) was added and the crucible was heated strongly over a Bunsen burner until the carbonate melted and turned clear;
- The crucible was cooled and the residue dissolved in 50% (v/v) nitric acid (ca. 10 mℓ), using a watch glass to catch splashing due to CO_2 evolution. Small increments of the nitric acid solution were added until CO_2 evolution stopped and the residue was completely dissolved;
- The contents of the crucible were transferred quantitatively to a 25 mℓ volumetric flask, diluted to the mark with 50% nitric acid, and the orthophosphate concentration determined by the vanadate-molybdate method described elsewhere in this section. It was found that a blank consisting of 50% v/v nitric acid gave an absorbance to within 0.002 of that for very dilute (0.2% v/v) nitric acid only. Orthophosphate standards made up in 0.2% v/v nitric acid were therefore considered appropriate for the carbonate fusion method.
- The above steps were carried out for six replicates.

The results of the above-mentioned experiment are given in Table 2.1. The digestion method using 1 M final sulphuric acid concentration failed because all tubes (including blanks and

standards) produced a uniform orange colour upon addition of the colour reagent for orthophosphate determination. Presumably this was due to the high acid strength and is analogous to the inhibition of colour development at high acid concentrations in the molybdate-ascorbic acid method (de Haas *et al.*, 1990).

Table 2.1 shows that, relative to the carbonate fusion method, sulphuric acid-persulphate digestion at 0.1M H_2SO_4 gave acceptable recovery of total P, while that at 0.02 M H_2SO_4 did not. This indicates a deficiency in the method of Burke *et al.* (1986), making it inadequate for determination of phosphorus in mixed liquor samples. For such samples, the recommendations in *Standard Methods* (1985) should be followed.

In view of the above, the standard method adopted for total P digestion in this study was as follows:

- Sample (20 mℓ) pre-diluted with distilled-deionised water to contain 1 to 100 mgP/ℓ was transferred to a 50 mℓ rimless test tube (*Note: For samples of 1 M NaOH extracts, these were neutralised by taking 10 mℓ sample and adding 10 mℓ 1 M HCl, giving an initial dilution of two-fold);*
- 0.6 M H_2SO_4 (5 mℓ) and freshly dissolved 6% m/v $K_2S_2O_8$ (5 mℓ) were added;
- The tube was covered with aluminium foil and autoclaved in a pressure cooker at 100 kPa (15 lbs/ in^2) for 1 hour;
- The tubes were cooled to room temperature and filtered (where necessary) through ashless filter paper (Whatman No. 41 or equivalent);
- An aliquot (5 mℓ) of each was taken for orthophosphate determination (see section 2.3).

Orthophosphate (ortho P) standards in the range 5 to 100 mgP/ℓ (see section 2.3) were included with every total P run and passed through the above-mentioned digestion procedure. A typical standard curve for this method is given in Figure 2.1.

Table 2.1: Results of Total P determination of one mixed liquor sample (from BEPR plant) using digestion by sulphuric acid- persulphate and carbonate fusion methods.

Method	Linear regression for standard curve of absorbance (470 nm)		Result for mixed liquor Total P (mgP/ℓ)	Dilution	% Recovery
Carbonate fusion	1/Slope: Y-Intercept: R^2:	80.49 0.011 0.9998	146.9	5	100% (assume)
0.02 M H_2SO_4 1% m/v $K_2S_2O_8$	1/Slope: Y-Intercept: R^2:	118.83 0.066 0.9999	107.0 112.2 110.1	6.66 4 2	73% 76% 75%
0.1 M H_2SO_4 1% m/v $K_2S_2O_8$	1/Slope: Y-Intercept: R^2:	118.85 0.068 0.9997	140.2 140.2 156.2 (Ave. 145.5)	6.66 4 2	95% 95% 106% (99%)

2.2.2 Molybdate-ascorbic method

In cases where the effluent total P was < 1 mgP/ℓ, the vanadate-molybdate method became unreliable. For such samples, the molybdate-ascorbic acid method (*Standard Methods, 1985,* as described by de Haas *et al.,* 1990) was applied with one exception: ortho P standards (range 0.2 to 1.5 mgP/ℓ) were carried through the digestion process described under 2.2.1 with this method. It was found that with 1% potassium persulphate used in the digestion (see section 2.2.1), colour development at room temperature was delayed. Accordingly, a period

of 2h for colour development at room temperature was allowed, after which a standard curve comparable to that for ortho P was obtained, taking dilution from the digestion reagents into account (Figure 2.2).

2.3 ORTHOPHOSPHATE METHOD

2.3.1 Vanadate-molybdate spectrophotometric method

This method was selected since it has been reported to obey Beer's Law up to 300 mgP/l (Burke *et al.*, 1986), which is the range for mixed liquor samples of activated sludge. It was also suitable for influent and effluent samples from the laboratory-scale plants used in this study since phosphate was added to the influent in most experiments. The performance of the method was only tested up to 100 mgP/ℓ, which was adequate for the experiments performed in this investigation and gave absorbances up to ca. 0.9 and 0.6 respectively for ortho P and total P (see Fig. 2.1). According to Peters *et al.* (1974), in spectrophotometry the ideal range for absorbances is 0.2 to 0.7, with diminished accuracy at low and high absorbance.

The method used was that described by Burke *et al.* (1986). A colour reagent was prepared as follows:

- Solution A: 20 g ammonium molybdate tetrahydrate was dissolved in ± 250 mℓ distilled water;
- Solution B: 1 g ammonium metavanadate was dissolved in ± 200 mℓ distilled water and 40 mℓ conc. nitric acid;
- Solutions A and B were mixed, a further 100 mℓ conc. nitric acid added and diluted to 1ℓ with distilled water after cooling.

It was found that the mixed vanadate-molybdate reagent has a limited shelf life. It should be kept (in the dark) for a maximum of approximately one week, and should not be used if a precipitate forms in the bottom of the bottle.

Effluent samples containing particulate material were filtered through Whatman no. 41 paper (or equivalent) before the determination. For each ortho P determination, 5 mℓ sample (pre-diluted if necessary into the range 1 to 100 mgP/ℓ) was mixed with 5 mℓ colour reagent and colour development allowed for 30 minutes at room temperature. The absorbance was read at 470 nm using a spectrophotometer with a flow cell of 1 cm pathlength against a distilled water blank. In cases where samples were coloured or slightly turbid (even after paper filtration), a blank correction was performed in which the absorbance at 470 nm of 5 mℓ sample plus 5 mℓ distilled water (instead of colour reagent) was read against distilled water and subtracted from that for the sample with colour reagent.

A stock standard (100 mgP/ℓ) was prepared from 562.8 mg dipotassium hydrogen phosphate (K_2HPO_4) dissolved in ca. 500 mℓ distilled-deionised water to which conc. nitric acid (2 mℓ) was added as a preservative, and the solution made up to a final volume of 1ℓ with distilled-deionised water. Working standards of 5, 10 , 15, 25 and 50 mgP/ℓ were prepared from the stock standard by dilution with distilled-deionised water also containing 2% v/v nitric acid. Standards were included in each run for ortho P or total P (see 2.2.1). A typical standard curve for this method is given in Figure 2.1.

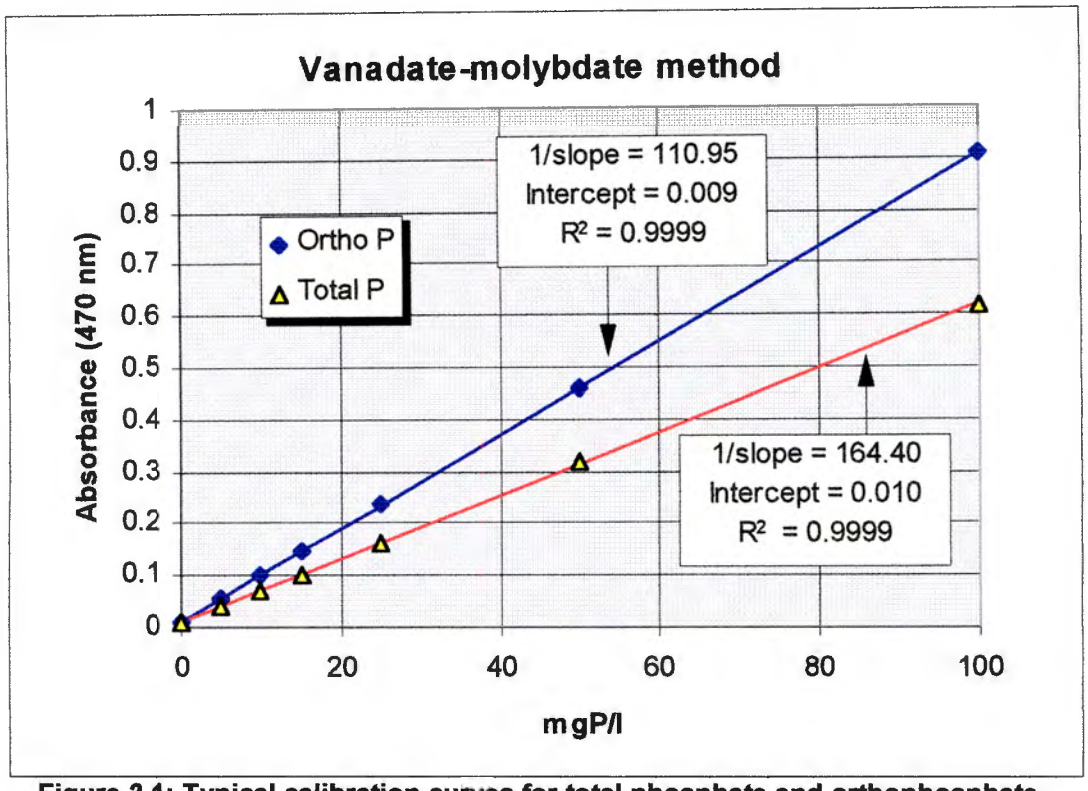


Figure 2.1: Typical calibration curves for total phosphate and orthophosphate determination by the vanadate-molybdate method. Path length = 1 cm.

2.3.2 Molybdate-ascorbic acid spectrophotometric method

For certain samples it was not possible to use the vanadate-molybdate ortho P method because interference was produced by the sample matrix. The most common example was sodium hydroxide extracts of activated sludge where 1M NaOH produced a dark blue complex with the vanadate-molybdate colour reagent. Neutralisation of the undiluted extract prior to the analysis was not possible since this produced a precipitate in the sample (probably protein-nucleic acid complexes and potentially including other phosphate species). The simplest alternative was to dilute the sample approximately twenty-fold and then to neutralise with an appropriate aliquot of HCl (e.g. 1 mℓ of 1M HCl per mℓ extract in 1M NaOH - this gave no visible precipitate). This was followed by further dilution of the sample to a total of 25-fold, and determination of ortho P using the molybdate-ascorbic acid method. This method has a linear range of approximately 0.01 to 1 mgP/ℓ (*Standard Methods*, 1985). Details of the exact method used here have been described by de Haas *et al.* (1990). In the case of coloured samples (e.g. NaOH extracts of activated sludge were coloured brown), a blank correction was performed by substituting distilled-deionised water for colour reagent, and subtracting the absorbance from that for the sample with colour reagent.

A typical standard curve for this method is shown in Figure 2.2.

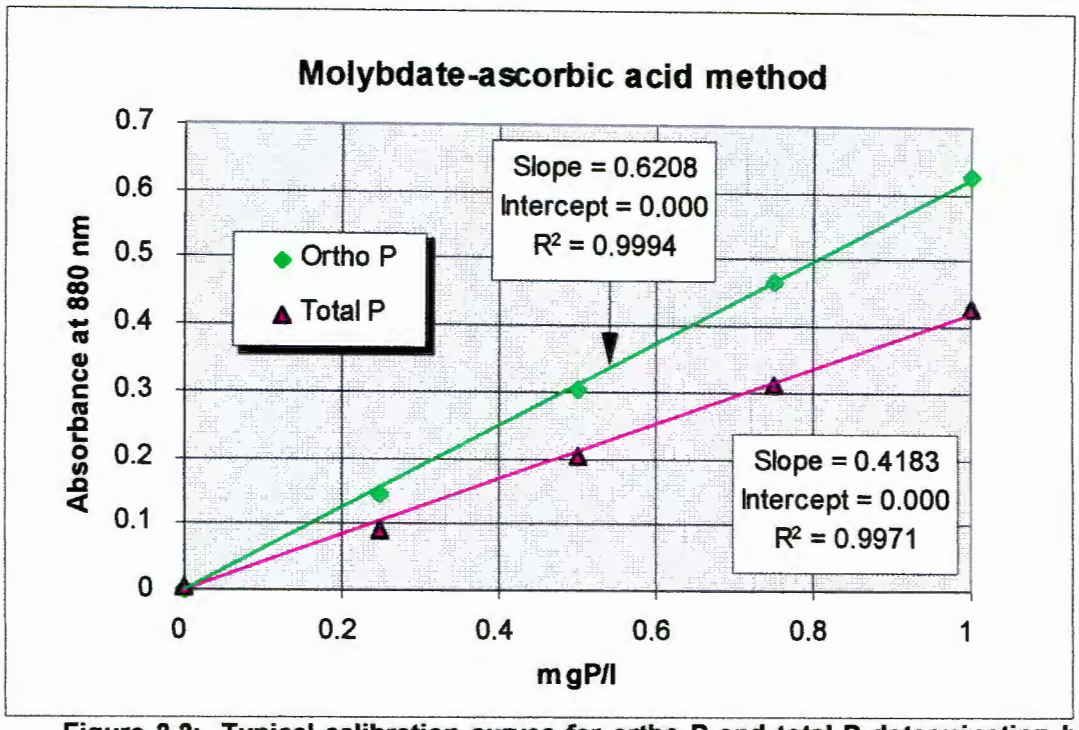


Figure 2.2: Typical calibration curves for ortho P and total P determination by the molybdate-ascorbic acid method. Path length = 1 cm.

2.4 FRACTIONATION PROCEDURES

As outlined in section 2.1 above, a suitable fractionation procedure was required to broadly distinguish biologically-stored forms of phosphate (mainly poly P) from chemically precipitated forms of phosphate (mainly ortho P) in activated sludge. A procedure using cold perchloric acid was selected on the basis that it appeared to meet this requirement, was relatively simple to perform, and did not require specialised analytical equipment.

2.4.1 Cold perchloric acid (PCA) procedure

De Haas (1989) reviewed the use of cold perchloric acid (PCA) for extraction of phosphate compounds from biomass, including activated sludge. Proteins, which form the structural backbone of all living matter, are precipitated in cold perchloric acid. In various extraction procedures dating back more than fifty years, PCA (as well as trichloroacetic acid, or TCA) has been used, either on its own, or in combination with ethanol, acetone or ethyl ether for crude extraction of nucleotides, nucleic acid, phospholipids and similar phosphorus compounds from animal, plant, fungal or bacterial biomass. Most of the protein-related complexes are left in the pellet. In application to activated sludge samples from BEPR systems, PCA (and TCA) have been found to be effective for extracting poly P (*inter alia* Mino *et al.*, 1985; de Haas, 1989). PCA (but not TCA) also has been found to be effective in dissolving chemical precipitates of phosphate (e.g. ferric and calcium precipitates) and substantive evidence has been put forward that the ortho P content of cold PCA extracts of activated sludge is a measure of the chemically bound fraction (de Haas, 1989). Since PCA is a strong acid, one may expect hydrolysis of polyphosphate (poly P), even at cold temperatures. De Haas (1989, 1991) showed that fragmentation of poly P to shorter chain lengths had apparently occurred in extracts from activated sludge and that the degree of hydrolysis appeared to be related to the type of acid (PCA or TCA) used. (For this reason, the definition of "acid soluble poly P" or "low molecular weight poly P" frequently found in the literature should be seen primarily in the context of the extraction procedure itself - de Haas,

1991). Nevertheless, the rate of hydrolysis of poly P to ortho P in cold (0 to 4 °C) PCA was found to be slow (de Haas, 1989; Kerdachi and Roberts, 1985). Provided ortho P analysis followed the extraction step directly, the contribution of poly P hydrolysis to the ortho P result may be neglected (de Haas, 1989). Thus, although some hydrolysis of poly P can be expected in the cold PCA extraction, a negligible amount of ortho P is formed. It should be remembered that the aim in such procedures is not to extract "intact" chains of poly P, for which more complex procedures such as those of Müssig-Zufika *et al.* (1994) would be more appropriate (see Chapter 1, section 1.7). Rather, the aim here is to broadly distinguish phosphate in the sludge matrix which is strictly of biological origin (poly P) from that which involves chemical precipitation (ortho P). For this purpose, the cold PCA extraction is suitable. In the cold PCA extract, the ortho P concentration would reflect the chemically precipitated phosphorus[1], and the (total P - ortho P) concentration the biological phosphorus, comprised mainly of poly P and nucleic acid P.

De Haas (1989) found that the extraction times with cold PCA for activated sludge samples could be reduced to around 5 min., in three or four replicate steps, without significantly compromising the extraction of poly P or chemical precipitates. Since this would not only reduce the potential for poly P hydrolysis, but also speed up the fractionation procedure as a whole, it was decided to adopt three 5 min. extractions at 0 to 3 °C in the basic procedure used here. Similarly, several preliminary experiments showed that the fractionation procedures described by de Haas (1989) could be simplified as follows:

- The nucleic acid fraction is the third major group of phosphorus-containing compounds in activated sludge biomass (after poly P and ortho P of "chemical precipitation" origin) (de Haas, 1989). This phosphorus fraction also may be extracted into cold PCA; the remainder will be largely extracted in a subsequent alkaline step (if used), or will reside largely in the residue (de Haas, 1989). The nucleic acid content of a range of sludges was found to be relatively constant (de Haas, 1989 - see Chapter 1, section 1.7). Thus, poly P could be loosely grouped with the nucleic acids and termed "complex P" to distinguish it from ortho P. Hence, in the PCA extract (or subsequent NaOH extract) :

  Poly P + Nucleic acid P + (phospholipids? + ...?) = Complex P = Total P - Ortho P

- For the purposes of comparison with the mathematical model predictions of activated sludge poly P content (see 2.4.6 below), an estimate of the poly P content of the extracts could be obtained by subtracting the expected nucleic acid P from the sum of the complex P fractions (PCA+ Residue, or PCA + NaOH + Residue).

The above simplifications led to the basic PCA procedure described in Table 2.2.

2.4.2 Testing the cold PCA fractionation procedure

The cold PCA procedure was tested on various samples of activated sludge :

1. Samples of activated sludge were taken from the aerobic zone of a modified UCT (MUCT) laboratory system operated at a 20 d sludge age with cyclic (12 h) feed and exhibiting BEPR (Wentzel *et al.*, 1993). These were compared with a sample taken from a completely aerobic 2.5 d sludge age unit, also with cyclic (12 h) feed, used for readily biodegradable COD (S_{bsi}) determination (Ekama *et al.*, 1984).
2. Samples were taken from a unit set up for the development of an "enhanced culture" of BEPR organisms by feeding incremental concentrations of sodium acetate (50; 100; 250 mg/ℓ as COD) and decremental amounts of sewage such that the target influent total COD was a constant 500 mg/ℓ.
3. Samples of mixed liquor taken from the above-mentioned "enhanced culture" unit were spiked with dissolved ortho P (50 mgP/ℓ or 1.62 mmol P/ℓ). Ferric chloride (524 mg/ℓ as $FeCl_3$ or 3.23 mmol Fe/ℓ) was then dosed to achieve a 2:1 molar ratio of Fe:P, based on the spiked ortho P. A control sample of mixed liquor was treated with the same dose of

[1] From measured values in the literature, de Haas (1989) calculated that the ortho P of biological origin is negligible.

ferric chloride, but without phosphate spike. In both cases, the pH was corrected to 7.0 with a known volume (8 to 12 mℓ) of 10% (m/v) sodium bicarbonate solution. A mixing period of 15 min. was allowed for precipitation to proceed.

4. Some of the enhanced culture samples were subjected to an anaerobic P-release batch test prior to the fractionation procedure. The batch test involved the following steps:
    - Aliquots (50 mℓ) of mixed liquor were each placed in the centrifuge tube (used for performing the extractions) and a known amount of sodium acetate was added.
    - The amount of acetate added was calculated as follows:
      It was assumed that the mixed liquor sample would contain a maximum of approx. 300 mgP/ℓ poly P which could be biologically released and that the nitrate concentration in the mixed liquor would not exceed 20 mg N/ℓ. It was accepted that approx. 0.5 mg P release may be expected per mg acetate COD added (Wentzel *et al.*, 1990) and that approx. 8.6 mg readily biodegradable COD would be used per mg N denitrified (WRC, 1984). On this basis, a maximum of approx. 800 mg/ℓ acetate (as COD) would be required for the batch test. In order to ensure that excess acetate was always present, an amount of sodium acetate equivalent to 1000 mg/ℓ as COD (64 mg per 50 mℓ mixed liquor aliquot) was added at the start of the batch test.
    - The acetate was dissolved by inverting the tubes several times over the first 5 minutes;
    - The tubes were allowed to stand for 4 h, inverting approx. once every hour [2];
    - The tubes were then centrifuged (start of the fractionation procedure see Table 2.2, step 2).

University of Cape Town

Table 2.2 ...../

[2] Experience with batch tests of this type using enhanced cultures has shown that P release is essentially complete after 3h under anaerobic conditions in the presence of excess acetate (Wentzel *et al.*, 1989).

Table 2.2: Basic PCA fractionation procedure as applied to activated sludge.
Note: The mixed liquor sample should contain ca. 2500 mg VSS/ℓ. Refer to Table 2.11 below for optional pre-concentration step.

Step	Procedure	Sample preparation and Analysis	Interpretation
1.	Transfer one aliquot (50 mℓ) of mixed liquor to each of two centrifuge tubes with screw cap lids for sealing. *(Note: if available, one tube of 100 mℓ may be used; double subsequent vols. below)*	Analyse original mixed liquor for: • total P • MLSS, VSS [Take precaution to mix sample well and perform in duplicate at least]	
2.	Centrifuge at 3000 rpm (max. 2000 *g*) for 5 min. Collect and pool supernatant and retain pellet.	Label supernatant *SUP*. Retain.	Original supernatant corresponding to "effluent" at point of sampling
3.	Add 0.9% (m/v) NaCl (20 mℓ) to pellet in each tube. Cap and shake well to mix/ re-suspend.		
4.	Centrifuge at 3000 rpm (max. 2000 *g*) for 5 min. Collect and pool with supernatant with that marked *SUP (step 2).* Retain pellet.	Filter about half *SUP* sample through ashless filter paper (Whatman No. 41 or equivalent). *SUP* and *filtered SUP (fSUP)* analysed for • ortho P immediately • total P [Correct by a factor of 1.2 i.e. 60 ml extract per 50 ml original mixed liquor]	"Interstitial" loosely bound phosphate pooled with that present in the original supernatant.
5.	Extract three times with ice-cold 0.5 M PCA (20 mℓ) in a refrigerated water bath (0-3°C) for 5 min. each time. Centrifuge between extractions (as before but preferably with centrifuge refrigerated at 5°C) and keep the extracts ice cold. Retain residue.	Pool extracts and label *PCA*. Filter about half *PCA* sample (see step 4). *PCA* and *filtered PCA (fPCA)* analysed for: • ortho P **immediately** • total P [Correct by a factor of 1.2 i.e. 60 ml extract per 50 ml original mixed liquor]	Acid-soluble complex P (poly P and nucleic acids) extracted as well as chemical precipitates (ortho P). ["Fatty" fragments may float in the PCA extract but these have a small total P content, as judged from the difference: *PCA- fCPA.*]
6.	Residue resuspended by serial washing in a total of 50 mℓ distilled water per centrifuge tube.	Analyse residue (*RES*) for: • total P [Take precaution to mix sample well and perform in duplicate]	Non acid-extractable P compounds grouped. Allows check for overall P mass recovery.

2.4.2.1 MUCT versus S_{bsi} unit

Results for the fractionation are set out in Table 2.3. It can be seen from Table 2.3 that the ortho P content of the PCA extract (on a VSS basis) from the MUCT unit (4.41 and 5.52 mgP/gVSS) was very similar to that of the S_{bsi} unit (4.32 mgP/gVSS), despite the two units exhibiting very different BEPR behaviour. The low value for this fraction suggests that chemical precipitation mechanisms were not strongly present in either unit. This can be explained by the low hardness of water in the Cape Town area from which the influent sewage to these units was derived, and the fact that no chemical precipitant was dosed.

Furthermore, the fractionation procedure appeared to be capable of correctly distinguishing biologically stored phosphate (poly P) in mixed liquor. The PCA extract from the MUCT unit contained significant amounts of complex P (25.18 and 30.26 mgP/gVSS), which may be reasonably explained by the storage of poly P in the mixed liquor of this unit. In contrast, the PCA extract from the S_{bsi} unit contained very little complex P (1.80 mgP/gVSS); this was expected since this unit did not exhibit BEPR. Thus the method would seem to be capable of correctly distinguishing poly P in broad terms, although poly P is not distinguished from other forms of complex P (e.g. nucleic acid).

Assuming that the residue contains a negligible amount of ortho P (see 2.4.4), with little error the total P content of the residue may be taken to be equal to complex P. On this basis, the S_{bsi} unit contained a total complex P (PCA extract + residue) of about 17 mgP/gVSS, which is in good agreement with the nucleic acid content of sludges from full-scale activated sludge plants measured by more direct methods (de Haas, 1989). Since the poly P content of the sludge from the S_{bsi} unit is negligible, what removal did occur may be explained in terms of biomass growth: the observed total P content of S_{bsi} unit sludge was 25.4 mgP/gVSS, which agrees reasonably well with the P content of heterotrophic non-poly P organism active and endogenous masses (30 mg P/gVSS) accepted by Wentzel *et al.* (1990) for modelling purposes. From the data presented here, approximately 5 mgP/gVSS of this may actually be due to natural P precipitation reactions for Cape Town (low hardness) sewage.

Overall, the data in Table 2.3 suggests that the cold PCA fractionation method gave reasonable results which were in agreement with general observations of the BEPR phenomenon.

Table 2.3: Fractionation results for activated sludge samples from MUCT and S_{bsi} unit.

Sample/ Extract	Ortho P		Total P		Complex P (Total P - Ortho P)	
	mgP/ℓ	mgP/gVSS	mgP/ℓ	mgP/gVSS	mgP/ℓ	mgP/gVSS
MUCT unit 13/8/93 VSS = 2772 mg/ℓ						
SUP.	2.41	0.87	2.11	0.76	(-0.3)	0
PCA	**12.21**	**4.41**	96.10	34.67	**83.89**	**30.26**
RES.	-	-	47.71	17.22	(47.71)	(17.22)
Mixed liquor	-	-	**140.04**	**50.52**		
Sum of extracts	-	-	145.92	52.65		
Recovery	-	-	104%	104%		
MUCT unit 27/8/93 VSS = 2908 mg/ℓ						
SUP.	15.84	5.45	15.67	5.39	(-0.17)	0
PCA	**16.04**	**5.52**	**89.26**	**30.69**	**73.22**	**25.18**
RES.	-	-	67.52	23.22	(67.52)	(23.22)
Mixed liquor	-	-	**166.62**	**57.30**		
Sum of extracts	-	-	172.45	59.30		
Recovery	-	-	103%	103%		
S_{bsi} unit 27/8/93 VSS = 1106 mg/ℓ						
SUP.	7.22	6.53	5.86	5.30	(-1.36)	
PCA	**4.78**	**4.32**	**6.77**	**6.12**	**1.99**	**1.80**
RES.	-	-	16.25	14.69	(16.25)	(14.69)
Mixed liquor	-	-	**28.12**	**25.43**		
Sum of extracts	-	-	29.05	26.11		
Recovery	-	-	103%	103%		

2.4.2.2 Enhanced culture development

Table 2.4 shows that as the enhanced culture developed, the complex P fraction in the PCA extract increased by nearly three-fold, from 38.15 to 109.50 mgP/gVSS. This can be ascribed to the increase in poly P storage in response to the increase in acetate supplemented to the influent. In contrast, the ortho P content of the PCA fraction remained virtually constant, indicating that the chemical precipitate fraction remained largely unchanged while the biological P removal mechanism developed. This provides further evidence that the fractionation procedure can correctly distinguish chemically and biologically bound P. It also indicates that the degree of poly P hydrolysis in the fractionation procedure is negligible in so far as it does not affect the ortho P result of the PCA extract (refer to Chapter 1 and discussion of the findings of Müssig-Zufika *et al.*,1994).

Table 2.4: Fractionation results for samples of "enhanced culture" activated sludge for different stages of incremental acetate COD (mg/ℓ) supply in the feed.

Sample/ Extract	Ortho P		Total P		Complex P (Total P - Ortho P)	
	mgP/ℓ	mgP/gVSS	mgP/ℓ	mgP/gVSS	mgP/ℓ	mgP/gVSS
50 mg/ℓ acetate 24/9/93 VSS = 2395 mg/ℓ						
SUP.	13.90	5.80	14.02	5.85	0.12	0.05
PCA	**13.01**	**5.43**	**104.39**	**43.59**	**91.38**	**38.15**
RES.	-	-	58.64	24.48	-	-
Mixed liquor	-	-	**181.15**	**75.64**	-	-
Sum of extracts	-	-	177.05	73.93	-	-
Recovery	-	-	98%	98%	-	-
100 mg/ℓ acetate 5/10/93 VSS = 2350 mg/ℓ						
SUP.	11.49	4.89	11.79	5.02	0.30	0.13
PCA	**15.67**	**6.67**	**186.24**	**79.25**	**170.58**	**72.58**
RES.	-	-	68.93	29.33	-	-
Mixed liquor	-	-	**246.48**	**104.89**	-	-
Sum of extracts	-	-	266.96	113.60	-	-
Recovery	-	-	108%	108%	-	-
250 mg/ℓ acetate 31/10/93 VSS = 2088 mg/ℓ						
SUP.	27.63	13.23	28.34	13.57	0.71	0.34
PCA	**12.57**	**6.02**	**241.20**	**115.52**	**228.63**	**109.50**
RES.			39.29	18.82	-	-
Mixed liquor			**316.11**	**151.39**	-	-
Sum of extracts			308.83	147.91	-	-
Recovery			98%	98%	-	-

Table 2.5: Fractionation results for samples of "enhanced culture" activated sludge (developed with acetate influent supplement) after addition of ferric chloride with or without added dissolved ortho P in two batch tests. Refer to Table 2.4 for comparison with control sludges (before dosing).

Sample/ Extract	Ortho P		Total P		Complex P (Total P - Ortho P)	
	mgP/ℓ	mgP/gVSS	mgP/ℓ	mgP/gVSS	mgP/ℓ	mgP/gVSS
100 mg/ℓ acetate 5/10/93 VSS = 2350 mg/ℓ 3.23 mmol/ℓ Fe added as $FeCl_3$	**No P added**					
SUP.	0.29	0.12	0.73	0.31	0.44	0.19
PCA	**24.56**	**10.45**	**175.94**	**74.87**	**151.38**	**64.42**
RES.	-	-	86.86	36.96	-	-
Mixed liquor	-	-	**248.15**	**105.60**	-	-
Sum of extracts	-	-	263.53	112.14	-	-
Recovery	-	-	106%	106%	-	-
100 mg/ℓ acetate 5/10/93 VSS = 2350 mg/ℓ 3.23 mmol/ℓ Fe added as $FeCl_3$	**50 mgP/ℓ added as K_2HPO_4**					
SUP.	5.57	2.37	5.73	2.44	0.16	0.07
PCA	**68.66**	**29.22**	**213.09**	**90.68**	**144.43**	**61.46**
RES.	-	-	93.72	39.88	-	-
Mixed liquor	-	-	**295.22**	**125.63**	-	-
Sum of extracts	-	-	312.54	133.00	-	-
Recovery	-	-	106%	106%	-	-
250 mg/ℓ acetate 31/10/93 VSS = 2088 mg/ℓ 3.23 mmol/ℓ Fe added as $FeCl_3$	**No P added**					
SUP.	0.41	0.20	0.24	0.12	(-0.17)	0
PCA	**36.61**	**15.62**	**247.44**	**118.51**	**214.83**	**102.89**
RES.	-	-	58.19	27.87	-	-
Mixed liquor	-	-	**317.20**	**151.92**	-	-
Sum of extracts	-	-	305.87	146.49	-	-
Recovery	-	-	96%	96%	-	-
250 mg/ℓ acetate 31/10/93 VSS = 2088 mg/ℓ 3.23 mmol/ℓ Fe added as $FeCl_3$	**50 mgP/ℓ added as K_2HPO_4**					
SUP.	12.93	6.19	13.45	6.44	0.52	0.25
PCA	**65.11**	**31.18**	**281.25**	**134.70**	**216.14**	**103.52**
RES.	-	-	62.41	29.89	-	-
Mixed liquor	-	-	**368.12**	**176.30**	-	-
Sum of extracts	-	-	357.11	171.03	-	-
Recovery	-	-	97%	97%	-	-

Table 2.6: P mass balances for the fractions obtained in ferric chloride batch experiments (refer to Tables 2.4 and 2.5).

FRACTION	ΔOrtho P mgP/gVSS	ΔComplex P mgP/gVSS	ΔOrtho P mgP/gVSS	ΔComplex P mgP/gVSS
Date:	5/10/93	5/10/93	5/10/93	5/10/93
Batch test:	Fe only	Fe only	P + Fe	P + Fe
SUP	- 4.77	0.06	- 2.52	- 0.06
PCA	+ 3.78	- 8.16	+ 22.55	- 11.52
RES	?	+ 7.63	?	+ 10.55
Σ	-0.99	- 0.47	+ 20.03	- 0.57
Σ overall (Recovery %)	- 1.46 (N/A)		+ 19.46 (92%)	
Δ Mixed liquor total P (Recovery %)	+ 0.53 (N/A)		+ 20.74 (97%)	
P added	0		21.28	
Date:	31/10/93	31/10/93	31/10/93	31/10/93
Batch test:	Fe only	Fe only	P + Fe	P + Fe
SUP	- 13.04	- 0.34	- 7.04	- 0.09
PCA	+ 9.60	- 6.61	+ 25.16	- 5.98
RES	?	+ 9.05	?	+ 11.07
Σ	- 3.44	+ 2.10	+ 18.12	+ 5.00
Σ overall (Recovery %)	- 1.34 (N/A)		+ 23.12 (97 %)	
Δ Mixed liquor total P (Recovery %)	- 0.53 (N/A)		+ 24.91 (104%)	
P added	0		23.95	

(N/A) : Not applicable

2.4.2.3 Ferric chloride addition in batch tests

Table 2.5 shows the effect of ferric chloride addition on fractionation results for two of the original sludge samples given in Table 2.4. P mass balances for the respective fractions (after P and/or Fe addition), relative to the fractions from the original sludge are shown in Table 2.6.

Table 2.6 shows that good recovery of added phosphate was obtained in the sludge fractions and mixed liquor. Iron addition at a 2:1 molar ratio relative to the added ortho P was apparently in excess of the stoichiometric amount since ortho P removal from the original sludge supernatant also occurred (observed Fe:P removal molar ratio = 1.55 to 1.66). Hence, although the increment in the PCA ortho P fraction was numerically similar to the added ortho P, a more complex transformation took place in the sludge. Most notable was a decrease in the PCA complex P fraction and an increase in the residue (RES) total P fraction. This observation has one of two explanations: either (i) iron addition resulted in rapid hydrolysis of a portion of the acid-soluble poly P pool and the resultant ortho P was bound with iron in a non-acid-soluble form; or (ii) iron complexed with a part of the poly P pool and converted it into an non-acid-soluble form (i.e. non-cold PCA extractable). The loss of poly P from the PCA extract appeared to be smaller in the second experiment (31/10/95) than the first (5/10/95), possibly because the amount of available iron after reaction with dissolved ortho P was smaller in the former, due to the higher supernatant ortho P concentration at the start (Table 2.5).

In summary, the results in Table 2.6 confirm that the cold PCA fractionation procedure is able to quantitatively recover ferric-phosphate precipitate formed from added Fe and ortho P. The results also clearly demonstrate that the addition of Fe causes an apparent shift in P from complex PCA fraction to the residue. It raises the question of whether an alkaline

soluble complex between Fe and poly P forms in the mixed liquor biomass, or whether such complexation is an artefact of the fractionation procedure itself. This aspect will be further examined in section 2.4.7 below.

2.4.2.4 Anaerobic P release batch tests

Table 2.7 gives the results of a fractionation experiment conducted on aerobic mixed liquor taken from a "semi-enhanced culture" fed 100 mg/ℓ acetate COD. Prior to the fractionation, the mixed liquor sample was divided into two sub-samples. One was fractionated immediately and the other was subjected to a 4h anaerobic period after adding 1000 mg/ℓ COD as sodium acetate. Fractionation followed directly after the anaerobic period. The original (filtered) mixed liquor sample contained 12.9 mg N/ℓ as nitrate. The expected COD loss due to denitrification in the early part of the batch test would be 8.6 mgCOD/mg N denitrified (i.e. 110 mg COD/ℓ). Hence 890 mg acetate COD/ℓ would be available for P release. This should be sufficient for release of approximately 445 mgP/ℓ (Wentzel *et al.*, 1990). Prior to the experiment it was determined that the mixed liquor total P content did not exceed 300 mgP/ℓ, meaning that a theoretical acetate excess of $\geq$ 50% had been supplied to the batch test.

From the results in Table 2.7 it can be seen that almost 80% of the PCA extract complex P was degraded in the anaerobic period. This phosphate could be accounted for entirely as ortho P released to the supernatant (taking total P recovery into account). The PCA ortho P and residue fractions remained virtually unchanged before and after the anaerobic period. Thus, the P release in the anaerobic test is derived solely from the PCA extract complex P, i.e. poly P. On release, this P moved to the supernatant as ortho P; very little was precipitated [3].

The data in Table 2.7 further corroborate the view that the cold PCA fractionation procedure is able to reliably distinguish between activated sludge ortho P (chemical precipitate) and sludge complex P (mainly poly P) fractions. Under anaerobic conditions over a period of 4h in the presence of excess acetate, for a semi-enhanced culture it was found that not all the phosphate present in the mixed liquor batch was released; rather, only about 80% of the phosphate identified as "complex P" (corresponding to release of about 146 mgP/ℓ), or about 60% of the mixed liquor total P was released[4]. This is in approximate agreement with the finding by Wentzel *et al.* (1989) for fully enhanced cultures that about 70% of the mixed liquor total P could be released in the presence of excess acetate (corresponding to release of about 300 mgP/ℓ).

It is worth noting from Table 2.7, that the poly P estimate from the extent of anaerobic P release was 66.7 mgP/gVSS. This gives a difference of 1.9 mg P/g VSS from the complex P estimate by fractionation, which may be attributable to cell components other than poly P (mainly nucleic acids). Furthermore, approximately 7.6 mg P/g VSS was unaccounted for (i.e. 7% of mixed liquor TP, from recoveries in Table 2.7), giving a total of 9.5 mg P/g VSS which may be attributable mainly to nucleic acids. This is in close agreement with approximation applied in section 2.4.6 below on the basis of the results of de Haas (1989) for "semi" enhanced cultures.

...../ Table 2.7

[3] It should again be noted that that the mixed liquor used in this batch test was derived from a laboratory-scale unit (see above) which had never been dosed with chemical precipitants and which received an influent from an area with soft water (Cape Town). A large number of similar batch tests were later conducted using mixed liquor derived from units operated with and without the addition of metal precipitants; an increase in the chemical precipitate (ortho P) fractions after the period of anaerobic P release was sometimes found. These results are described in Chapters 3, 4 and 5 (sections 3.3.3.4; 4.3.7; 4.3.11 and 5.3.6). Refer also to section 2.4.7 of this chapter.

[4] The average extent of P release found in approximately twenty such anaerobic batch tests for mixed liquor samples from the Control pilot plant in this study (Chapters 3,4 & 5) was 62% of the total "complex P".

Table 2.7: Fractionation results before and after batch anaerobic P release test. Mixed liquor sample from semi-enhanced culture system fed 100 mg/ℓ acetate COD.

Sample/ Extract	Ortho P		Total P		Complex P (Total P - Ortho P)	
	mgP/ℓ	mgP/gVSS	mgP/ℓ	mgP/gVSS	mgP/ℓ	mgP/gVSS
BEFORE 22/10/93 VSS = 2522 mg/ℓ						
SUP.	16.28	6.46	16.68	6.61	0.40	0.16
PCA	**18.30**	**7.26**	**191.26**	**75.84**	**172.96**	**68.58**
RES.	-	-	40.85	16.20	-	-
Mixed liquor	-	-	**275.34**	**109.18**	-	-
Sum of extracts	-	-	248.33	98.65	-	-
Recovery	-	-	90%	90%	-	-
AFTER 22/10/93 VSS = 2252 mg/ℓ						
SUP.	166.43	65.99	163.14	64.69	(-3.29)	0
PCA	**19.99**	**7.93**	**57.83**	**22.93**	**37.84**	**15.00**
RES.	-	-	42.16	16.72	-	-
Mixed liquor	-	-	**275.34**	**109.18**	-	-
Sum of extracts	-	-	**263.13**	104.33	-	-
Recovery	-	-	96%	96%	-	-
Poly P estimate from anaerobic P release :					*150.15*	**66.67**

2.4.3 "Indirect" sludge ortho P method

According to Blonda *et al.* (1994), it is possible to measure the ortho P content of activated sludge by means of the conventional method for ortho P. Blonda *et al.* (1994) used the molybdate-ascorbic acid method described in *Standard Methods* (1989). The essence of this method is that an *unfiltered* sample is subjected to the colour-forming reaction. Prior to spectrophotometry, the sludge residue is filtered off. If the ortho P content of a filtered sample is measured concurrently, the difference between the ortho P content of the unfiltered and filtered samples yields the sludge ortho P content. With the terms used by Blonda *et al.* (1994):

Solid phase ortho P = Total ortho P (unfiltered) - Liquid phase ortho P (filtered).

The rationale behind this approach is that the ortho P determinations take place in an acid medium so that the period of colour development could serve both for extraction of sludge ortho P and simultaneous colorimetric reaction. This would obviate the need to extract (and separate) the sludge ortho fraction by a separate procedure such as that with cold perchloric acid (section 2.4.2 above).

It was decided to test this approach as a possible simplification of the fractionation procedure. Firstly, the molybdate-ascorbic acid method applied by Blonda *et al.* (1994) was tested. Secondly, it was recognised that the dilutions required when subjecting activated sludge samples to phosphate analysis with the ascorbic acid method (*Standard Methods*, 1985, 1989) increased the risk of dilution errors and entailed additional work. Since the vanadate-molybdate method for ortho P (see section 2.3.1 above) has a higher working range, it was tested in a similar manner to the "indirect method" described by Blonda *et al.* (1994). The vanadate-molybdate method was modified to give a final concentration of nitric acid equivalent to the sulphuric acid concentration in the ascorbic acid method (see box

insert). Accordingly, the amount of acid in the molybdate-vanadate reagent had to be reduced to one third of that normally used (i.e. from 140 to 47 mℓ/ℓ).

Molybdate - Ascorbic acid method

- Mixed reagent receives 5N H_2SO_4 (50 mℓ per 100 mℓ)
- Each test receives 8 mℓ mixed reagent per 50 mℓ sample
- Final H_2SO_4 concentration = 0.172 M = 0.345 N

Molybdate - Vanadate method

- Colour reagent contains 140 mℓ/ℓ conc. HNO_3 = 2.17 N (conc. HNO_3 = 70% m/m, S.G. = 1.42, i.e. 15.5 N)
- Each test gets 5 mℓ colour reagent per 5 mℓ sample
- Final HNO_3 concentration = 1.085 N

In order to establish whether the reduced acid concentration in the vanadate-molybdate method presented any problems with the colorimetric reaction itself, the conventional and modified molybdate-vanadate methods were compared using ortho P standards (Figure 2.3).

From Fig. 2.3 it can be seen that the reduction in acid concentration did not significantly affect colour development, producing a negligible increase in absorbance for the same range of standards (5 to 100 mgP/ℓ).

Table 2.8 shows the results of an experiment comparing the ascorbic acid and vanadate "indirect" methods applied to the same mixed liquor sample. The sample was taken from the aerobic zone of a "semi-enhanced" culture fed 50 mg/l acetate COD, and had a filtered ortho P concentration of 13.8 mgP/ℓ. From Table 2.8 it is clear that both methods gave less ortho P than that present in the filtered sample supernatant. This implies that the sludge ortho P component was zero (or negative, which is impossible). It was observed during the experiments that a significant part of the coloured complex which formed between the sludge solid phase and colour reagent, remained bound in the solid phase and, hence, was filtered off prior to spectrophotometry. This appeared to be a fundamental deficiency of the "indirect" method (Blonda *et al.*, 1994).

Table 2.8: "Indirect" ortho P determination (Blonda *et al.*, 1994) of the same sludge sample by two methods. The filtered sample (supernatant) contained 13.8 mgP/ℓ.

Method:	Molybdate-ascorbic acid	Molybdate-vanadate
Ortho P (mgP/ℓ) , unfiltered sample:	7.88	13.02

Table 2.9 shows the results of further attempts to compare the "indirect" method of sludge ortho P determination with the "direct" method of extraction into cold PCA (c.f. Blonda *et al.*, 1994). Table 2.9 shows that the "indirect" method recovered at best ca. 20% of the sludge ortho P determined by extraction. This finding is in contradiction with that of Blonda *et al.* (1994) who concluded that the direct and indirect methods do not give appreciably different results for sludge ortho P. One possible explanation for this contradiction is that in the procedure presented here (Tables 2.2 and 2.11), the cold PCA extraction procedure causes rapid hydrolysis of poly P to ortho P. However, this hypothesis would contradict the results presented in Section 2.4.2 above; moreover, the rate of hydrolysis of poly P to ortho in 0.5 M PCA at 0 to 4°C has been found to be sufficiently slow to be negligible (Kerdachi and Roberts, 1985; de Haas, 1989; Blonda *et al.*, 1994). A more likely explanation of the results in Table 2.9 is that proposed earlier, i.e. that a substantial amount of the ortho P-molybdate colour complex, formed in the "indirect" method when colour reagent is added to the mixed liquor sample, remains bound in the sludge matrix and is filtered off prior to the spectrophotometry.

For this reason, this method was rejected for subsequent use and the PCA extraction method retained (refer to section 2.4.5 and Table 2.11 below).

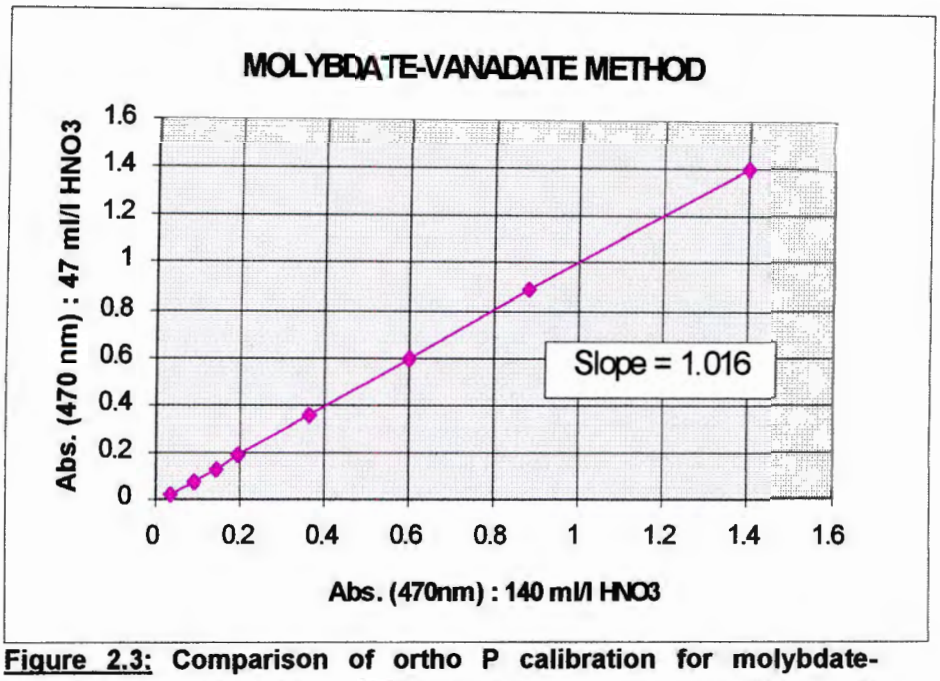


Figure 2.3: Comparison of ortho P calibration for molybdate-vanadate method with standard colour reagent (140 mℓ/ℓ nitric acid) and modified colour reagent (47 mℓ/ℓ nitric acid).

2.4.4 Inclusion of NaOH step in PCA fractionation procedure

The cold PCA fractionation procedure described in section 2.4.1 was applied to two parallel identical enhanced culture systems strongly exhibiting the BEPR mechanism: one system (the Test system) was dosed with chemical precipitant, while the other (the Control) was not. The results of these trials are detailed in Chapters 3, 4 and 5. To some degree during periods of alum addition, but more notably during periods of ferric chloride addition, it was observed that:

i. the complex P content of the PCA extract was decreased in the Test unit; and

ii. the total P content of the residue (RES) fraction in the Test unit was increased significantly compared to the Control.

This suggested that chemical dosing, particularly with ferric ions, encouraged the formation of a fraction which was not "acid-soluble" (i.e. not extractable into cold PCA). A similar observation was noted in batch tests with ferric chloride addition (see section 2.4.2.3). Röske and Schönborn (1994 a,b) noted that, according to Psenner *et al.* (1984), complexes/ precipitates of iron salts with either ortho P or poly P were considered extractable into alkaline bicarbonate-dithionite solutions[5]. However, the Psenner extraction procedure applied by Röske and Schönborn (1994 a,b) did not include a preceding acid step (e.g. PCA). For the purposes of this study, it was considered important to determine whether an increase in the RES fraction denoted an increase in the ortho P content of the sludge (as reported for iron addition in bench and full-scale trials by Röske and Schönborn, 1994 a,b), or whether this fraction represented an alkaline-extractable form of complex (poly) P. In order to make this possible, a 1M NaOH extraction step was included in the basic fractionation procedure

[5] Dithionite is a strong reducing agent.

described in Table 2.2. It was found that the time of extraction into 1M NaOH could be kept fairly short (30 min. + 15 min. + 15 min. in three steps) whilst still extracting virtually all the residue phosphate.

Table 2.10 gives an example of the effect of including the NaOH step. It is important to note that problems were experienced with applying the vanadate-molybdate colorimetric method for ortho P to the NaOH extracts, even after pH neutralisation. These problems were overcome by using the molybdate-ascorbic acid method after suitable neutralisation and dilution of the NaOH extracts (refer to section 2.3.2).

From Table 2.10 it can be seen that the unit with iron dosing contained significantly more total P in the RES fraction compared to the Control at the same time. With the NaOH step included, only about 1% of the mixed liquor total P remained in the residue. The NaOH extract contained small amounts of ortho P, but mainly complex P. The complex P forms extracted with NaOH may be poly P associated in some manner with proteins, particularly since the latter are known to be insoluble in cold PCA but are dissolved in alkaline solution (de Haas, 1989). Similarly, complexes between poly P and polysaccharides could form, possibly mediated by metal ions. For example, high molecular weight extracellular polysaccharides are produced in large amounts in activated sludge and are known to have the propensity to bind metal ions (Brown and Lester, 1979). The appearance of larger amounts of complex P in the NaOH extract is further examined in section 2.4.7 below and in Chapters 3, 4 and 5 for alum, ferric chloride and ferrous-ferric chloride dosing, respectively.

2.4.5 The full fractionation procedure

With the inclusion of the NaOH step in the basic PCA fractionation procedure, the full procedure is given in Table 2.11 along with the interpretation thereof.

...../ Table 2.9

Table 2.9: Results of "indirect" and "direct" (PCA extraction) determinations of sludge ortho P fraction for several mixed liquor samples. SUP denotes filtered sample.

Sample/ Extract	Ortho P	
	mgP/ℓ	mgP/gVSS
MUCT unit 11/8/93 VSS = 3108 mg/ℓ		
SUP	1.84	0.58
Indirect	4.17	1.31
Indirect - SUP	2.33	0.73
Direct (PCA)	**17.25**	**5.43**
MUCT unit 13/8/93 VSS = 2772 mg/ℓ		
SUP	2.41	0.87
Indirect	5.21	1.88
Indirect - SUP	2.80	1.01
Direct (PCA)	**12.21**	**4.41**
MUCT unit 27/8/93 VSS = 2908 mg/ℓ		
SUP	15.84	5.45
Indirect	19.16	6.59
Indirect - SUP	3.32	1.14
Direct (PCA)	**16.04**	**5.52**
S_{bsi} unit 27/8/93 VSS = 1106 mg/ℓ		
SUP	7.22	6.53
Indirect	7.32	6.62
Indirect - SUP	0.10	0.09
Direct (PCA)	**4.78**	**4.32**
50 mg/ℓ acetate 16/9/93 VSS = 2505 mg/ℓ		
SUP	12.94	5.17
Indirect	16.02	6.40
Indirect - SUP	3.08	1.23
Direct (PCA)	**13.11**	**5.23**
50 mg/ℓ acetate 20/9/93 VSS = 2221 mg/ℓ		
SUP	11.96	5.39
Indirect	14.12	6.36
Indirect - SUP	2.16	0.97
Direct (PCA)	**13.65**	**6.15**

Table 2.10: **Effect of inclusion 1M NaOH step in cold PCA fractionation procedure. Mixed liquor samples from laboratory-scale units fed settled sewage containing 150 mg/l acetate COD. Ferric chloride dose to R1 was 10 mg/ℓ as Fe. Control not dosed precipitant.**

Sample/ Extract	Ortho P		Total P		Complex P (Total P - Ortho P)	
	%Total P	mgP/ℓ	%Total P	mgP/ℓ	%Total P	mgP/ℓ
4/7/95, R1 $FeCl_3$ dosed VSS = 2396 mg/ℓ						
SUP. (filtered)	3%	16.40		17.72	<1%	1.32
SUP. (unfiltered)			4%	18.21	<1%	1.81
PCA (filtered)	26%	134.90	(73%)	374.01	47%	239.11
PCA (unfiltered)			79%	399.60		
RES.	-	-	**17%**	**85.63**	-	-
Mixed liquor	-	-	-	**509.34**	-	-
Sum of extracts	-	-	-	503.44	-	-
Recovery	-	-	99%	-	-	-
4/7/95, R2 CONTROL VSS = 2499 mg/ℓ						
SUP. (filtered)	5%	20.43		21.82	<1%	1.39
SUP. (unfiltered)		-	5%	21.82	<1%	1.39
PCA (filtered)	9%	39.07	(81%)	352.36	72%	313.29
PCA (unfiltered)			84%	364.17		
RES.	-	-	**13%**	**57.09**	-	-
Mixed liquor	-	-	-	**433.89**	-	-
Sum of extracts	-	-	-	443.08	-	-
Recovery	-	-	102%	-	-	-
18/7/95, R1 $FeCl_3$ dosed VSS = 2184 mg/ℓ						
SUP. (filtered)	2%	11.11		11.08	0%	0
SUP. (unfiltered)		-	2%	12.26	<1%	1.15
PCA (filtered)	27%	139.37	(77%)	397.50	50%	258.13
PCA (unfiltered)			79%	403.44		
NaOH	2%	9.5	**18%**	**93.35**	16%	83.85
RES.	-		**1%**	**6.92**	-	-
Mixed liquor	-		-	**514.19**	-	-
Sum of extracts	-		-	515.97	-	-
Recovery	-		100%	-	-	-
18/7/95, R2 CONTROL VSS = 2675 mg/ℓ						
SUP. (filtered)	5%	26.08		23.93	0%	0
SUP. (unfiltered)			5%	25.51		0
PCA (filtered)	9%	45.12	(82%)	431.12	73%	386.00
PCA (unfiltered)			85%	450.90		
NaOH	1%	4.00	**6%**	**30.32**	5%	26.32
RES.			**1%**	**3.96**	-	-
Mixed liquor			-	**529.02**	-	-
Sum of extracts			-	510.69	-	-
Recovery			97%	-	-	-

Note: Small errors in total P recovery (≤5%) unavoidably occur where filtered/ unfiltered total P results differ significantly.

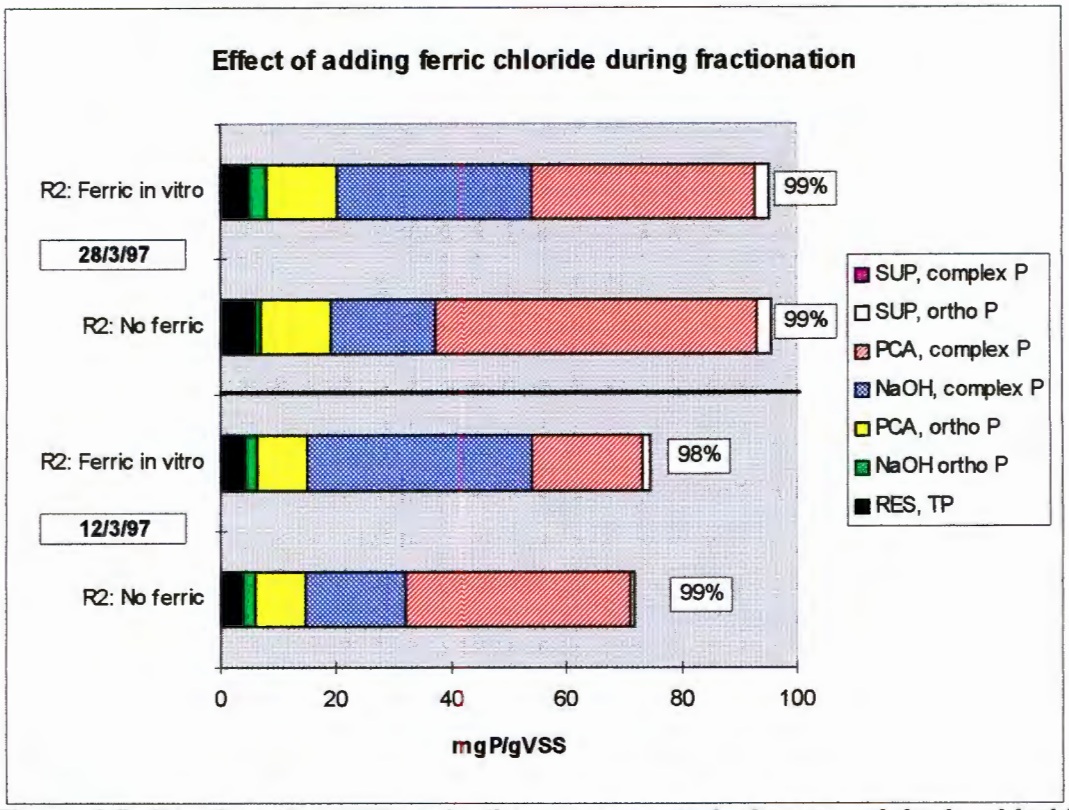


Figure 2.5: **Fractionation pattern in the presence and absence of ferric chloride added to the 0.5M perchloric acid used in the PCA step. The mixed liquor used in this experiment was taken in all cases from a control reactor (R2) exhibiting BEPR. Percentage figures quoted are for % TP recovery in the fractionation procedure compared to the measured P/VSS content.**

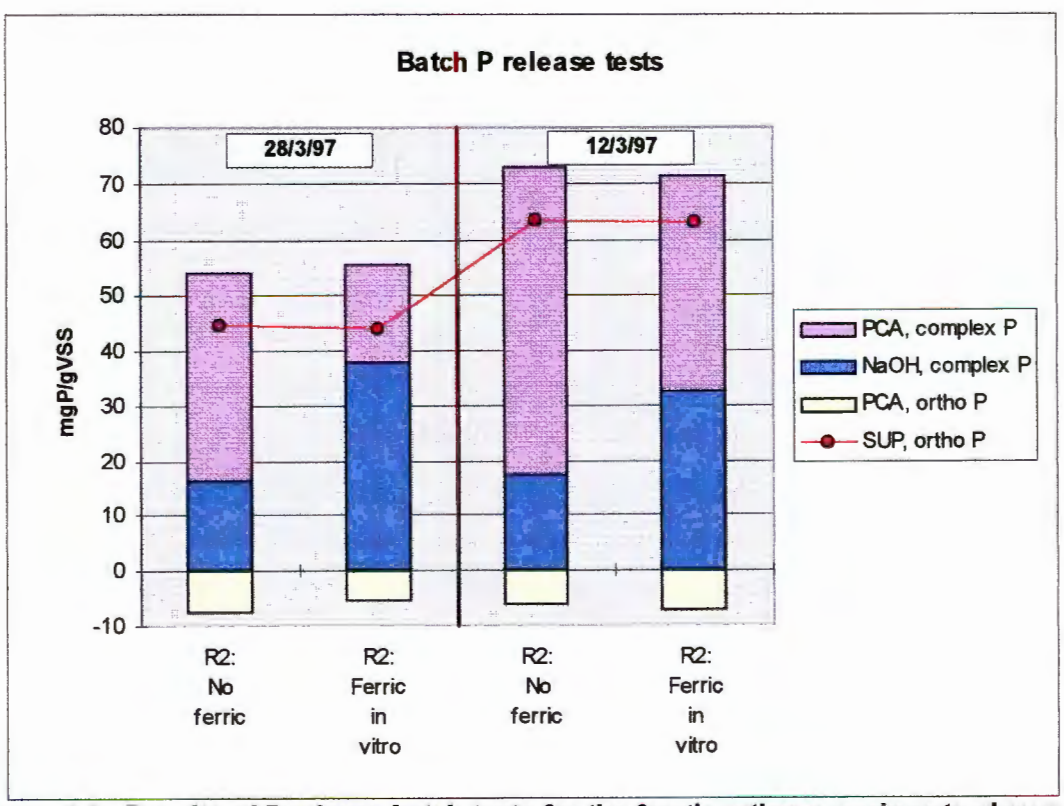


Figure 2.6: **Results of P release batch tests for the fractionation experiments shown in Fig. 2.5. Note: addition of iron during the PCA step of the procedure resulted in an apparent shift in P release from the acid (PCA) fraction to the alkaline (NaOH) step.**

Table 2.11: Full PCA-NaOH fractionation procedure as applied to activated sludge. Mixed liquor sample should contain ca. 2500 mg VSS/ℓ. Refer to 1.3.5 below for optional pre-concentration step.

Step	Procedure	Sample preparation and Analysis	Interpretation
0.	Pre-thickening of mixed liquor: For starting VSS = ca. 1000 mg/ℓ, take 2 ℓ mixed liquor and allow to settle in a measuring cylinder. When sludge has settled, withdraw 1700 mℓ supernatant and discard. Re-suspend solids into remaining 800 mℓ using magnetic stirrer.	Mixed liquor should contain ca. 2500 mg VSS/ℓ.	Allows suitable dilution of extracts to ensure minimal interference in ortho P and total P determination from ionic strength, colour and turbidity.
1.	Transfer one aliquot (50 mℓ) of well stirred mixed liquor to each of two centrifuge tubes with screw cap lids for sealing. *(Note: if available one tube of 100 mℓ may be used; double subsequent vols. below)*	Analyse original mixed liquor for: • total P • MLSS, VSS [Take precaution to mix sample well and perform in duplicate at least]	Recovery of summed extract total P will be related to mixed liquor total P. Allows extract P content to be expressed on VSS basis.
2.	Centrifuge at 3000 rpm (max. 2000 *g*) for 5 min. Collect and pool supernatant and retain pellet.	Label supernatant *SUP*. Retain.	Original supernatant corresponding to "effluent" at point of sampling.
3.	Add 0.9% (m/v) NaCl (20 mℓ) to pellet in each tube. Cap and shake well to mix/ re-suspend.		"Interstitial" loosely bound phosphate washed out with osmotically neutral saline.
4.	Centrifuge at 3000 rpm (max. 2000 *g*) for 5 min. Collect and pool with supernatant with that marked *SUP(step 2)*. Retain pellet.	Filter about half *SUP* sample through ashless filter paper (Whatman No. 41 or MN 615). *SUP* and *filtered SUP (fSUP)* analysed for • ortho P immediately • total P [Correct by a factor of 1.2 for 60 ml extract per 50 ml original mixed liquor]	Loosely bound phosphate extracted with saline is pooled with that present in the original supernatant.
5.	Extract three times with ice-cold 0.5 M PCA (20 mℓ) in a refrigerated water bath (0-3°C) for 5 min. each time. Centrifuge between extractions (as before but preferably with centrifuge refrigerated at 5°C) and keep the extracts ice cold. Retain residue.	Pool extracts and label *PCA*. Filter about half *PCA* sample (see step 4). *PCA* and *filtered PCA (fPCA)* analysed for: • ortho P **immediately** • total P [Correct by a factor of 1.2 i.e. 60 ml extract per 50 ml original mixed liquor]	Acid-soluble complex P (poly P and nucleic acids) extracted as well as chemical precipitates (ortho P). ["Fatty" fragments may float in the PCA extract but usually have a small total P content judged by *PCA- fCPA*.]

continued...../

6.	Extract three times with 1 M NaOH (20 mℓ) at room temperature (e.g. 30 min.; 15 min., 15 min.). Centrifuge as before between extractions with centrifuge at room temp.	Pool extracts (brown coloured) and label *NaOH*. Analyse for: • total P [neutralise extract with 1M HCl] • ortho P [use molybdate-ascorbic acid method on neutralised , dilute sample e.g. 25-fold dilution] [Correct by a factor of 1.2 i.e. 60 ml extract per 50 ml original mixed liquor]	Formation of phosphate compounds extractable into NaOH appeared to be favoured by dosing of iron salts. Minor fraction of ortho P occurs in this extract; mainly complex P is extracted. Poly P or metal hydroxide complexes with proteins or other biopolymers suspected.
7.	Residue resuspended by serial washing in a total of 50 mℓ distilled water per centrifuge tube.	Analyse residue (*RES*) for: • total P [Take precaution to mix sample well and perform in duplicate]	Minor fraction of P compounds not extractable into cold PCA or NaOH. Allows check for overall P mass recovery.
8.	Expose original mixed liquor to excess acetate under anaerobic conditions for 4h.	Add acetate in excess of denitrification needs (8.6 mgCOD/ mg NO_3-N) and P release needs (2 mg COD/ mg P release). Example: Dissolve 96 mg anhydrous sodium acetate in 50 mℓ aliquot mixed liquor in capped centrifuge tube [See 2.4.2.4.].	Anaerobic batch P release test indicates which complex P fraction(s) are principally labile in the BEPR mechanism.
9.	Repeat steps 1 through 7 on mixed liquor after P release.		

Table 2.12: Acetate recovery tests by COD determination using open (conventional) and closed (microwave) reflux digestion procedures.

- [M] = Microwave, closed reflux digestion
- [O/D] = Open reflux digestion (Darvill laboratory)
- [O/U] = Open reflux digestion (UCT laboratory)

Solution composition	COD METHOD	Theoretical COD mg O_2/ℓ	Measured COD mg O_2/ℓ	Recovery %
Pure Na acetate 193 mg/ℓ	[M]	150	135.5 134.2 135.5 132.2 132.2 138.7 Average: 134.7	 90%
Pure Na acetate 320 mg/ℓ: • undiluted • diluted 1.66 fold • diluted 2.5 fold • diluted 5 fold	[O/D]	 • 250 • 150 • 100 • 50	 149 92 59 28	 60% 61% 59% 56%
Pure Na acetate 642 mg/ℓ	[M]	500	445; 451 Ave. 448	90%
	[O/D]	500	235; 270 Ave. 252	50%
	[O/U]	500	469	94%
Test 2 sewage only	[M]	Unknown	289	-
	[O/D]	Unknown	256	-
Test 2 sewage + 193 mg/ℓ Na acetate	[M]	289+150 = 439	403; 396 Ave. 400	91%
	[O/D]	256+150 = 406	352;327;366 Ave. 348	86%

2.7 DISCUSSION & CONCLUSIONS

2.7.1 Methods developed

In this chapter, methods were investigated for the measurement of biological versus chemical P removal in activated sludge systems. The most fundamental of these methods was for total P and ortho P measurement, where the importance of aspects such as the range of the method for measurement of ortho P, and the concentration of acid or persulphate during the digestion step for total P, were highlighted. An attempt to measure the ortho P fraction bound in the sludge matrix directly, by a modification of the methods used for dissolved ortho P, proved unsuccessful. Instead, a fractionation procedure based on extraction with perchloric acid (with an optional subsequent extraction step using alkali) was tested using activated sludge samples subjected to various conditions which influenced biological or chemical P removal in batch tests or continuous-flow laboratory-scale systems. The fractionation procedure appeared to be capable of broadly distinguishing between chemical and biological forms of stored phosphorus in activated sludge systems, and showed satisfactory agreement with the predicted results for biological poly P accumulation obtained using a mathematical model applied to such systems. It was concluded that the chemical fractionation procedure developed would be useful in measuring the relative sizes of chemically-bound versus biologically-stored forms of phosphorus in activated sludge systems with or without simultaneous addition of metal precipitants. However, caution in interpretation of the fractionation data was advised since artefacts imposed by the fractionation procedure itself may be difficult to avoid.

Finally, methods for the routine measurement of other parameters necessary for monitoring the performance of pilot or full-scale (activated sludge) plants were described. These included COD, TKN, nitrate, DSVI, MLSS and VSS.

In the following three chapters, the results of long-term tests using pilot-scale activated sludge systems set up to measure P removal in the presence or absence of simultaneous metal salt addition will be presented, along with results obtained using the fractionation procedure described here.

2.7.2 Definition of terms "inhibition" and "P release"

The primary aims of this study (see section 1.11.1) was to study the interaction between the biological and chemical P removal mechanisms in modified activated sludge systems dosed simultaneously with chemical precipitants. Therefore, a key issue is the possible "inhibitory effect" on the biological mechanism of metal ions added as phosphate precipitants. This chapter has shown that it is possible to measure the magnitude of the biological P removal component in at least two ways, namely:

- (chemical) fractionation of the mixed liquor phosphate fractions to identify the size of the "complex P" (or "poly P") fractions ; and
- anaerobic batch P release tests in the presence of excess acetate (readily biodegradable substrate), again to provide a measure of the size of the stored poly P fraction.

A further method for estimating the magnitude of the bio-P removal component would be to use the steady-state results from laboratory (or pilot) scale activated sludge systems to calculate the extent of P release in the anaerobic reactor by means of a mass balance. In this case, P release will be measured in the supernatant (or filtrate) of centrifuged (or filtered) mixed liquor samples.

All three of the above-mentioned methods are subject to approximations. The limitations of the fractionation method were discussed in Chapter 1 (section 1.5); nevertheless its suitability for broadly distinguishing the biological and chemical fractions in mixed liquor was identified in this chapter. Similarly, the anaerobic batch P release test would be subject to the physiological capability of the poly P accumulating organisms (PAOs) in a mixed liquor sample to release phosphate in the presence of excess acetate. As pointed out by Mino et al. (1987) in their biochemical model, that capability may be constrained not only by the size of the poly P pool, but also by the glycogen reserve in the cells. Likewise, where metal precipitants are dosed simultaneously, the extent of P release to the mixed liquor supernatant in the anaerobic zone of a continuous activated sludge system may not be representative of true P release by the PAOs: a portion of the biologically released P may be precipitated or complexed by the metals ions and hence not measured in the supernatant.

Questions such as the above lie deeply in the realm of the biochemistry of activated sludge systems, particularly in the presence of simultaneous metal ion addition. The mechanisms of many of the biochemical/ chemical interactions in such systems are not precisely understood. That understanding is limited by the difficulty of measuring the individual reactions or processes taking place simultaneously. For example, even in the absence of deliberate addition of metal salts to the process, it is commonly found that a significant portion (ca. 5 to 20 %) of the phosphate accumulated in activated sludge appears to be in the form of chemical precipitate[8]. This implies that P release to the mixed liquor supernatant is inevitably the result of *net release* from respective biological and chemical processes. Such limitations were recognised from the outset in this study. Accordingly, the objective here was to use all three of above-mentioned methods for measuring the relative magnitude of the biological and chemical P fractions *defined only in broad terms*. For example, **"P release"** was used for both the change observed in the complex P fractions identified through the fractionation procedure (both before and after the anaerobic batch test) and that measured by mass balance across the anaerobic zone of the continuous (pilot plant) systems. The two sets of results were compared and discussed in relation to each other and the systems' overall P removal performance. It was possible only to speculate on the exact nature of interactions which may have been taking place between the biological and chemical mechanisms.

In view of the above, for the purposes of this study, the term **"inhibition"** was used *in its broadest sense in relation to the BEPR mechanism*, namely : a "reduction" or "depression" in the magnitude of the biological fractions or the process of anaerobic P release normally associated with the BEPR mechanism. The possible interactions between the chemical and biological P removal mechanisms in this regard are discussed in Chapter 8 when drawing overall conclusions and identifying areas requiring further research.

[8] Refer to sections 1.5 and 1.7 in Chapter 1.

REFERENCES

Arvin, E. (1983) Observations supporting phosphate removal by biologically mediated chemical precipitation - a review. *Water Sci. Technol.* 15 (3/4), 43-63.

Arvin, E. (1985) Biological removal of phosphorus from wastewater. *CRC Crit. Rev. Environ. Control* 15, 25-64.

Blonda, M, Brunetti, A, Morrone, S, Ramadori, R and May, JW. (1994) Determination of orthophosphate in activated sludges from wastewater-treatment systems showing enhanced biological phosphate removal. *Water Res.*, 28 (1), 155-159.

Burke, RA, Dold, PL and Marais, GvR. (1986) *Biological excess phosphorus removal in short sludge age activated sludge systems.* Report No. W58. University of Cape Town, Depts. of Chemical Engineering and Civil Engineering, December 1986.

Brown, MJ and Lester, JN. (1979) Metal removal in activated sludge: the role of bacterial extracellular polymers. *Water Res.*, 13, 817-837.

De Haas, DW. (1989) Chemical fractionation of activated sludge with special reference to enhanced biological phosphate removal. MSc. Thesis, Dept. of Biochemistry, Rand Afrikaans university, Johannesburg., November 1989.

De Haas, DW, Lötter, LH and Dubery, IA. (1990) An evaluation of the methods used for the determination of orthophosphate and total phosphate in activated sludge extracts. *Water SA* 16 (1), 55-74.

De Haas, DW. (1991) Significance of fractionation methods in assessing the chemical form of phosphate accumulated by activated sludge and an *Acinetobacter* pure culture. *Water SA* 17 (1), 1-10.

Ekama, GA and Marais, GvR. (1984) Two improved activated sludge settleability parameters. *IMIESA*, June 1984, 20-25.

Kerdachi, DA and Roberts, MR. (1985) Further investigations into the modified STS procedure as used specifically to quantitatively assess 'metal phosphates' in activated sludge., *Proc. Int. Conf. Management Strategies for Phosphorus in the Environment.*, Lisbon, Selper, UK, 66-71.

Mino, T, Kawakami, T and Matsuo, T. (1985) Location of phosphorus in activated sludge and function of intracellular polyphosphates in biological phosphorus removal process. *Water Sci. Technol.*, 17 (11/12), 93-106.

Mino, T, Arun, V, Nakamura, K and Matsuo, T. (1987). Effect of phosphorus accumulation on acetate metabolism in the biological phosphorus removal processes. *In: Biological phosphate removal from wastewaters. Advances in Water Pollution Control 4.* (Ramadori, R (ed.), Pergamon Press, Oxford, p27-88.

Müssig-Zufika, M, Kömmuller, A, Merkelbach, B and Jekel, M. (1994) Isolation and analysis of intact polyphosphate chains from activated sludges associated with biological phosphate removal., *Water Res.*, 28 (8), 1725-1733.

Peters, DG, Hayes, JM and Hieftje, GM. (1974) *Chemical Separations and Measurements: Theory and Practiceof Analytical Chemistry.* Saunders, Philadelphia, p 639-640.

Psenner, R, Pucsko, R and Sager, M. (1984) 4. Fractionation of phosphorus in suspended matter and sediment. *Arch. Hydrobiol. Beih. Ergebn. Limnol.*, 30 , 98-103.

Rabinowitz, B and Marais, GvR. (1980) *Chemical and biological phosphorus removal in the activated sludge process.* Research Report No. W32, University of Cape Town, Dept. of Civil Engineering, March 1980.

Röske, I and Schönborn, C. (1994a) Interactions between chemical and advanced biological phosphorus elimination. *Water Res.*, 28 (5), 1103-1109.

Röske, I and Schönborn, C. (1994b) Influence of the addition of precipitants on the biological phosphorus elimination in a pilot plant. *Water Sci. Technol.*, 30 (6), 323-332.

Slatter, NP and Alborough, H (1990) Chemical oxygen demand using microwave digestion: A tentative new method. *Water SA* 18 (3), 145-148.

Standard Methods for the Examination of Water and Wastewater (16th edn.) (1985). American Public Health Association, Washington DC.

Standard Methods for the Examination of Water and Wastewater (17th edn.) (1989) American Public Health Association, Washington DC.

Wentzel, MC, Ekama, GA, Lowenthal, RE, Dold, PL and Marais, GvR. (1989) Enhanced polyphosphate organism cultures in activated sludge systems. Part II: Experimental behaviour. *Water SA* 15 (2), 71-88.

Wentzel, MC, Ekama, GA, Dold, PL and Marais, GvR. (1990) Biological excess phosphorus removal - Steady state process design. *Water SA* 16 (1), 29-48.

Wentzel, MC, Ekama, GA and Marais, GvR. (1992) Processes and modelling of nitrification and denitrification biological excess phosphorus removal systems - a review. *Water Sci. Technol.*, 25 (6), 59-82.

Wentzel MC, Mbewe A, Izzett H, Ozinsky AE, Ekama GA and Marais GvR. (1993). Progress report to the Water Resarch Commission on the research contract "Consolidation of Activated Sludge Research", July 1993, Annexure B: *Dynamic Response of nitrification - denitrification biological excess phosphorus removal plants* by Lakay MT, Wentzel MC Ekama GA and Marais GvR.

WRC (1984). *Theory, design and operation of nutrient removal activated sludge processes.* Water Research Commission, PO Box 824, Pretoria, South Africa.

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting biological enhanced phosphate removal.

Chapter 3

Enhanced culture development and Alum dosing to pilot plants

DW de Haas

CHAPTER THREE

ENHANCED CULTURE DEVELOPMENT AND ALUM DOSING TO PILOT PLANTS

3.1 INTRODUCTION

Due to the relevance of the research topic to Umgeni Water and its operation of Darvill Wastewater Works (WWW) in Pietermaritzburg (South Africa), it was decided to set up a pilot plant facility at this Works with a view to testing the effect of simultaneous chemical dosing on biological phosphate removal in activated sludge systems. The initial phase of the research using pilot plants was aimed at dosing aluminium sulphate (alum) as simultaneous precipitant. For historical reasons, alum was in use at Darvill WWW and was thus both readily available and relevant. From the literature review (Chapter 1) it appeared that very few studies examining the impact of alum on biological P removal had been published. At Darvill WWW, alum had been used as simultaneous precipitant with fair success over an approximately eighteen months period prior to the commencement of this study. The biological P removal mechanism was apparently still operative in the full-scale plant at Darvill WWW in the presence of alum dosing (as evidenced by P release in the anaerobic zone, for example), but the absence of a control reactor made it impossible to determine the extent to which the chemical mechanism inhibited or "competed with" the biological mechanism. There was also limited scope for testing precipitants other than alum at full scale, partly because of constraints with the dosing system and partly because of concerns over the reported inhibitory effects of iron salts on biological P removal mechanism (Lötter, 1991).

The objective at the outset of this study was to set up two parallel pilot plants which strongly exhibited the biological enhanced P removal (BEPR) phenomenon, in order to observe as clearly as possible any effects which simultaneous chemical precipitants (e.g. alum) may have on the biological mechanism. After an initial phase in which so-called "enhanced cultures" with strongly developed biological P removal had been established in both pilot plants (Wentzel *et al.*, 1988), chemical precipitant would be dosed into only one unit (named the Test unit or R1), while the other served as the Control (R2). The effect of chemical dosing to either the anaerobic or aerobic zone could then be studied over several experimental periods. The results of these experiments at pilot-scale are reported in this chapter. Phosphate was always added to the influent of the pilot plants, on the basis that it would allow the P removal *potential* to be measured and compared between Test and Control units. Since alum had been dosed on the Darvill full-scale plant with considerable success over at least two years, experiments with influent P-limitation were not conducted at pilot-scale; however, reference is made in this chapter to the results at full scale.

3.2 MATERIALS AND METHODS

3.2.1 Pilot plants

3.2.1.1 Pilot plant set-up

A modified, insulated shipping container (6m long) was used as an outside laboratory for housing the pilot plants. In view of the space constraints, laboratory-scale units (manufactured by UCT Dept. of Civil Engineering Workshop) were used. It was also necessary to provide a facility for withdrawing sewage from the full-scale plant for feeding to the pilot plants. This was accomplished using a small submersible pump (ca. 50 ℓ/min) suspended in a sump containing settled sewage where the sewage is pumped continuously from the balancing tank to the full-scale activated sludge modules at Darvill WWW. The submersible pump was used to fill a refrigerated tank (500 ℓ, 2 to 4 °C) with settled sewage either once or twice per week. The option of pumping raw sewage was considered but would have been logistically more difficult in terms of the layout of the Works

The reactor interior surfaces were brushed every day. Occasional problems were experienced with "filamentous" protozoa or red worm growth in the reactors; during these periods it proved necessary to sieve the contents of the AN and AX zone on a regular basis, as well to periodically clean-out all reactors. The mixed liquor was always recovered after sieving and returned to the reactors after the latter had been washed.

Pump tubing lines were cleaned daily by means of squeezing or brushing. Soft silicone tubing proved to be the easiest to keep clean.

3.2.3 Alum dosing

As a point of departure, it was assumed that a molar ratio of 0.5 mol $P_{removed}$/ mol Al_{dosed} should be achievable (Wiechers, 1987). Accepting this ratio, a dose of 6.2 mmol Al/d and 12.4 mmol Al/d at a sewage flow rate of 32 ℓ/d translates into an additional P removal of ca. 3 and 6 mgP/ℓ respectively (or 2.67 and 5.34 mgP/ℓ at a flow rate of 36 ℓ/d). On the basis of full-scale operating experience at Darvill, this appeared to be a reasonable target for "low" and "high" alum dosage rates.

A dilute solution of chemical precipitant was prepared according to Table 3.2 and dosed into R1 AN or AE1 zone (see Results and Discussion) at the rate of 500 mℓ/d. It was found that a small amount of acid was required to prevent coagulation (hydroxide formation) in the diluted solutions of alum precipitant. For this reason, a minimum of 10 mmol/d of HCl was added to the diluted solution of precipitant dosed to system R1, and the same amount of acid was fed in tap water only to the system R2, also at a rate of 500 mℓ/d.

3.2.4 Acid dosing

Table 3.3 describes the experimental periods of enhanced culture development, along with the alum and acid doses used. As the enhanced culture was developed, the acid dose was initially increased in an attempt to keep the pH in the aerobic reactors below 7.8 to minimise "background" chemical precipitation of phosphorus as calcium or magnesium salts. The acid was dosed as dilute hydrochloric acid to the first aerobic zone of both units (10 to 140 mℓ of 1M HCl diluted to 500 mℓ and fed over a day), or incorporated with the solution of dilute alum in the case of R1 (see Table 3.3). However, it was found that high doses of acid resulted in operational problems with the pilot plants (see section 3.3.2), which lead to the acid dose being reduced to the minimum required to prevent pre-coagulation of the dilute alum solution prior to dosing (10 mmol/d or 10 mℓ of 1M HCl, diluted to 500 mℓ and fed over a day). At an influent flow rate of 32 to 36 ℓ/d, an acid dose of 10 mmol/d as HCl is equivalent to 14 (to 16) mg/ℓ as $CaCO_3$. This was considered small in relation to the influent alkalinity supplement of 100 mg/ℓ as $CaCO_3$ for most periods (Tables 3.1 and 3.3).

Table 3.1: Sewage supplement composition by experimental period.
(Refer to Table 3.3 for relevant alum and acid dose, and Tables 3.4, 3.7 and 3.12 for total COD).

Period Date range	No. of days	Na-acetate mg/ℓ as COD	K_2HPO_4 mgP/ℓ	$MgCl_2$ mg Mg/ℓ	K_2HPO_4 mg K/ℓ	$NaHCO_3$ mg/ℓ as $CaCO_3$
3.1.1 (No Alum) 23/2/94 to 15/3/94	20	50	10	2.8	25	0
3.1.2 (No Alum) 16/3/94 to 6/4/94	22	100	20	5.6 till 31/3/96 8.4 thereafter	50	0
3.1.3 (No Alum) 7/4/94 to 30/4/94	24	150	30	12.6	75	0
3.1.4 (No Alum) 1/5/94 to 16/5/94	16	200	40	16.8	100	0
3.1.5 (No Alum) 17/5/94 to 31/5/94	15	250	40	21.0	100	0
3.1.6 (Alum) 1/6/94 to 20/7/94	50	250	40	21.0	100	0
New enhanced culture developed 27/7/94 to 19/8/94	24	50 then 100 then 150	20 then 30 then 40	12.6	50 then 75 then 100	50
3.2.1 (No alum) 19/8/94 to 31/8/94	13	150	40	12.6	100	50
3.2.2 (Alum) 1/9/94 to 26/9/94	26	150	40	12.6	100	50
3.2.3 (Alum) 27/9/94 to 7/11/94	40	150	40	12.6	100	100
3.2.4 (Alum) 8/11/94 to 26/12/94	49	150	40	12.6	100	100
3.2.5 (Alum) 27/12/94 to 9/1/95	14	150	40	12.6	100	150
3.2.6 (Alum) 10/1/95 to 23/1/95	14	150	40	12.6	100	150
New enhanced culture developed (No alum) 25/1/95 to 19/2/95	26	50 then 100 then 150 then	20 then 30 then 40	12.6	50 then 75 then 100	150
3.2.7 (Alum) 20/2/95 to 22/3/95	31	150	40	12.6	100	150
3.2.8a (Alum) 23/3/95 to 13/4/95	22	150	40	12.6	100	0
3.2.8b (Alum) 16/4/95 to 25/4/95	10	150	40	12.6	100	0

Table 3.2: Alum dosing protocol for UCT pilot plant R1.

Chemical (Source)	% m/m S.G. (kg/ℓ)	First dilution for working stock	Daily feed Volume diluted to 500 mℓ/d with tap water	Expected dose based on Q_I (ℓ/d)		
Aluminium sulphate Alum $Al_2(SO_4)_3.14H_2O$ MW = 594 g/mol *(Minemet, Durban)*	46 % m/m as alum 1.302 kg/ℓ [599 g/ℓ as alum]	123 mℓ /ℓ [73.7 g/ℓ as alum]	**25 mℓ (6.2 mmol/d Al)** [167 mg/d Al)	32 ℓ/d :	5.2 mg/ℓ as Al	57 mg/ℓ as alum
				34 ℓ/d :	4.9 mg/ℓ as Al	54 mg/ℓ as alum
				36 ℓ/d :	4.6 mg/ℓ as Al	51 mg/ℓ as alum
			50 mℓ (12.4 mmol/d Al) [334 mg/d Al)	36 ℓ/d :	9.3 mg/ℓ as Al	102 mg/ℓ as alum

3.2.5 Parameters measured

All parameters measured were in accordance with Standard Methods (1985) or methods described in Chapter 2 or Appendices 1 through 4. The only exceptions were: OUR, which was measured according to Randall *et al.* (1991); DSVI, which was measured according to Ekama and Marais (1984); and COD, which was measured both by the open reflux digestion and manual titration method given in Standard Methods (1985) and by a microwave digestion method, followed by automated potentiometric titration (Slatter and Alborough, 1990). In the case of COD, it was found that the open reflux method gave poor recoveries (56 to 66%) of sodium acetate COD, both from pure solutions and in admixture with settled sewage, possibly due to the reflux condenser length (50 cm) being inadequate (refer to Chapter 2, section 2.5). Better recoveries (90 to 105%) were obtained by the microwave method which uses closed reflux in Teflon pressure vessels (see Chapter 2, section 2.5).

In summary, the parameters routinely measured were:

- COD (influent, effluents): Chapter 2, section 2.5;
- TKN (influent, effluents): Appendix 1;
- Total P (influent, effluent, mixed liquor, filtered AN, AX, AE1 and AE2 zones): Chapter 2 (2.2);
- Soluble reactive P or SRP (effluents): Chapter 2 (2.3);
- Soluble ammonia (effluents): Appendix 1;
- Soluble nitrate (effluents, filtered AN, AX, AE1, AE2 zones): Appendix 2a & b;
- MLSS, VSS (mixed liquor sample taken from AE2 zone): Standard Methods (1985);
- DSVI (mixed liquors): Ekama and Marais (1984);
- pH (in AN, AX, AE1, AE2 zones): Standard Methods (1985);
- OUR (AE2 zone): Randall *et al.* (1991);
- Total Mg (influent, effluents): Appendix 4.

Readily biodegradable COD (RBCOD) was not measured for most of the experimental periods in this study, for reasons given in section 7.2.1 of Chapter 7. From a modelling point of view, this was a limitation. In two of the latter experimental periods (Periods 3.6.1 and 3.6.2 (a&b) with ferric chloride dosing - see Chapter 4, section 4.3.11), RBCOD was measured by the physico-chemical method described by Mamais *et al.* (1993).

3.2.6 Chemical fractionation of sludge samples

Fractionation and P release batch tests was carried out according to the procedure described in Chapter 2 and summarised in Table 2.11 of that chapter.

Table 3.3: Experimental periods of alum and acid dosing to UCT pilot plants.
Refer also to Table 1 for feed composition details.

Period name Date range	No. of days	Alum dose to R1 (Test) reactor (mmol/d as Al)	Zone dosed with alum/ acid	Acid (HCl) dose (mmol/d)	TARGET FLOW RATE (ℓ/d)	Sludge age Rs (d)
3.1.1 : 50 Acetate, No alum 23/2/94 to 15/3/94	20	0	-	0	32	20
3.1.2 : 100 Acetate, No alum 16/3/94 to 6/4/94	22	0	-	0	32	20
3.1.3 : 150 Acetate, No alum 7/4/94 to 30/4/94	24	0	-	0 to 20 (R1 avg. = 14) (R2 avg. = 0)	32	20
3.1.4 : 200 Acetate, No alum 1/5/94 to 16/5/94	16	0	-	20 to 40	32	20
3.1.5 : 250 Acetate, No alum 17/5/94 to 31/5/94	15	0	-	60 to 120	32	20
3.1.6 : 250 Acetate, Low alum 1/6/94 to 20/7/94	50	6.2	AE1	60 to 120 (R1 avg. = 90) (R2 avg. = 100)	32	20
3.2.1 : 150 Acetate, No alum 27/7/94 to 31/8/94	13	0	-	0	34	20
3.2.2 : 150 Acetate, Low Alum 1/9/94 to 26/9/94	26	6.2	AE1	0	34	20
3.2.3 : 150 Acetate, Low Alum 27/9/94 to 7/11/94	40	6.2	AE1	10	36	20
3.2.4 : 150 Acetate, Low Alum 8/11/94 to 26/12/94	49	6.2	AN	10	36	20
3.2.5 : 150 Acetate, High Alum 27/12/94 to 9/1/95	14	12.4	AN	10	36	20
3.2.6 : 150 Acetate, High Alum 10/1/95 to 23/1/95	14	12.4	AE1	10	36	20
New enhanced culture developed 25/1/95 to 19/2/95	26	0	-	0	36	20
3.2.7 : 150 Acetate, High Alum 20/2/95 to 22/3/95	31	12.4	AE1	10	36	20
3.2.8a : 150 Acetate, High Alum 23/3/95 to 13/4/95	22	12.4	AE1	10	36	20
3.2.8b : 150 Acetate, High Alum 16/4/95 to 25/4/95	10	12.4	AE1	10	36	20

3.3 RESULTS AND DISCUSSION

3.3.1 Enhanced culture development and fractionation method verification

Table 3.4 shows the results of routine monitoring of the pilot plants for experimental periods 3.1.1 to 3.1.5, during which the enhanced cultures were developed. Although complete steady-state was not achieved during each period of enhanced culture development, it can be seen from Table 3.4 that for periods 3.1.1 through 3.1.4, TP removal increased in proportion to the increased acetate added. However, with the increase in acetate from 200 mg COD/ℓ (period 3.1.4) to 250 mg COD/ℓ (period 3.1.5), average TP removal decreased. This is also reflected in the stagnation of the P/VSS content of the mixed liquor (Table 3.4). These observations may be related to the increased dose of acid to the reactors, as discussed below. In all other respects, the two units behaved as expected.

Although, the experimental periods were fairly short (one sludge age or less - Table 3.3), nitrogen, COD and phosphorus mass balances were calculated. The results are given in Table 3.5. The results were:

- 91 to 144% for nitrogen;
- 81 to 101% for COD; and
- 60 to 105 % for phosphorus.

These results suggest that confidence in the results, particularly in terms of P removal, should be guarded since steady state was probably not achieved in each experimental period.

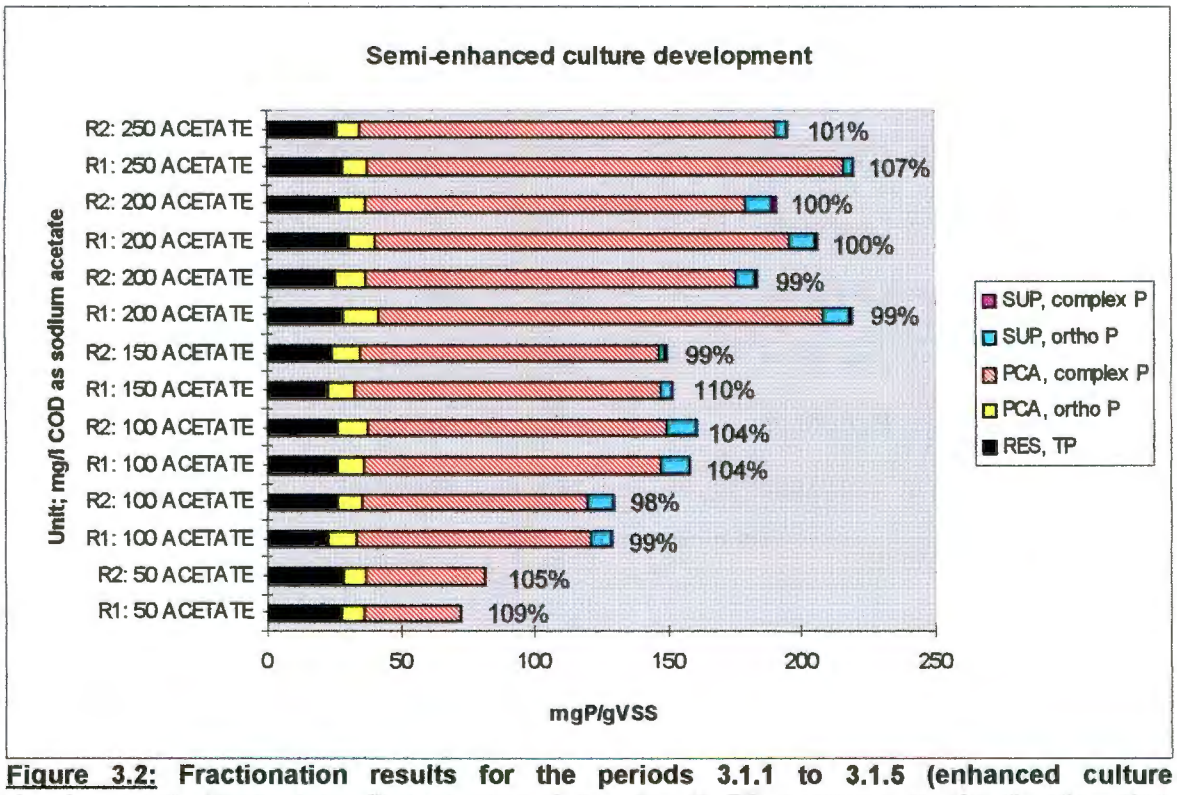


Figure 3.2: Fractionation results for the periods 3.1.1 to 3.1.5 (enhanced culture development). Percentage figures quoted are for % TP recovery in the fractionation procedure compared to the measured P/VSS content.

Table 3.4: Pilot plant results for experimental periods 3.1.1 to 3.1.5.
Results are averages with sample standard deviations in parentheses. N.D. = Not determined.
See Appendix 8 for definition of symbols.

Period Unit	Days (Al dose, mg/ℓ Al)	Sti mgO/ℓ	Ste mgO/ℓ	Nti mgN/ℓ	Nte mgN/ℓ	Nae mgN/ℓ	No3e mgN/ℓ	Pti mgP/ℓ	Pte mgP/ℓ	Pt_{rem} mgP/ℓ	P/VSS mgP/gVSS	TSS mg/ℓ	VSS mg/ℓ	% VSS	DSVI mℓ /g	fPt,a mgP/ℓ	fPt,d mgP/ℓ	fPt,b1 mgP/ℓ	fPt,b2 mgP/ℓ
3.1.1 R1	20 days (0 mg/ℓ)	285 (87)	28 (14)	39.7 (10.8)	3.42 (2.28)	0.32 (0.22)	11.16 (4.94)	13.92 (1.52)	5.97 (4.30)	7.96 (4.95)	75.42 (10.18)	2406 (126)	1678 (111)	69.7 (1.6)	123 (15)	N.D.	N.D.	N.D.	N.D.
3.1.1 R2	20 days (0 mg/ℓ)	285 (87)	28 (12)	39.7 (10.8)	2.59 (1.18)	0.23 (0.09)	12.58 (6.93)	13.92 (1.52)	5.15 (4.01)	8.77 (4.71)	76.92 (6.31)	2180 (233)	1507 (171)	69.1 (1.5)	124 (28)	N.D.	N.D.	N.D.	N.D.
3.1.2 R1	22 days (0 mg/ℓ)	339 (51)	18 (2)	36.4 (11.7)	2.15 (0.68)	0.33 (0.19)	6.66 (2.93)	31.00 (4.83)	11.14 (7.94)	19.86 (5.72)	121.89 (25.32)	3050 (184)	1962 (64)	64.9 (3.6)	120 (11)	N.D.	N.D.	N.D.	N.D.
3.1.2 R2	22 days (0 mg/ℓ)	339 (51)	20 (1)	36.4 (11.7)	2.04 (0.78)	0.19 (0.13)	6.55 (4.26)	31.00 (4.83)	13.07 (8.40)	17.93 (5.55)	124.07 (23.54)	2951 (151)	1852 (121)	63.2 (4.7)	91 (8)	N.D.	N.D.	N.D.	N.D.
3.1.3 R1	24 days (0 mg/ℓ)	458 (54)	29 (17)	35.2 (5.6)	2.51 (0.88)	0.37 (0.07)	8.30 (3.76)	36.9 (6.79)	11.79 (6.14)	24.60 (6.51)	164.71 (19.59)	3778 (335)	2277 (142)	60.5 (3.8)	93 (5)	N.D.	N.D.	N.D.	N.D.
3.1.3 R2	24 days (0 mg/ℓ)	458 (54)	28 (14)	35.2 (5.6)	2.82 (1.85)	0.35 (0.30)	8.90 (3.26)	36.9 (6.79)	8.14 (6.68)	27.68 (7.51)	149.88 (20.70)	3464 (227)	2175 (82)	62.9 (2.6)	94 (5)	N.D.	N.D.	N.D.	N.D.
3.1.4 R1	16 days (0 mg/ℓ)	465 (47)	21 (2)	44.0 (10.5)	3.37 (2.16)	0.95 (1.41)	7.25 (3.97)	49.70 (8.41)	15.35 (7.51)	34.34 (10.08)	183.93 (20.30)	4002 (230)	2433 (67)	60.2 (3.0)	95 (4)	N.D.	N.D.	N.D.	N.D.
3.1.4 R2	16 days (0 mg/ℓ)	465 (47)	20 (2)	44.0 (10.5)	3.60 (1.79)	0.86 (1.41)	7.25 (3.79)	49.70 (8.41)	15.30 (7.17)	34.39 (9.94)	181.86 (26.24)	3934 (362)	2368 (172)	60.3 (2.2)	98 (7)	N.D.	N.D.	N.D.	N.D.
3.1.5 R1	15 days (0 mg/ℓ)	545 (24)	23 (2)	47.9 (8.8)	2.32 (0.50)	0.52 (0.25)	7.12 (2.32)	49.73 (3.44)	16.92 (4.27)	32.81 (4.63)	194.86 (12.73)	4703 (225)	2682 (126)	57.0 (1.8)	76 (4)	N.D.	N.D.	N.D.	N.D.
3.1.5 R2	15 days (0 mg/ℓ)	545 (20)	22 (1)	47.9 (8.8)	2.25 (0.52)	0.58 (0.37)	7.17 (2.19)	49.73 (3.44)	18.76 (5.09)	30.97 (4.85)	187.37 (14.36)	4582 (171)	2659 (193)	58.0 (3.2)	88 (4)	N.D.	N.D.	N.D.	N.D.

f = filtered; a = anaerobic; d = anoxic; b1 = 1st aerobic; b2 = 2nd aerobic reactors of 3-stage Phoredox system (see Fig. 3.1).

Table 3.5: Mass balances for experimental periods 3.1.1 to 3.1.5.
Results are averages with sample standard deviations (S.D.) in parentheses. Sludge age (R_s) = 20 d.

Period Unit	Days (Al dose, mg/ℓ Al)	Flow Qi, ℓ/d	VSS mg/ℓ	No3a mgN/ℓ	No3d mgN/ℓ	No3b2 mgN/ℓ	Nte mgN/ℓ	No3e mgN/ℓ	Nti mgN/ℓ	% N Bal.	Ot mgO/ℓ.h	Sti mgO/ℓ	Ste mgO/ℓ	% COD Bal.	Pt_{rem} mgP/ℓ	P/VSS mgP/gVSS	% P Bal.
3.1.1 R1	20 days (0 mg/ℓ)	32.1 (3.0)	1678 (111)	0.05	3.00	11.2 (4.9)	3.42 (2.28)	11.16 (4.94)	39.7 (10.8)	**133%**	13.70 (2.63)	285 (87)	28 (14)	**89%**	7.96 (4.95)	75.42 (10.18)	**79%**
3.1.1 R2	20 days (0 mg/ℓ)	30.1 (3.2)	1507 (171)	0.05	3.50	12.6 (6.9)	2.59 (1.18)	12.58 (6.93)	39.7 (10.8)	**141%**	13.84 (3.15)	285 (87)	28 (12)	**89%**	8.77 (4.71)	76.92 (6.31)	**70%**
3.1.2 R1	22 days (0 mg/ℓ)	32.6 (0.8)	1962 (64)	0.05	1.80	6.7 (2.9)	2.15 (0.68)	6.66 (2.93)	36.4 (11.7)	**100%**	14.97 (1.94)	339 (51)	18 (2)	**94%**	19.86 (5.72)	121.89 (25.32)	**105%**
3.1.2 R2	22 days (0 mg/ℓ)	32.6 (1.6)	1852 (121)	0.05	1.80	6.6 (4.3)	2.04 (0.78)	6.55 (4.26)	36.4 (11.7)	**96%**	16.94 (2.05)	339 (51)	20 (1)	**101%**	17.93 (5.55)	124.07 (23.54)	**86%**
3.1.3 R1	24 days (0 mg/ℓ)	32.4 (0.8)	2277 (142)	0.05	2.50	8.3 (3.8)	2.51 (0.88)	8.30 (3.76)	35.2 (5.6)	**121%**	16.40 (1.24)	458 (54)	29 (17)	**80%**	24.60 (6.51)	164.71 (19.59)	**85%**
3.1.3 R2	24 days (0 mg/ℓ)	31.6 (1.2)	2175 (82)	0.05	2.50	8.9 (3.3)	2.82 (1.85)	8.90 (3.26)	35.2 (5.6)	**130%**	21.40 (2.61)	458 (54)	28 (14)	**95%**	27.68 (7.51)	149.88 (20.70)	**60%**
3.1.4 R1	16 days (0 mg/ℓ)	33.6 (0.6)	2433 (67)	0.05	1.60	7.3 (4.0)	3.37 (2.16)	7.25 (3.97)	44.0 (10.5)	**99%**	19.21 (3.28)	465 (47)	21 (2)	**85%**	34.34 (10.08)	183.93 (20.30)	**62%**
3.1.4 R2	16 days (0 mg/ℓ)	33.4 (1.2)	2368 (172)	0.05	1.60	7.3 (3.8)	3.60 (1.79)	7.25 (3.79)	44.0 (10.5)	**99%**	20.21 (5.68)	465 (47)	20 (2)	**88%**	34.39 (9.94)	181.86 (26.24)	**60%**
3.1.5 R1	15 days (0 mg/ℓ)	32.5 (1.3)	2682 (126)	0.05	1.86	7.1 (2.3)	2.32 (0.50)	7.12 (2.32)	47.9 (8.8)	**90%**	19.69 (2.26)	545 (24)	23 (2)	**81%**	32.81 (4.63)	194.86 (12.73)	**78%**
3.1.5 R2	15 days (0 mg/ℓ)	31.6 (1.6)	2659 (193)	0.05	1.67	7.2 (2.2)	2.25 (0.52)	7.17 (2.19)	47.9 (8.8)	**91%**	18.86 (2.76)	545 (20)	22 (1)	**81%**	30.97 (4.85)	187.37 (14.36)	**81%**
									Mean:	**110%**			Mean:	**88%**		Mean:	**77%**
									S.D.:	**19%**			S.D.:	**7%**		S.D.:	**14%**

Figure 3.2 shows the fractionation results for the first three-month period of enhanced culture development in the pilot plants. The P recoveries in the fractionation procedure were excellent (98 to 107%), indicating reliability of the method. From the results, it is clear that increasing acetate concentrations in the feed resulted in the PCA complex P (i.e. largely poly P) fraction of the mixed liquor increasing markedly, while the residue P and ortho P fractions remained largely unchanged. A very small amount of complex P was occasionally detected in the supernatant. (This was not due to suspended solids in the supernatant since the samples were filtered prior to total P and ortho P analysis). The results in Fig. 3.2 verify that the fractionation method does appear to distinguish between complex P (or poly P) and ortho P bound in the mixed liquor solids.

Table 3.6 gives a summary of the pH data for the aerobic zones in Periods 3.1.1 to 3.1.5 (the anaerobic zone pH was not measured for these periods). Table 3.6 shows that the pH differed significantly between the corresponding zones of the two reactors, but never by more than 0.32 pH units (median data). Because the pH was higher in R1 than R2, acid dosing was commenced sooner in R1 than in R2 during period 3.1.3 (Table 3.3) . Overall, Table 3.6 (Periods 3.1.3 to 3.1.5) shows that, based on the upper and lower quartile data, acid dosing had the effect of keeping the pH in the range 7.05 to 7.88. Particularly at the higher acetate feed rate (200 to 250 mg/ℓ as COD), this required significant acid doses (60 to 120 mmol/d, or approx. 94 to 188 mg/ℓ as $CaCO_3$, based on influent flow - refer to Tables 3.2 and 3.3 above). It was deemed necessary to keep the pH of the aerobic reactors below pH 8.0 at all times in order to discourage chemical precipitation of phosphate and hence to observe the effect of metal salt addition in a strongly active BEPR system.

3.3.2 First alum dosing period (with high acid dose)

Referring to Tables 3.1, 3.2 and 3.3, it may be seen that over a 47 day period (1/6/94 to 20/7/94), alum was dosed into R1 (6.2 mmol/d as Al into AE1), while R2 served as the Control. The acetate dose was kept constant at 250 mg/ℓ (as COD) and acid was dosed in a similar manner into both reactors. The results for this experimental period are given in Table 3.7. The corresponding mass balances are given in Table 3.8.

Table 3.7 shows that better phosphate removal was achieved in the unit dosed with alum (R1, 29.41 mgP/ℓ) compared to the Control (R2, 23.15 mgP/ℓ). On a molar basis, the additional P removal amounted to 1.08 mmol $P_{removed}$/mmol Al_{dosed}, which is very close to the stoichiometric molar ratio for $AlPO_4$.

On a P/VSS basis, Table 3.7 shows that, as expected, the phosphate content of the mixed liquor was greater in R1 (184.2 mgP/gVSS) than R2 (175.3 mgP/gVSS). The VSS concentration in R1 (2720 mg VSS/ℓ) was about 5% greater than in R2 (2595 mg VSS/ℓ), which may be significant in terms of overall sludge production. The TSS concentration in R1 (4549 mg TSS/ℓ) was significantly higher than in R2 (4173 mg TSS/ℓ). However, care should be taken in extrapolating TSS production from these experiments to a full-scale plant since the pilot plants received a phosphate supplement in the influent to ensure that P was never limiting; at full scale P may be limiting and less P will be present in the sludge, hence reducing the TSS. Sludge production is further discussed in section 3.3.6 below.

Table 3.7 suggests that P release in the anaerobic reactor ($fP_{t,a}$) of R1 was slightly lower than that of R2. Using the data in Table 3.7 (for P_{ti}, P_{te} and $fP_{t,a}$) and Table 3.8 (Q_i), and accepting $Q_i = Q_s$ (i.e. return sludge recycle ratio = 1:1, see Figure 3.1), from mass balance considerations around the anaerobic reactor it can be shown that:

$$M(P_{rel}) = [(Q_i + Q_s).fP_{t,a}] - [Q_i.P_{ti} + Q_s.P_{te}] \quad \text{..... Eqn. 3.1}$$

where $M(P_{rel})$ is the mass of phosphate released to the (filtered) supernatant in the anaerobic zone.

Table 3.6: Summary pH statistics for periods of enhanced culture development (3.1.1 to 3.1.5).

Period R1: Al dose	Unit: Zone:	R1 AE1	R2 AE1	R1 AE2	R2 AE2
3.1.1	Median	7.39	7.37	7.51	7.51
20 days	Min.	7.18	7.10	7.33	7.24
R1: 0 mg/ℓ	25% ile	7.32	7.22	7.44	7.37
	75% ile	7.49	7.52	7.62	7.57
	Max.	7.66	7.80	7.73	7.71
3.1.2	Median	7.43	7.32	7.59	7.55
22 days	Min.	7.10	6.92	7.28	7.13
R1: 0 mg/ℓ	25% ile	7.31	7.21	7.45	7.46
	75% ile	7.46	7.38	7.72	7.60
	Max.	7.68	7.61	7.82	7.69
3.1.3	Median	7.36	7.04	7.54	7.25
24 days	Min.	7.16	6.56	7.17	6.72
R1: 0 mg/ℓ	25% ile	7.26	6.82	7.48	7.15
	75% ile	7.40	7.15	7.61	7.42
	Max.	7.57	7.37	7.67	7.53
3.1.4	Median	7.42	7.25	7.68	7.57
16 days	Min.	6.89	6.62	6.71	6.81
R1: 0 mg/ℓ	25% ile	7.27	7.08	7.11	7.20
	75% ile	7.63	7.32	7.78	7.73
	Max.	7.75	7.68	8.01	8.05
3.1.5	Median	7.28	7.23	7.79	7.57
15 days	Min.	6.87	6.77	7.42	7.15
R1: 0 mg/ℓ	25% ile	7.05	6.90	7.48	7.31
	75% ile	7.39	7.33	7.88	7.73
	Max.	7.58	7.53	7.90	7.84

Table 3.9: Influent and effluent total magnesium data for period 3.1.6.
Mean (Std. Dev. in parentheses)

Sample	R1 mg Mg/ℓ	R2 mg Mg/ℓ
Influent	26.7 (2.7)	26.7 (2.7)
Effluent	18.7 (5.4)	20.3 (4.3)

Table 3.10: Summary pH statistics for period 3.1.6.

Unit:	R1	R2	R1	R2
Zone:	AE1	AE1	AE2	AE2
Median	7.12	7.16	7.47	7.52
Min.	6.02	6.62	6.87	6.81
25% ile	7.00	6.95	7.32	7.25
75% ile	7.22	7.28	7.59	7.67
Max.	7.62	7.55	7.96	7.94

Table 3.7: Pilot plant results for experimental period 3.1.6.
Results are averages with sample standard deviations in parentheses. N.D. = Not determined.
See Appendix 8 for definition of symbols.

Period Unit	Days (Al dose, mg/ℓ Al)	Sti mgO/ℓ	Ste mgO/ℓ	Nti mgN/ℓ	Nte mgN/ℓ	Nae mgN/ℓ	No3e mgN/ℓ	Pti mgP/ℓ	Pte mgP/ℓ	Pt_{rem} mgP/ℓ	P/VSS mgP/gVSS	TSS mg/ℓ	VSS mg/ℓ	% VSS	DSVI mℓ/g	fPt,a mgP/ℓ	fPt,d mgP/ℓ	fPt,b1 mgP/ℓ	fPt,b2 mgP/ℓ
3.1.6 R1	50 days 9 mg/ℓ, AE1	498 (57)	22 (11)	49.8 (10.2)	2.09 (0.55)	0.31 (0.22)	8.89 (3.97)	50.55 (3.78)	21.41 (6.78)	29.41 (6.90)	184.21 (19.42)	4549 (220)	2720 (103)	59.9 (2.2)	87 (8)	121.8 (10.8)	61.7 (9.8)	35.8 (9.8)	24.9 (9.0)
3.1.6 R2	50 days 0 mg/ℓ	498 (57)	22 (8)	49.8 (10.2)	2.45 (0.93)	0.24 (0.15)	9.60 (4.20)	50.55 (3.78)	27.66 (9.17)	23.15 (9.17)	175.32 (15.05)	4173 (333)	2595 (125)	62.5 (3.0)	100 (10)	127.1 (11.7)	64.2 (9.6)	40.2 (12.6)	28.1 (10.1)

f = filtered; a = anaerobic; d = anoxic; b1 = 1st aerobic; b2 = 2nd aerobic reactors of 3-stage Phoredox system (see Fig. 3.1).

Table 3.8: Mass balances for experimental period 3.1.6.
Sludge age (R_s) = 20 d. See Appendix 8 for definition of symbols.

Period Unit	Days (Al dose, mg/ℓ Al)	Flow Qi, ℓ/d	VSS mg/ℓ	No3a mgN/ℓ	No3d mgN/ℓ	No3b2 mgN/ℓ	Nte mgN/ℓ	No3e mgN/ℓ	Nti mgN/ℓ	% N Bal.	Ot mgO/ℓ.h	Sti mgO/ℓ	Ste mgO/ℓ	% COD Bal.	Pt_{rem} mgP/ℓ	P/VSS mgP/gVSS	% P Bal.
3.1.6 R1	50 days 9 mg/ℓ, AE1	31.9 (3.1)	2720 (103)	0.05 (0.01)	1.86 (1.43)	6.08 (3.19)	2.1 (0.6)	8.89 (3.97)	49.8 (10.2)	**79%**	15.67 (2.61)	498 (57)	22 (11)	**79%**	29.41 (6.90)	184.21 (19.42)	**117%**
3.1.6 R2	50 days 0 mg/ℓ	31.6 (1.8)	2595 (125)	0.05 (0.02)	1.67 (1.20)	6.16 (2.78)	2.5 (0.9)	9.60 (4.20)	49.8 (10.2)	**83%**	15.80 (3.28)	498 (57)	22 (8)	**77%**	23.15 (9.17)	175.32 (15.05)	**83%**

Using Eqn. 3.1 and the data as outlined above, P release in the anaerobic zone of the Test unit (R1), can be expressed as a percentage of that in the Control unit (R2). For Period 3.1.6, the result was 98%, which implies that, taking Period 3.1.6 as a whole, the biological mechanism was not significantly inhibited by alum addition. For the latter half of Period 3.1.6 (25/6/94 to 20/7/94), a slightly lower result (96%) could indicate emerging inhibition of the biological mechanism. However, these results need to be interpreted in the light of the apparent overall deterioration in BEPR for both the Test and Control units during Period 3.1.6.

Figure 3.4 shows the trends in P removal for the Test and Control units in Period 3.1.6. Seen against the background of the high acid dose applied during this period (Table 3.3 and Fig. 3.4), it is likely that the apparent deterioration of the BEPR performance (first in R2, and then in R1) may have been caused by the increased acid dose. The increased acid dose was applied in response to the second aerobic reactor pH exceeding ca. 7.8, first in R1 and then in R2. When the acid dose was reduced, P removal performance of both systems recovered partially (Fig. 3.4). The observed response in BEPR performance over this period are probably related to the finding by Smolders *et al.* (1994) that a decrease in reactor pH (and specifically the anaerobic reactor pH) reduces the stoichiometry (yield) of P release in proportion to carbon substrate (e.g. acetate) uptake under anaerobic conditions. For example, on the basis of the data presented by Smolders *et al.* (1994), a decrease in anaerobic reactor pH by 0.5 to 1 units may be expected to reduce the yield of P release (i.e. the poly P stored and hence BEPR performance as a whole) by approximately 17 to 33%. Anaerobic pH was not specifically measured during Period 3.1.6, but the available pH (aerobic) data (Table 3.10) showed a range of approx. one pH unit (ca. pH 7.9 to 6.9), but the difference between the upper and lower quartiles was <0.5 pH units. Hence pH effects may not fully account for the loss of BEPR performance shown in Fig. 3.4.

In addition to a deterioration in BEPR performance, operation of the units became very difficult during Period 3.1.6 due to settling problems associated with the emergence of a pin-floc sludge. This did not impact on the DSVI results, but from visual observations the settling rate of the sludge was reduced, at first in R1, but progressively also in R2 (Control). In association with the settling problems, the effluents tended to be turbid, presumably due to large numbers of free bacteria in the effluent. By the third week of July 1994, the units were deemed inoperable; the mixed liquor of both was discarded and a new enhanced culture developed (see below).

Notwithstanding the operational problems experienced with the pilot plants, phosphorus fractionation of mixed liquor withdrawn from the pilot plant units was conducted during Period 3.1.6. The data are summarised in Figure 3.3. From Fig. 3.3 it can be seen that alum dosing produced an increase in the cold PCA ortho P fraction, which may be attributable to chemical precipitate (Chapter 2). This increase was approximately three-fold, relative to the Control (without alum). Concomitant with this increase, the complex P fraction of the cold PCA extract decreased, while the residue (RES.) fraction increased slightly. The decrease in the PCA complex P fraction could be attributed to a decrease in poly P of biological origin, while the small increase in phosphorus in the residue fraction could be attributed to phosphorus which is not extractable into cold PCA but may nevertheless be biologically active. Taking the net difference between the two units (R1 vs. R2) (i.e. decrease in PCA complex P less increase in RES TP), it was observed that during the first month of alum dosing (Period 3.1.6), the magnitude of the "biological" P fractions of R1 (with alum) were in fact very similar to those of R2 (Control), with differences of $\leq$ 5 mgP/gVSS. However, after a further two weeks, with the noted deterioration in sludge settleability and emergence of pin floc sludge (particularly in R1), the decrease in the PCA complex P fraction in R1 became more marked: even after making allowance for the increase in the RES TP fraction, a decrease of 14 mgP/gVSS in this fraction was noted for R1, compared to R2 (i.e. a decrease of 8% of the mixed liquor TP). This suggested that the biological mechanism was being negatively affected by the alum dose, in spite of the deterioration in the system P removal also in the Control (see above). The question arose as to whether the settling problems had played a significant part in this deterioration of the biological excess P removal (BEPR) mechanism, and whether the high acid dose administered for pH control (first to R1 and then to R2 - see Table 3.3) had also played a part. No simple trend could be discerned from the TP removal data (Fig. 3.4) with the large variances being evident, as discussed above. Nevertheless, there was a tendency in the latter half of the experimental period for the TP removal in R1 (Test unit receiving alum) to become smaller in relation to R2, eventually resulting in TP removal similar to that of R2 (Control). It could be

hypothesised that this reduction in total P removal was linked to the reduction in PCA extract complex P (i.e. poly P) and indicated a slow deterioration of the BEPR mechanism due to alum addition. The deterioration in BEPR *per se* in R1 may have been obscured to some extent by the deterioration in settling, which occurred first in R1, but later also in R2. Since effluent TP was measured to determine P removal by the pilot plants, increases in fine sludge floc carryover to the effluent would have been reported as a decrease in TP removal[2]. However, no direct experimental evidence was available to fully substantiate the hypothesis that the BEPR mechanism was under gradual inhibition due to alum dosing and possibly more so in the presence of a high acid dose. The pH data did indicate problems in maintaining pH (Table 3.10). Accordingly, it was decided to restart the experiments, taking more care with pH control.

3.3.3 Second alum dosing period

In view of the operational (settling) problems experienced in the first alum dosing period, a second attempt was made to achieve steady operation in the presence of sustained simultaneous alum addition. The primary objective was to test whether significant and inevitable deterioration of the BEPR mechanism would occur in the unit dosed with alum compared to the control. A secondary objective was to attempt to test the hypothesis that pin floc sludge settling problems and BEPR deterioration in the first alum dosing period were associated with the high acid dose administered during that period. Accordingly, in the second alum dosing period the following operational strategy was adopted (refer to Tables 3.1 and 3.3):

- New "semi-enhanced" cultures were developed, starting with 50 mg/ℓ as acetate COD;
- The maximum acetate feed concentration was 150 mg/ℓ as COD (reduced from 250 mg/ℓ);
- Alkalinity supplement added to the sewage in the form of sodium bicarbonate viz. 50 to 150 (usually 100) mg/ℓ as $CaCO_3$;
- Acid dose reduced to the minimum required to prevent hydroxide coagulation in feed bottle (10 mmol/d as HCl or approx. 13 mg/ℓ as $CaCO_3$).

It was found that this strategy was successful in allowing stable operation of the pilot plants without the emergence of pin floc settling problems. The pH in the aerobic reactors never rose above pH 7.9 which was necessary to limit chemical P precipitation of calcite and struvite which may have arisen under more alkaline conditions (Table 3.11).

...../ Figure 3.3

[2] This tendency became very obvious toward the end of Period 3.1.6 when large differences (up to 11 mgP/ℓ) were noted between effluent TP and effluent (or filtered second aerobic zone) ortho P results. The effluent suspended solids became visible to the naked eye and effluent COD results also increased.

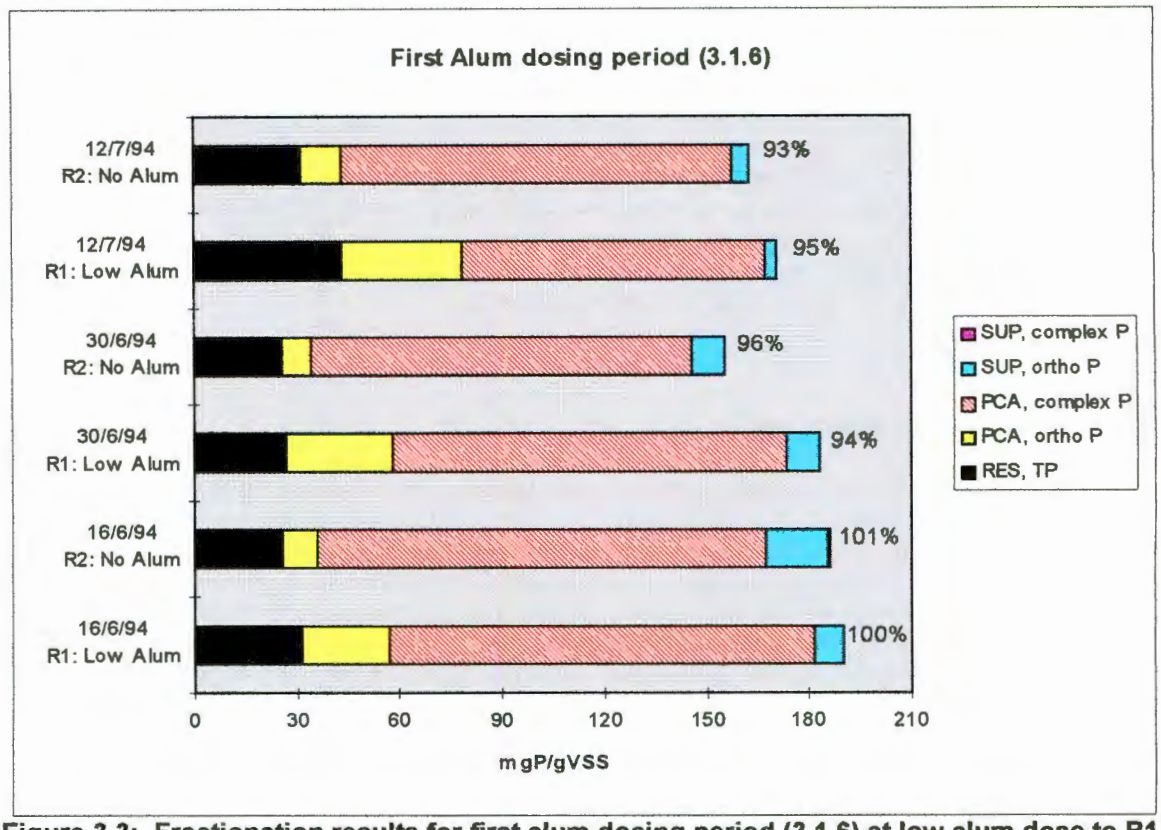


Figure 3.3: **Fractionation results for first alum dosing period (3.1.6) at low alum dose to R1 with high acid dose and with 250 mg/ℓ acetate feed (as COD). Pin floc sludge settling problems developed during this period.**

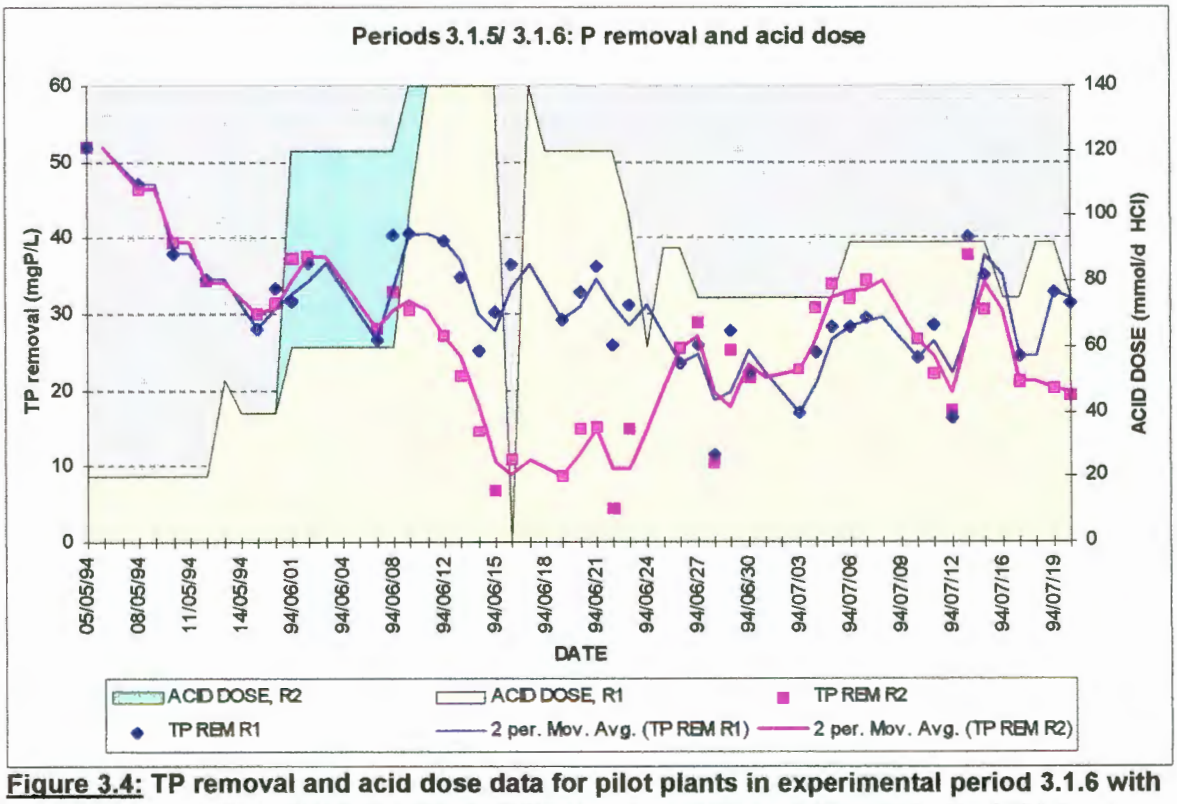


Figure 3.4: **TP removal and acid dose data for pilot plants in experimental period 3.1.6 with low alum dose to R1, 250 mg/ℓ COD acetate feed and high acid dose to both. Acid dose equal in R1 & R2 for period 06/10 to 07/20. Pin floc sludge settling problems developed.**

Table 3.11: Summary pH (and bicarbonate alkalinity) data for periods 3.2.1 to 3.2.8b.
Data in *italics* indicates mean instead of median.

Period (days) R1 Al dose	Unit: Zone:	R1 AN	R2 AN	R1 AE1	R2 AE1	R1 AE2	R2 AE2	R1 Effluent H_2CO_3* Alk. (mg/ℓ as $CaCO_3$)	R2 Effluent H_2CO_3* Alk. (mg/ℓ as $CaCO_3$)
3.2.1	Median	-	-	7.35	7.32	7.6	7.55	-	-
(13 d)	Min.	-	-	7.05	7.02	7.15	7.08	-	-
R1: 0 mg/ℓ	Max.	-	-	7.57	7.47	7.87	7.87	-	-
3.2.2	Median	-	-	7.27	7.28	7.48	7.50	-	-
(26 d)	Min.	-	-	7.15	7.15	7.28	7.25	-	-
R1: 5 mg/ℓ	25% ile	-	-	7.23	7.24	7.44	7.42	-	-
AE1 zone	75% ile	-	-	7.32	7.30	7.52	7.53	-	-
	Max.	-	-	7.48	7.48	7.71	7.84	-	-
3.2.3	Median	-	-	7.38	7.33	7.58	7.62	-	-
(40 d)	Min.	-	-	7.01	6.90	7.03	6.97	-	-
R1: 5 mg/ℓ	25% ile	-	-	7.34	7.30	7.55	7.57	-	-
	75% ile	-	-	7.42	7.39	7.64	7.65	-	-
	Max.	-	-	7.59	7.57	7.83	7.90	-	-
3.2.4	Median	-	-	7.32	7.35	7.53	7.62	-	-
(49 d)	Min.	-	-	6.96	6.93	7.03	6.86	-	-
R1: 5 mg/ℓ	25% ile	-	-	7.30	7.32	7.50	7.58	-	-
AN zone	75% ile	-	-	7.38	7.39	7.61	7.67	-	-
	Max.	-	-	7.52	7.51	7.78	7.81	-	-
3.2.5	Median	6.98	7.01	7.33	7.41	7.49	7.62	-	-
(14 d)	Min.	6.83	6.96	7.19	7.34	7.31	7.49	-	-
R1: 9 mg/ℓ	25% ile	6.94	6.97	7.31	7.37	7.40	7.56	-	-
AN zone	75% ile	7.09	7.08	7.39	7.45	7.50	7.66	-	-
	Max.	7.18	7.17	7.42	7.52	7.58	7.70	-	-
3.2.6	Median	7.11	7.02	7.58	7.60	7.65	7.70	-	-
(14 d)	Min.	7.04	6.94	7.47	7.53	7.52	7.61	-	-
R1: 9 mg/ℓ	25% ile	7.08	6.97	7.54	7.59	7.59	7.68	-	-
AE1 zone	75% ile	7.16	7.05	7.63	7.63	7.68	7.72	-	-
	Max.	7.24	7.13	7.67	7.70	7.76	7.86	-	-
3.2.7	Median	7.28	7.30	7.51	7.50	7.62	7.65	*281*	*319*
(31 d)	Min.	7.09	7.04	7.09	7.15	7.18	7.24	265	303
R1: 9 mg/ℓ	25% ile	7.21	7.22	7.41	7.40	7.56	7.57	-	
AE1 zone	75% ile	7.35	7.36	7.56	7.59	7.68	7.75	-	
	Max. #	9.49	9.88	8.51	8.71	8.40	8.45	301	326
3.2.8a	Median	7.00	6.95	7.25	7.20	7.32	7.37	*144*	*178*
(22 d)	Min.	6.75	6.80	6.87	6.99	6.81	7.01	110	145
R1: 9 mg/ℓ	25% ile	6.98	6.92	7.10	7.13	7.20	7.27	-	
AE1 zone	75% ile	7.08	6.99	7.30	7.26	7.42	7.49	-	
	Max.	7.26	7.24	7.53	7.60	7.67	7.80	229	265
3.2.8b	Median	7.01	6.95	7.07	7.11	7.17	7.28	*114*	*157*
(10 d)	Min.	6.77	6.76	6.90	7.04	6.98	7.23	92	132
R1: 9 mg/ℓ	25% ile	6.98	6.89	7.04	7.07	7.09	7.25	-	
AE1 zone	75% ile	7.03	7.00	7.14	7.22	7.19	7.43	-	
	Max.	7.05	7.19	7.16	7.58	7.29	7.88	136	182

:Sewage on 7/3/95 contained a slug of lime due to an operational fault on the full-scale plant.

Table 3.12: Pilot plant results for second experimental period during which alum was dosed to R1.

R2 = Control. Results are averages with sample standard deviations in parentheses. See Appendix 8 for definition of symbols.

Period Unit	Days (Al dose, mg/ℓ Al)	Sti mgO/ℓ	Ste mgO/ℓ	Nti mgN/ℓ	Nte mgN/ℓ	Nae mgN/ℓ	No3e mgN/ℓ	Pti mgP/ℓ	Pte mgP/ℓ	Pt_{rem} mgP/ℓ	P/VSS mgP/gVSS	TSS mg/ℓ	VSS mg/ℓ	DSVI ml/g	fPt,a mgP/ℓ	fPt,d mgP/ℓ	fPt,b1 mgP/ℓ	fPt,b2 mgP/ℓ
3.2.2	26 days	478	25	40.3	2.67	0.30	2.8	53.06	25.07	27.99	177.5	5076	3040	82	123.0	65.9	44.9	31.5
R1	5 mg/ℓ AE1	(61)	(2)	(6.3)	(0.64)	(0.23)	(0.78)	(2.01)	(7.73)	(7.20)	(10.2)	(153)	(101)	(7)	(9.7)	(4.9)	(4.5)	(3.6)
3.2.2	26 days	478	26	40.3	2.92	0.27	2.43	53.06	28.91	24.25	155.9	4222	2693	84	111.6	66.1	46.4	34.5
R2	0 mg/ℓ	(61)	(3)	(6.3)	(0.56)	(0.19)	(0.93)	(2.01)	(8.68)	(8.68)	(11.7)	(301)	(154)	(7)	(10.8)	(7.5)	(5.8)	(6.5)
3.2.3	40 days	379	23	38.3	3.80	0.57	7.63	49.67	22.83	26.84	215.8	4946	2756	79	114.2	57.4	35.3	23.3
R1	5 mg/ℓ AE1	(56)	(3)	(12.3)	(1.81)	(0.2)	(2.16)	(2.37)	(8.76)	(8.56)	(24.4)	(356)	(241)	(8)	(12.8)	(9.1)	(9.2)	(9.2)
3.2.3	40 days	379	22	38.3	3.68	0.42	5.78	49.67	25.29	24.38	185.1	4649	2749	79	114.9	59.2	37.2	24.6
R2	0 mg/ℓ	(56)	(4)	(12.3)	(2.02)	(0.17)	(1.84)	(2.37)	(8.10)	(7.66)	(21.8)	(248)	(152)	(5)	(12.0)	(8.90)	(9.4)	(9.0)
3.2.4	49 days	346	22	38.3	2.32	1.07	4.71	49.00	22.67	26.37	242.0	4654	2422	66	96.2	51.8	32.0	22.1
R1	5 mg/ℓ AN	(57)	(4)	(9.3)	(1.45)	(1.28)	(2.16)	(2.75)	(4.97)	(5.23)	(16.9)	(336)	(157)	(14)	(11.6)	(7.4)	(5.3)	(5.4)
3.2.4	49 days	346	20	38.3	2.44	0.79	3.28	49.00	23.72	25.28	223.5	4317	2386	81	107.3	58.0	36.0	24.1
R2	0 mg/ℓ	(57)	(2)	(9.3)	(2.09)	(1.03)	(1.24)	(2.75)	(4.42)	(5.19)	(19.9)	(260)	(197)	(16)	(11.4)	(8.2)	(5.3)	(4.2)
3.2.5	14 days	251	18	31.9	2.09	0.46	5.84	46.71	24.14	22.57	267.4	4198	2110	71	70.6	41.3	28.8	22.8
R1	9 mg/ℓ AN	(33)	(2)	(8.8)	(0.48)	(0.19)	(1.34)	(2.88)	(5.21)	(3.87)	(7.5)	(230)	(126)	(4)	(11.6)	(5.6)	(3.4)	(3.7)
3.2.5	14 days	251	16	31.9	1.93	0.43	6.03	46.71	29.74	16.69	234.5	3619	1911	99	85.1	49.8	35.7	28.3
R2	0 mg/ℓ	(33)	(3)	(8.8)	(0.77)	(0.15)	(1.48)	(2.88)	(4.64)	(3.49)	(36.4)	(167)	(86)	(4)	(13.0)	(6.3)	(3.5)	(3.1)
3.2.6	14 days	312	20	24.0	2.5	0.68	4.25	46.77	15.23	31.55	272.7	4297	2105	69	86.1	42.7	22.7	14.1
R1	9 mg/ℓ AE1	(56)	(2)	Estimate	Estimate	(0.65)	(0.78)	(1.98)	(4.99)	(6.48)	(14.7)	(324)	(259)	(3)	(4.8)	(3.7)	(5.2)	(5.3)
3.2.6	14 days	312	18	24.0	2.5	0.49	5.08	46.77	21.89	24.88	245.1	3603	1805	101	95.4	45.3	30.1	21.8
R2	0 mg/ℓ	(56)	(3)	Estimate	Estimate	(0.56)	(1.28)	(1.98)	(5.43)	(6.85)	(7.1)	(233)	(117)	(5)	(3.9)	(6.3)	(4.4)	(5.6)
3.2.7	31 days	350	16	31.0	2.16	0.00	4.80	47.02	21.41	25.66	162.4	3922	2095	52	71.6	40.5	28.5	22.4
R1	9 mg/ℓ AE1	(56)	(2)	(2.2)	(0.46)	(0.00)	(1.60)	(3.00)	(4.88)	(5.89)	(36.5)	(510)	(123)	(6)	(11.3)	(4.9)	(4.7)	(4.5)
3.2.7	31 days	350	18	31.0	2.03	0.00	4.33	47.02	28.27	18.99	115.7	3104	1894	56	75.7	47.6	36.5	30.0
R2	0 mg/ℓ	(56)	(3)	(2.2)	(0.55)	(0.01)	(1.6)	(3.00)	(6.20)	(6.73)	(13.7)	(231)	(140)	(7)	(11.1)	(8.7)	(6.0)	(5.3)
3.2.8a	22 days	317	15	28.0	2.25	0.37	4.35	45.31	19.63	26.00	245.3	4287	2069	52	73.9	39.5	26.3	18.3
R1	9 mg/ℓ AE1	(15)	(4)	Estimate	(0.55)	(0.26)	(1.31)	(2.87)	(5.44)	(6.45)	(22.0)	(156)	(102)	(2)	(14.1)	(4.2)	(5.2)	(6.6)
3.2.8a	22 days	317	16	28.0	2.30	0.25	3.62	45.31	26.75	18.84	169.3	3187	1885	55	80.4	48.8	33.6	24.8
R2	0 mg/ℓ	(15)	(5)	Estimate	(0.72)	(0.18)	(1.21)	(2.87)	(6.15)	(6.81)	(20.6)	(180)	(123)	(3)	(15.8)	(5.8)	(1.8)	(4.4)
3.2.8b	10 days	301	20	25.3	3.67	0.90	6.54	45.79	26.80	18.99	274.8	4215	2006	54	80.9	47.8	35.0	29.1
R1	9 mg/ℓ AE1	(35)	(1)	(4.3)	(0.42)	(0.10)	(2.04)	(2.00)	(3.97)	(3.43)	(27.7)	(109)	(49)	(3)	(10.5)	(6.8)	(3.8)	(4.2)
3.2.8b	10 days	301	16	25.3	3.66	1.56	4.99	45.79	27.41	18.38	204.2	3217	1817	59	89.9	53.7	39.4	31.0
R2	0 mg/ℓ	(35)	(1)	(4.3)	(1.16)	(0.27)	(1.58)	(2.00)	(6.18)	(4.92)	(14.2)	(69)	(37)	(4)	(12.3)	(6.1)	(3.9)	(3.5)

f = filtered; a = anaerobic; d = anoxic; b1 = 1st aerobic; b2 = 2nd aerobic reactors of 3-stage Phoredox system (see Fig. 3.1).

Table 3.13: Mass balances for experimental periods 3.2.2 to 3.2.8b. Sludge age (R_s) = 20 d. See Appendix 8 for definition of symbols.

Period Unit	Days (Al dose, mg/ℓ Al)	Flow Qi, ℓ/d	VSS mg/ℓ	No3a mgN/ℓ	No3d mgN/ℓ	No3b2 mgN/ℓ	Nte mgN/ℓ	No3e mgN/ℓ	Nti mgN/ℓ	% N Bal.	Ot mgO/ℓ.h	Sti mgO/ℓ	Ste mgO/ℓ	% COD Bal.	Pt_{rem} mgP/ℓ	P/VSS mgP/gVSS	% P Bal.
3.2.2 R1	26 days 5 mg/ℓ AE1	34.8 (0.8)	3040 (101)	0.01 (0.01)	0.98 (0.6)	5.47 (1.56)	2.67 (0.64)	2.8 (0.78)	40.3 (6.3)	**90%**	18.84 (3.18)	478 (61)	25 (2)	**94%**	27.99 (7.2)	177.52 (10.15)	**89%**
3.2.2 R2	26 days 0 mg/ℓ	34.6 (4.2)	2693 (154)	0.01 (0.01)	1.25 (0.94)	7.51 (3.26)	2.92 (0.56)	2.43 (0.93)	40.3 (6.3)	**103%**	20.86 (4.42)	478 (61)	26 (3)	**94%**	24.25 (8.68)	155.85 (11.69)	**80%**
3.2.3 R1	40 days 5 mg/ℓ AE1	35.6 (0.7)	2756 (241)	0.07 (0.03)	2.86 (1.09)	7.64 (1.94)	3.8 (1.81)	7.63 (2.16)	38.3 (12.3)	**105%**	16.09 (1.81)	379 (56)	23 (3)	**95%**	26.84 (8.56)	215.8 (24.43)	**100%**
3.2.3 R2	40 days 0 mg/ℓ	36.5 (0.8)	2749 (152)	0.06 (0.03)	1.09 (0.85)	6.03 (1.89)	3.68 (2.02)	5.78 (1.84)	38.3 (12.3)	**105%**	16.60 (2.17)	379 (56)	22 (4)	**95%**	24.39 (7.66)	185.11 (21.77)	**91%**
3.2.4 R1	49 days 5 mg/ℓ AN	35.7 (2.3)	2422 (157)	0.03 (0.04)	0.99 (0.88)	3.34 (2.78)	2.32 (1.45)	4.71 (2.16)	38.3 (9.3)	**100%**	15.75 (2.24)	346 (57)	22 (4)	**101%**	26.37 (5.23)	242.01 (16.9)	**100%**
3.2.4 R2	49 days 0 mg/ℓ	35.9 (2.4)	2386 (197)	0.02 (0.04)	0.71 (0.47)	2.69 (1.35)	2.44 (2.09)	3.28 (1.24)	38.3 (9.3)	**94%**	15.42 (2.05)	346 (57)	20 (2)	**101%**	25.28 (5.19)	223.53 (19.91)	**94%**
3.2.5 R1	14 days 9 mg/ℓ AN	36.3 (0.3)	2110 (126)	0.05 (0.01)	2.48 (0.73)	5.97 (0.89)	2.09 (0.48)	5.84 (1.34)	31.9 (8.8)	**110%**	10.79 (0.59)	251 (33)	18 (2)	**100%**	22.57 (3.87)	267.38 (7.53)	**110%**
3.2.5 R2	14 days 0 mg/ℓ	36.1 (0.2)	1911 (86)	0.05 (0.02)	2.91 (0.49)	6.13 (0.86)	1.93 (0.77)	6.03 (1.48)	31.9 (8.8)	**130%**	12.10 (3.03)	251 (33)	16 (3)	**107%**	16.69 (3.49)	245.62 (9.98)	**130%**
3.2.6 R1	14 days 9 mg/ℓ AE1	35.8 (0.6)	2105 (259)	0.06 (0.07)	1.28 (0.46)	3.93 (0.80)	2.5 **Estimate**	4.25 (0.78)	24.0 **Estimate**	106% **Estimate**	13.20 (1.35)	312 (56)	20 (2)	**96%**	31.55 (6.48)	272.69 (14.74)	**81%**
3.2.6 R2	14 days 0 mg/ℓ	35.8 (0.7)	1805 (117)	0.04 (0.01)	2.20 (0.63)	4.38 (1.12)	2.5 **Estimate**	5.08 (1.28)	24.0 **Estimate**	95% **Estimate**	14.17 (1.48)	312 (56)	18 (3)	**94%**	24.88 (6.85)	245.07 (7.06)	**79%**
3.2.7 R1	31 days 9 mg/ℓ AE1	36.4 (0.6)	2095 (123)	0.03 (0.03)	1.96 (0.98)	5.11 (2.65)	2.16 (0.46)	4.80 (1.6)	31.0 (2.2)	**86%**	10.76 (1.35)	350 (56)	16 (2)	**73%**	25.66 (5.89)	162.35 (36.46)	**58%**
3.2.7 R2	31 days 0 mg/ℓ	36.7 (0.7)	1894 (140)	0.04 (0.84)	1.61 (1.91)	4.84 (2.83)	2.03 (0.55)	4.33 (1.6)	31.0 (2.2)	**84%**	11.37 (1.48)	350 (56)	18 (3)	**71%**	18.99 (6.73)	115.73 (13.65)	**50%**
3.2.8a R1	22 days 9 mg/ℓ AE1	36.3 (0.7)	2069 (102)	0.01 (0.01)	1.55 (0.91)	3.77 (1.25)	2.25 (0.55)	4.35 (1.31)	27.0 Estimate	**141%**	10.71 (1.55)	317 (77)	15 (4)	**74%**	26.00 (6.45)	245.30 (22.04)	**86%**
3.2.8a R2	22 days 0 mg/ℓ	36.1 (1.1)	1885 (123)	0.0 (0.0)	0.65 (0.53)	3.08 (0.8)	2.30 (0.72)	3.62 (1.21)	27.0 Estimate	**97%**	11.05 (1.96)	317 (77)	16 (5)	**79%**	18.84 (6.81)	169.32 (20.58)	**75%**
3.2.8b R1	10 days 9 mg/ℓ AE1	36.9 (0.4)	2006 (49)	0.0 (0.0)	3.55 (1.09)	6.48 (1.81)	3.67 (0.42)	6.54 (2.04)	273 (4.3)	**156%**	10.39 (1.17)	301 (35)	20 (1)	**73%**	18.99 (3.43)	274.75 (27.67)	**89%**
3.2.8b R2	10 days 0 mg/ℓ	36.6 (1.5)	1817 (37)	0.0 (0.0)	2.32 (1.25)	5.04 (1.93)	3.66 (1.16)	4.99 (1.58)	25.3 (4.3)	**99%**	11.12 (1.13)	301 (35)	16 (1)	**80%**	18.38 (4.92)	204.18 (14.19)	**88%**
									Mean:	**106%**			Mean:	**89%**		Mean:	**88%**
									S.D.:	**20%**			S.D.:	**12%**		S.D.:	**19%**

3.3.3.1 Mass balances for COD, N and P (second alum dosing period)

The mass balance data in Table 3.13 show considerable variation. One of the root causes of this variation was a deficiency in the experimental set-up, namely, that the influent COD and TKN concentrations varied considerably. This problem stemmed from the fact that the source sewage at Darvill WWW usually was so dilute that even with acetate addition (theoretical 150 mg/ℓ as COD), the influent COD to the pilot plants seldom exceeded 500 mg/ℓ (the original target concentration). Since it was not considered desirable (from the point of view of affecting the biological nutrient removal mechanisms) to further dilute the stronger batches of sewage to the same concentrations as the weaker batches, nor to add any other artificial substrates to maintain a constant COD or TKN, it was decided to accept the variations arising from the experimental set-up. Moreover, in reality the full-scale plant at Darvill is subjected to such variations in influent strength, and one of the long-term objectives of the work was to determine whether chemical addition could confer a consistent P removal advantage under such conditions. However, on the basis of the mass-balances, the variance in the data was problematic.

During the periods under review (Table 3.13) the N mass balances were also adversely affected by problems experienced with the TKN method used. The time used for the digestion step under sulphuric acid reflux was found to be critical. The method (Appendix 1) requires digestion at 380°C for 2½ h after the water has been evaporated off over approximately 1 h at 180 °C. It was found that that accurate control of the heating block temperature was difficult to achieve in practice and required considerable trial-and-error. A general observation was that if the initial heating period was too long (or too rapid, at temperatures exceeding 180 °C), then at the end of the total digestion time, the samples often crystallised. Difficulty was then experienced in re-dissolving the precipitate at room temperature and low recovery of nitrogen sometimes occurred in quality control checks. On the other hand, if the digestion period was made too short, low TKN results were reported, probably due to incomplete digestion. The ideal digestion time and heat setting on the block were found to be those which produced a clear syrup after digestion for 2 h (following the initial hour for water evaporation) and cooling to room temperature. If crystallisation occurred, the sample was discarded and the analysis repeated.

3.3.3.2 P mass balance around the anaerobic reactor

Using Eqn 3.1 (see 3.3.2 above) and the measured data given in Tables 3.12 and 3.13, the mass of P release in the anaerobic reactor of the Test unit (R1, alum dosed) can be compared to that of the Control on a percentage basis. These results (R1/R2) were as follows, the respective experimental periods with alum dosing (refer to Table 3.3):

- Period 3.2.2: 120% (5 mg/ℓ alum[3] as Al, AE1 zone, 50 mg/ℓ $CaCO_3$ added bicarb.)
- Period 3.2.3: 98% (5 mg/ℓ as Al, AE1 zone, 100 mg/ℓ $CaCO_3$ added bicarb.)
- Period 3.2.4: 85% (5 mg/ℓ as Al, AN zone, 100 mg/ℓ $CaCO_3$ added bicarb.)
- Period 3.2.5: 75% (9 mg/ℓ as Al, AN zone, 150 mg/ℓ $CaCO_3$ added bicarb.)
- Period 3.2.6: 90% (9 mg/ℓ as Al, AE1 zone, 150 mg/ℓ $CaCO_3$ added bicarb.)
- Period 3.2.7: 97% (New culture; 9 mg/ℓ as Al, AE1 zone, 150 mg/ℓ $CaCO_3$ added bicarb.)
- Period 3.2.8a: 94% (9 mg/ℓ as Al, AE1 zone, No added bicarb., good P removal in R1)
- Period 3.2.8b: 84% (9 mg/ℓ as Al, AE1 zone, No added bicarb., poor P removal in R1)

These data suggest that initially (Period 3.2.2) alum dosing stimulated the biological P removal mechanism (as measured by P release in the anaerobic zone) in a newly developed semi-enhanced culture. During Period 3.2.3, this stimulatory effect was lost and P release in the Test and Control units was very similar. It seems unlikely that this effect was directly attributable to the increase in bicarbonate alkalinity supplement added to the influent since the Test and Control units received the identical influent. Rather, it appears that a slow process of inhibition of the biological P removal mechanism set in due to the alum addition in the Test unit (Periods 3.2.2 through 3.2.6). A change of alum dosing point from the first aerobic to the anaerobic zone appeared to cause a significant decrease in observed P release, and the decrease became more pronounced

[3] In all cases, the alum dose is expressed as mg/ℓ as Al based on *influent*.

when the alum dose was doubled. This may be expected since the alum would precipitate a portion of the biologically released phosphate. Conversely, when the high alum dose was switched from the anaerobic back to the first aerobic zone, P release in the Test unit increased and was only 10% less than that in the Control.

A new enhanced culture was developed between Periods 3.2.6 and 3.2.7 (see Table 3.1). With the resumption of alum dosing (to the aerobic zone) in Period 3.2.7, initially the magnitude of P release in the anaerobic zone of the Test unit was similar to that of the Control unit, but deteriorated through Periods 3.2.8a and 3.2.8b (see above). The withdrawal of the bicarbonate alkalinity supplement in Period 3.2.8a appeared to have contributed to the inhibitory effect of alum on the biological P release in the anaerobic zone, but there was a delay of approximately one sludge age (Period 3.2.8a = 22 days, see Table 3.1; sludge age = 20d) before the effect became particularly noticeable. This effect also became apparent with the deterioration in system P removal for the Test unit (R1) compared to the Control (R2) (Table 3.12). The delay suggests that the partial loss of system P removal in the Test unit relative to the Control, was growth-related; by implication, a decline in the growth of poly-P accumulating organisms (PAO) may be deduced. As a corollary, a slow rate of change of the inert solids (including chemical precipitates) according to sludge age may be implicated.

In summary, from P release considerations in the anaerobic zone, the biological mechanism appeared to be significantly inhibited by alum dosing, particularly when administered directly to the anaerobic zone. A low dose of alum (5 mg/ℓ as Al) to the aerobic zone appeared to have the smallest inhibitory effect on the biological mechanism (i.e. 2% inhibition relative to the Control, or possibly even a stimulatory effect on the biological mechanism). A high alum dose (9 mg/ℓ as Al) to the anaerobic zone exerted a more inhibitory effect (25%, compared to the Control). The inhibitory effect of alum appeared to be greater when the influent bicarbonate alkalinity was lower. However, the Test system's response to the inhibitory effect of alum, including that resulting from reduced alkalinity, tended to be slow and may be growth-related or related to the "turnover" of inert solids with sludge age.

3.3.3.3 P removal

Figure 3.4 shows a plot of TP removal (influent- effluent) for experimental periods 3.2.2 to 3.2.6. It illustrates that no simple trend in P removal pattern could be identified. Some of the variance in these data could be ascribed to the units not achieving ideal steady-state for various practical reasons. As noted above, one such reason was the tendency for settled sewage at Darvill WWW to be dilute: many batches of sewage fell well below the target total COD concentration of 500 mg/ℓ (Table 3.12). This was especially evident in the summer months when rain and groundwater ingress to the sewer network diluted the sewage and weakened biological P removal (Fig. 3.4, e.g. periods of October 1994 and December 1994/ early January 1995).

Figures 3.5 and 3.6 show the TP removal data broadly grouped into low and high alum dosing periods respectively, and numerically sorted from lowest to highest to produce normal probability plots. The median value would lie at the intersection of the plot with the vertical line for 50% of the observations, while the lower and upper quartiles would lie on the 25% and 75% lines respectively.

Both Figs. 3.5 and 3.6 indicate that alum dosing produced an advantage in terms of higher P removal in R1 (alum dosed) compared with the Control (R2). However, Fig. 3.5 shows that at a dose of 5 mg/ℓ alum (as Al), the Test unit (R1) showed a relatively small advantage compared to the Control (R2) on median basis, noting that the longest experimental period at this (low) dose was for alum dosing to the anaerobic zone[4] when significant inhibition of the biological P removal mechanism was observed, based on P release data for the anaerobic zone (see 3.3.3.2 above). Furthermore, it was noted in section 3.3.3.2 that the inhibitory effect of alum on the biological P removal mechanism appeared to be exerted slowly. Since the periods of high alum dose (9 mg/ℓ

[4] The tendency for the lines to converge near the median in the case of the low alum dosing periods (Fig. 3.5) is due to the fact that nearly half of the data for this figure was collected during the period of weakest *additional* P removal in R1 vs. R2, namely, Period 3.2.4 (9 mg/ℓ Al to AN zone of R1, covering 49 days of a total of 115 days for Periods 3.2.2 to 3.2.4) - see Table 3.1.

as Al) were of comparatively short duration (Periods 3.2.5 and 3.2.6 = 14d each, compared to a sludge age of 20d), these periods may have been too short to allow the deterioration in biological P removal to reach a point that the reduction in *net P removal due to alum addition* (i.e. difference in P removal between Test and Control units) became obvious. Hence, the difference in the P removal for the two units plotted in Fig. 3.6 may have been smaller had the experimental period(s) been several sludge ages in duration.

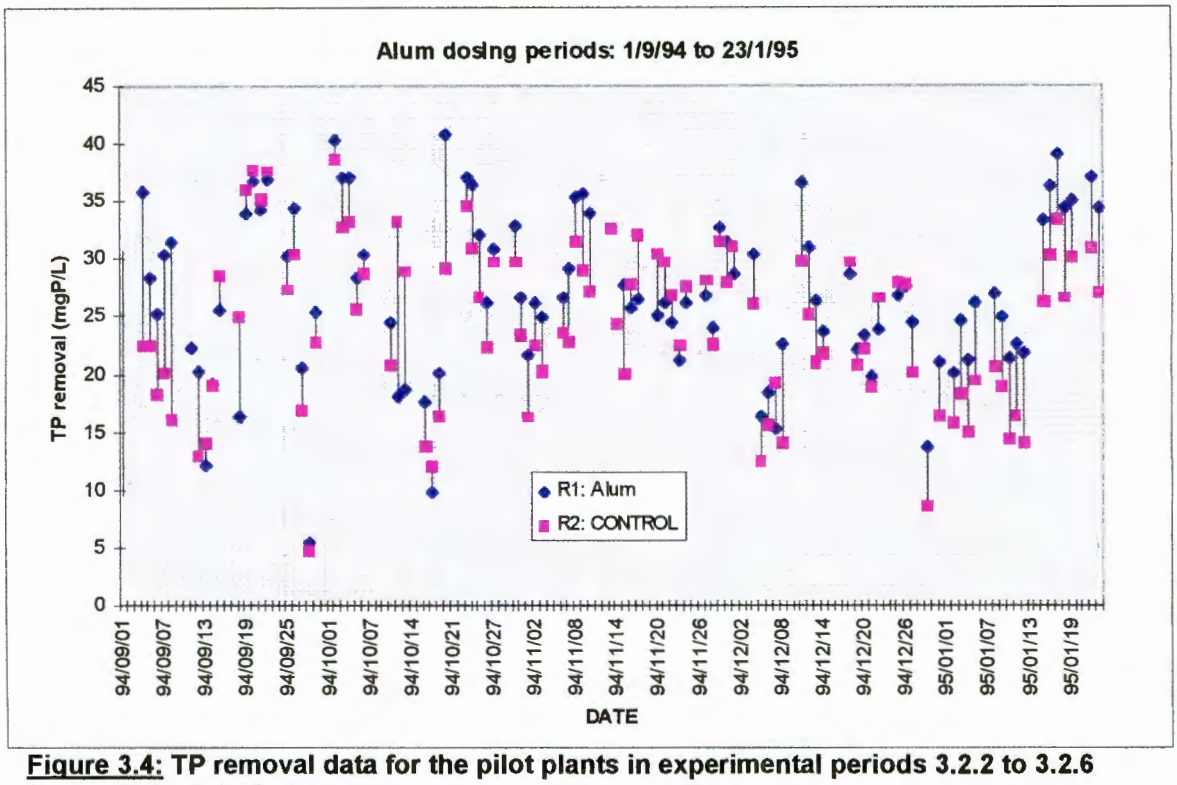


Figure 3.4: TP removal data for the pilot plants in experimental periods 3.2.2 to 3.2.6 (second alum dosing period).

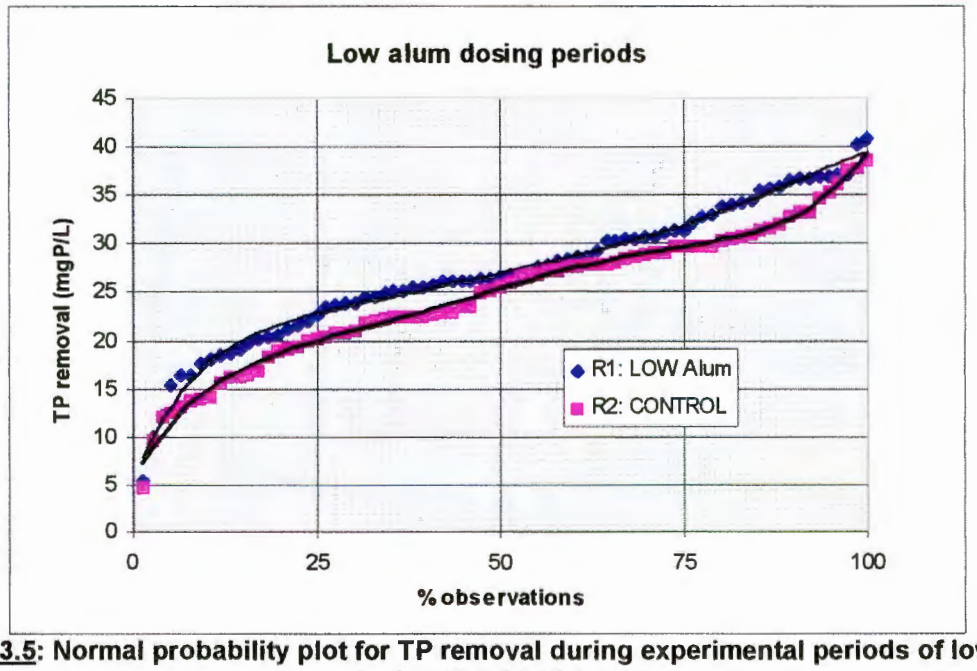


Figure 3.5: Normal probability plot for TP removal during experimental periods of low alum dosing (3.2.2 to 3.2.4).

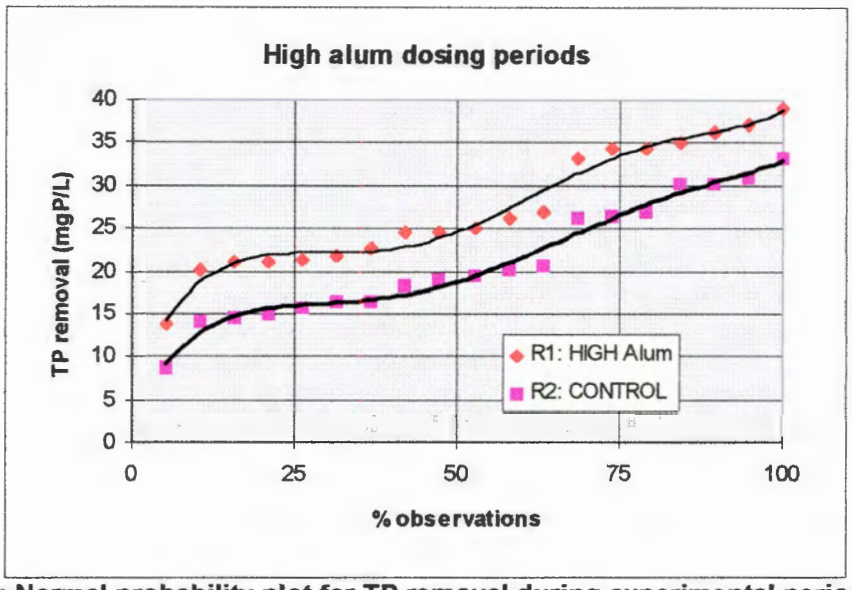


Figure 3.6: Normal probability plot for TP removal during experimental periods of high alum dosing (3.2.5 & 3.2.6).

Table 3.14: Summary of P removal due to alum dosing, as measured in the pilot plants. Pt_{rem} implies TP removal (Influent - Effluent) : **(1)** = R1 (Alum dosed); **(2)** = R2 (Control).

Period	Al dose, (1) mmol/d ; (zone)	Δ Pt_{rem} ($Pt_{rem,R1}$ - $Pt_{rem,R2}$) mgP/ℓ	M (Δ Pt_{rem}) mgP/d	mol $P_{removed}$ / mol Al_{dosed}
3.1.6	6.2; AE1	6.25	206.64	1.08
3.2.2	6.2; AE1	3.74	135.00	0.70
3.2.3	6.2; AE1	2.45	65.26	0.34
3.2.4	6.2; AN	1.09	33.86	0.18
3.2.5	12.4; AN	5.88	216.78	0.57
3.2.6	12.4; AE1	6.67	238.79	0.62
3.2.7	12.4; AE1	6.67	237.09	0.62
3.2.8a	12.4 AE1	7.16	263.68	0.69
3.2.8b	12.4 AE1	0.61	28.03	0.07

The additional P removal due to alum addition is illustrated in Figs. 3.5 & 3.6. Based on the observed P removals (Pt_{rem}) for the Test and Control systems in Table 3.12 and the actual flow rates and alum doses given in Table 3.3, the additional P removal and alum dose in the Test (R1) compared with the Control (R2) is given in Table 3.14, according to experimental period. From these data, the molar ratio mol $P_{removed}$ / mol Al_{dosed} (i.e. *additional* P removed) was calculated and also is listed in Table 3.14. This ratio varied from 1.08 for Period 3.1.6 to 0.07 for Period 3.2.8b after deterioration of P removal in the Test unit. The alum dosing regime was based on the assumption that a molar ratio of 0.5 mmol $P_{removed}$/ mmol Al_{dosed} would materialise. Calculation of the average molar ratio of $P_{removed}$/ Al_{dosed} in Table 3.14 is based on the assumption that the difference in P removal between R1 and R2 is *only ascribable to chemical addition*. The difficulty with this assumption is that the effects of both chemical and biological origin are lumped; if the biological mechanism was weaker in R1 than R2, it will reflect as a lower molar ratio of $P_{removed}$/ Al_{dosed} but could be incorrectly interpreted as indicative of a weaker chemical precipitation mechanism. For example, biological P removal may not have been the same between the Test

and Control units for Periods 3.2.3 and 3.2.4. Fractionation data (discussed in sections 3.3.3.4 and 3.4 below; see also Table 3.18) showed that the additional P removal component in the Test unit compared to the Control ($Pt_{rem,R1}$ - $Pt_{rem,R2}$) for Periods 3.2.5, 3.2.6 and 3.2.8(b) could be accounted for as ortho P in the PCA extract (i.e. the fraction ascribed to chemical precipitate). This gave good agreement between the two methods of determining the molar ratio of P/Al (Tables 3.18 and 3.14) for these periods. However, this was not the case for Periods 3.2.3 and 3.2.4 which gave similar molar ratios to the other experimental periods based on the PCA ortho P fraction (Table 3.18), but lower results from the difference in system P removal between the Test and Control units (Table 3.14). The mass balance data (section 3.3.3.2) and fractionation data (section 3.3.3.4) did indicate a degree of inhibition of the biological P removal mechanism during Periods 3.2.3 and 3.2.4 (more so in the latter), but not to such a degree that the lower molar ratios in Table 3.14 for these periods could be fully explained. A fuller explanation is possible in the light of the modelling results obtained with the IAWQ (or UCT) model results for these periods (Chapter 7, section 7.2.3.2.1). The models showed poor agreement between predicted and observed effluent (or second aerobic reactor) phosphate results for both units in Periods 3.2.3 and 3.2.4, which suggests that steady-state conditions were not approximated sufficiently closely in the pilot plants to validate the results in Table 3.14 for these periods. Similarly, the experimental data for Period 3.1.6 (see section 3.3.2 and Fig. 3.4) showed that the P removal performance of the Control (R2) decreased significantly during the middle of the experimental period (ca. 15/6/94 to 23/6/94), but improved subsequently; this could have resulted in over-estimation of the additional P removal in the Test unit (R1) relative to R2, and hence produced the very high ratio of 1.08 mol $P_{removed}$/ mol Al_{dosed} (greater than stoichiometric for $AlPO_4$). Fractionation data (Table 3.18) suggested that the stoichiometry of P precipitation between 0.5 and 0.6 mol $P_{removed}$/ mol Al_{dosed} for Period 3.1.6, which is more line with that for later periods.

Bearing in mind the above-mentioned constraints, certain important points emerge from the results in Table 3.14. Some of these have been already been examined in preceding sections of this chapter and may be summarised as follows:

- The alkalinity of the influent sewage does not appear to greatly influence the molar ratio of $P_{removed}$/ Al_{dosed}. Neglecting the results for Periods 3.2.3 and 3.2.4 for reasons given above and accepting the fractionation result for Period 3.1.6 (from Table 3.18, as discussed above), the molar ratio of additional $P_{removed}$ / Al_{dosed} was in the range 0.53 to 0.70 (average 0.62) for Periods 3.1.6, 3.2.2, 3.2.5, 3.2.6, 3.2.7 and 3.2.8a, despite the fact that the influent bicarbonate supplement varied from 0 to 150 mg/ℓ (as $CaCO_3$). This could indicate that it is not the alkalinity *per se* but the reactor pH which is an important factor in determining the efficiency of chemical precipitation (see below);
- The additional bicarbonate alkalinity *appeared* to play an important part in the stable operation of the pilot plants. In order to illustrate this, experimental periods 3.2.7 and 3.2.8 (a&b) may be examined. A new enhanced culture was developed between Periods 3.2.6 and 3.2.7. Despite this, P removal performance was virtually identical in the two periods. However, when the additional influent bicarbonate was withdrawn (Period 3.2.8a), initially P removal was little affected, or may even have improved slightly in R1, relative to R2 (possibly indicating more efficient chemical precipitation). However, after about one sludge age, settling began to deteriorate, particularly in R1, with the appearance of pin floc sludge and a turbid effluent, and P removal deteriorated in both units (Period 3.2.8b). Virtually the identical pattern had been observed earlier in experimental period 3.1.6 (see above) when a high acid dose to both units apparently caused the emergence of a pinfloc sludge, first in R1 (dosed 6.2 mmol/d Al) and subsequently also in R2 (Control).
- The loss of additional P removal advantage in Period 3.2.8b (Table 3.14) connects with the weaker P release in the anaerobic reactor of the Test unit, compared to the Control (section 3.3.3.2). Hence, there may be a connection between increased efficiency of the chemical precipitation mechanism (at lower reactor pH) and inhibition of the biological P removal mechanism.
- Changes in reactor pH were noted in response to the presence (or magnitude) of alkalinity supplement (refer to data in Tables 3.10 and 3.11). During Period 3.1.6, the first aerobic reactor of the Test unit (i.e. point of alum and acid addition in R1) had a median pH = 7.12 , while the second aerobic reactor of R1 had a median pH = 7.47. During Period 3.2.2 (with 50 mg/ℓ as $CaCO_3$ influent alkalinity supplement) the first aerobic zone of the Test unit (point of alum dosing) showed a median pH of 7.27, while the second aerobic reactor of R1 had a median pH

University of Cape Town

= 7.48. During Period 3.2.3 (with 100 mg/ℓ as $CaCO_3$ influent alkalinity supplement), the first aerobic zone of the Test unit (point of alum dosing) showed a median pH = 7.38, while the second aerobic reactor had a median pH = 7.58. During Period 3.2.5 (with 150 mg/ℓ as $CaCO_3$ influent alkalinity supplement), the *anaerobic* zone of the Test unit (point of alum dosing) showed a median pH = 6.98, while the first and second aerobic reactors respectively had median pH values of 7.33 and 7.49. During Period 3.2.6 (with 150 mg/ℓ as $CaCO_3$ influent alkalinity supplement), the first aerobic zone of the Test unit (point of alum dosing) showed a median pH = 7.58, while the second aerobic reactor had a median pH = 7.65. From these data it can be seen that the effect of the bicarbonate influent supplement (in the absence of significant acid dosing to the units) was to increase the pH in the aerobic reactors between 0.1 and 0.3 pH units on a median basis, which is comparatively small. The significant observations relating pH to the system performances appear to be as follows:

* Period 3.1.6 saw alum dosed to the first aerobic zone (with a relatively large acid dose and no influent alkalinity supplement) at a median pH of ca. 7.1, and produced chemical precipitation of similar (or better) efficiency[5] to later alum dosing periods but a large apparent deterioration in the biological P (bio-P) removal mechanism during the last month of the experimental period;
* Period 3.2.2 (using a newly developed enhanced culture) saw alum dosed to the same point as in Period 3.1.6 (first aerobic zone) but with a much smaller acid dose and a moderate alkalinity supplement, giving a median pH of ca. 7.3 at the dosing point; this period saw less efficient chemical precipitation than Period 3.1.6 but a healthy bio-P mechanism without signs of inhibition (possibly even bio-P stimulation), relative to the Control (see section 3.3.3.2);
* Period 3.2.3 continued from Period 3.2.2 but with a higher alkalinity supplement and a slightly higher median pH (ca. 7.4) at the dosing point; the precipitation efficiency for this period (from fractionation data - Table 3.18) was little affected but the anaerobic zone P release data (section 3.3.3.2) and fractionation data (section 3.3.3.4) suggested that the bio-P mechanism was beginning to show signs of inhibition relative to the Control;
* Period 3.2.4 continued with the same alkalinity dose as in Period 3.2.3, but the point of alum dosing was moved to the anaerobic zone (pH not measured at this point). This did not change the precipitation efficiency significantly (from fractionation data - Table 3.18) but appeared to increase the degree of inhibition of the bio-P mechanism, as judged from the P release and fractionation data (sections 3.3.3.2/ 4);
* In Period 3.2.5, the influent alkalinity supplement was increased and the alum dose was also increased. The anaerobic zone pH was measured and found to be 7.0 on a median basis (minimum 6.8). Chemical precipitation efficiency was slightly lower (from fractionation data -Table 3.18), and the bio-P mechanism showed a greater degree of inhibition, as judged from the P release and fractionation data (sections 3.3.3.2/ 4);
* In Period 3.2.6, the alum dose and alkalinity supplement were left unchanged from Period 3.2.5, but the dosing point was moved back to the aerobic zone where the median pH was higher (pH ca. 7.6). The precipitation efficiency increased slightly and the bio-P mechanism showed signs of recovery (more so in the mass balance results for the release in the anaerobic zone - section 3.3.3.2, but to some extent also in the fractionation results - section 3.3.3.4);
* In Period 3.2.7, using a newly developed enhanced culture, with the same alum dosing conditions as in Period 3.2.6, chemical precipitation efficiency was the same as in Period 3.2.6, and the bio-P mechanism (although not yet fully developed) showed signs of only slight inhibition (similar to Period 3.2.3);
* In Period 3.2.8a, the alkalinity supplement was withdrawn, and the pH at the dosing point (aerobic zone) showed a decrease to pH ca. 7.3 (but with a wider variance, falling as low as pH 6.9). The chemical precipitation efficiency appeared to improve to a certain extent while the bio-P mechanism showed signs of slightly greater inhibition;
* Finally, in Period 3.2.8b, about one month (or 1.5 sludge ages) after the withdrawal of the alkalinity supplement, the system P removal performance in the Test unit (alum

[5] The term precipitation efficiency is used here to mean the difference in P removal between the Test unit (chemical dosed) and the Contol unit, as measured by the molar ratio of additional P removed ($P_{removed}$) to metal dosed (Al_{dosed}).

dosed) showed a sudden marked deterioration; seen in isolation, this could have suggested that chemical P removal efficiency had dropped dramatically. However, the anaerobic zone P release data (section 3.3.3.2) and especially the fractionation data (section 3.3.3.4), indicated that the bio-P mechanism was significantly inhibited in the Test unit. The weakened bio-P mechanism appeared to have reduced the system P removal in the Test unit (with alum) to approximately the same as that of the Control, thereby creating the *appearance* of reduced chemical precipitation efficiency. In fact, the fractionation data (Table 3.18) showed that the chemical precipitation efficiency during Period 3.2.8a was amongst the highest for alum dosing periods.

- Finally the higher alum doses (especially when dosing to the anaerobic zone) tended to increase the effluent turbidity slightly, judged by visual observation. Problems with whitish lumps of suspected protozoa[6] in the mixed liquor were also encountered, particularly when dosing to the anaerobic zone. It is not clear what the significance of this observation is. Effluent turbidity is sometimes linked to excessive grazing by protozoa or sometimes to loss of protozoan predators in the mixed liquor. The microbial ecology of the experimental systems was not examined in detail in this study, but microscope observations of the mixed liquor suggested that smaller flocs and more free bacteria occurred in the Test unit (with alum), compared to the Control unit.

From the above discussion, the following conclusions may be drawn:

1. The efficiency of the chemical P removal mechanism cannot be measured only on the basis of the *system* P removal of a Test unit dosed with a chemical P precipitant (e.g. alum), even if the additional system P removal (i.e. chemical component) is determined in relation to a Control unit operated in parallel without chemical addition. The reason is that inhibition of the biological P (bio-P) removal mechanism may occur in the Test unit as a result of simultaneous precipitation processes, which may be falsely interpreted as a decrease in chemical precipitation efficiency.
2. It appears that inhibition of the bio-P removal mechanism in the presence of simultaneous alum addition is more pronounced under conditions where the reactor pH at the point of dosing is $\leq$ pH 7.2. Under such conditions, the bio-P removal mechanism may deteriorate to such an extent that the benefit of adding alum is lost in terms of the system (i.e. total) P removal. The bio-P removal mechanism need not disappear entirely for the loss of benefit from chemical addition to be noticed.
3. It is surprising to find observations of a small but significant degree of inhibition of the bio-P removal mechanism under conditions where a large excess of ortho P was present in the effluent of the Test (and Control) systems.
4. There are also signs that partial inhibition of the bio-P removal mechanism occurs where alum is dosed under conditions (or at a point) of higher reactor pH (in range 7.2 to 7.6). However, provided that the system is not phosphate-limited, a sustainable benefit from chemical addition may be realised in terms of system P removal.
5. No major differences in chemical precipitation efficiency were found between alum dosing to the anaerobic zone compared to the aerobic zone. There was some evidence that dosing to the anaerobic zone may be slightly less efficient than dosing to the aerobic zone. This may be due to metal complexation/ coagulation of soluble organic matter being present in the anaerobic zone to a greater degree than the aerobic zone.

3.3.3.4 Fractionation results (second alum dosing period)

Fractionation results for the alum dosing periods (Periods 3.2.1 through 3.2.8 a&b) are summarised in Fig. 3.7. The results in Fig. 3.7 show that alum dosing had the effect of increasing the ortho P ("chemical precipitate") fraction by between 2.8 times (at the low alum dose of 5 mg/ℓ as Al) and 5.2-times (at the higher alum dose of 9 mg/ℓ as Al). The biggest increase in the ortho P fraction of the Test versus Control unit was for the high alum dose to the anaerobic zone (Period 3.2.5), implying that the chemical mechanism was relatively strong during this period. This connects with the observation in section 3.3.3.2 that the biological mechanism was relatively

[6] Microscopic investigations during later experimental periods when these white lumps recurred suggested that they may have been caused by excessive growth of the protozoan *Vorticella* forming dense colonies which result in tangled masses of its "stalk".

inhibited during this period, as measured by the mass of P release in the anaerobic reactor, compared to the Control.

The PCA-extracted complex P (poly P) fraction decreased by 16% in the Test unit when receiving the low alum dose (5 mg/ℓ as Al) to the aerobic zone, relative to the Control (Table 3.16). This decrease was more pronounced (24%) with the low alum dose to the anaerobic zone, and very pronounced (37 to 40%) at the high alum dose (9 mg/ℓ as Al) to either the anaerobic or aerobic zones (Table 3.16). Concomitant with the decrease in the PCA complex P fraction there was an increase in the residue total P (Fig. 3.7). Since the NaOH step had not been included in the fractionation procedure used at this stage (refer to Chapter 2, section 2.4.4), the complex ("biological") P content of the residue fraction was estimated from the extent to which it registered P release in the anaerobic batch test (refer to Chapter 2, Table 2.11 for details). By addition, the total complex ("biological") P fractions of the PCA and residue fractions could be compared for the two units (Table 3.16). On this basis, the inhibition of the biological P fraction(s) in the Test unit was 11 to 16% at the low alum dose, and 23 to 24% at the high alum dose. Again, these results are in approximate agreement with the degree of inhibition of the biological mechanism judged from the mass of P released in the anaerobic zone (section 3.3.3.2).

As noted in Table 3.3, new (semi-) enhanced cultures were re-developed for Periods 3.2.7 and 3.2.8 (a/b). The principal difference in operation of the units between Periods 3.2.7 and 3.2.8 (a/b) was the withdrawal of the influent bicarbonate supplement at the end of Period 3.2.7. Table 3.16 shows that the biological fractions were still increasing through Periods 3.2.8(a) & (b), suggesting that the steady-state was not fully established despite the preceding period of three sludge ages with the same acetate feed concentration. Nevertheless, alum dosing initially appeared to have a stimulatory effect on the biological P fractions during Period 3.2.8(a) (see "Total 'Biological'" fractions for this period in Table 3.16), possibly in a similar manner to that observed for Period 3.2.2 from mass balance considerations (see 3.3.3.2 above). However, approximately one month later (Period 3.2.8b), inhibition of the biological fractions was apparent in the Test unit (Table 3.16). The percentage inhibition was similar in Period 3.2.8(b) to that noted for the high alum dose in Periods 3.2.5 and 3.2.6, viz. 24%. Furthermore, Table 3.1.6 shows that the chemical P fraction had reached a large difference (more than five-fold) between the Test and Control units during Period 3.2.8(b). As suggested in section 3.3.3.3 above, it appears that the lower bicarbonate alkalinity of the system increased the efficiency of chemical precipitation mechanism with alum, The biological mechanism was unable to function as effectively under such conditions and the key factor may be the pH at the point of alum dosing (see section 3.3.3.3). Had Period 3.2.8(b) been extended for a longer time, it is likely that the biological fractions in the Test unit would have diminished even further, relative to the Control.

Anaerobic batch P-release tests with excess acetate (Figs. 3.8a & 3.8b), showed that release did occur from the residue fraction of the Test unit sludge such that the residue TP after P-release was similar to that of the Control. This provides justification for including the estimated complex P fraction of the residue with that of the PCA extract when estimating the total "biological" P component from fractionation results (see above discussion in relation to Table 3.16). However, the apparent shift in solubility of the complex P fraction from the PCA extract to the residue (or alkaline extract, as later incorporated in the full fractionation procedure - see Table 2.11 in Chapter 2) is probably not significant in respect of the biological P removal mechanism *per se.* An experiment was reported in Chapter 2 (section 2.4.7) which showed that partitioning of complex P between the PCA and alkaline fractions is strongly influenced by the presence of metal ions during the fractionation test. In that experiment (see section 2.4.7) iron chloride was artificially added during the fractionation test. However, aluminium ions would probably exert a similar effect, and the resultant phosphorus fractionation pattern may be the similar irrespective of whether the metal ions arose from the mixed liquor solids or from *in vitro* addition (as in the experiment described in section 2.4.7). Similarly, the apparent shift (or uptake) in complex P from the PCA fraction to the residue fraction for the Control after the anaerobic batch P-release test, could be an artefact of the fractionation procedure and may not be biologically significant Fig. 3.8b).

Comparing ortho P release to the supernatant in anaerobic batch tests (Figs. 3.8a and 3.8b), the Test unit showed a depression of 7 to 17% for low alum dosing periods (5 mg/ℓ as Al, based on influent), compared to the Control. For high alum dosing periods (9 mg/ℓ as Al, based on influent),

the depression was 20 to 23 %. This is in good agreement with the results based on the estimated total biological fractions (see Table 3.16 and above discussion) and the mass balance results for P release in the anaerobic reactors of the Test and Control units themselves.

3.3.5 Magnesium removal

Table 3.15 shows magnesium removal for all alum dosing periods during which it was measured. From Table 3.15 it can be seen that the molar ratio of $Mg_{removed}$ / $P_{removed}$ increased significantly in both the Test and Control units during Periods 3.1.6 and 3.2.8 (a&b) when the system alkalinity was expected to be lower, either due to acid dosing or the absence of a bicarbonate supplement in the influent (Tables 3.1 and 3.3). The underlying cause of this observation is uncertain. It suggests that the system alkalinity is important in the role which magnesium ions play as a counter-ion for poly P charge neutralisation in the biological P removal mechanism. It is not clear whether there is a link between this observation and the weakening of system P removal in the Test unit found during Periods 3.1.6 and 3.2.8b (see 3.3.2 and 3.3.3.3 above). On the other hand, it is also possible that magnesium is chemically co-precipitated with aluminium. Arvin (1985) pointed out that in biological systems a wide range of phosphate precipitates could theoretically form, including poorly crystallised or amorphous calcium phosphates which include variable amounts of various cations and anions, including magnesium and aluminium ions.

Ignoring the results for Periods 3.1.6 and 3.2.8(a&b), Table 3.15 shows that the average molar ratio of $Mg_{removed}$ /$P_{removed}$ was 0.26. The same value was reported by Wentzel *et al.* (1988) for batch P release and P uptake tests, implying that this magnesium fraction serves as counter-ion to biologically stored poly P. Furthermore, on the basis of the magnesium data, inhibition of the biological P removal mechanism in the presence of alum dosing did not exceed approx. 0.04 mol $Mg_{removed}$ /mol $P_{removed}$ during Periods 3.2.2 through 3.2.7 (with supplemented influent alkalinity). This suggests that the biological mechanism was inhibited by up to about 15% during these periods, which is in agreement with the P release mass balance estimates (section 3.3.3.2 above).

Table 3.15: Magnesium removal data for alum dosing periods. ND: Not determined.

Unit Period	Flow ℓ/d	Influent mg Mg/ℓ	Effluent mg Mg/ℓ	Removal mg Mg/d	No. of results	P removal mg P/d	mol Mg removed per mol P removed
3.1.6 R1	31.9	26.68	18.66	255.848	13	938.18	0.35
3.1.6 R2	31.6	26.68	20.25	203.198		731.54	0.36
3.2.2 R1	34.8	17.01	11.67	185.83	8	974.05	0.25
3.2.2 R2	34.6	17.01	12.39	159.85		839.05	0.25
3.2.3 R1	35.6	17.48	12.66	171.59	11	955.50	0.23
3.2.3 R2	36.5	17.48	12.46	183.23		890.24	0.27
3.2.4 R1	35.7	17.22	11.3	211.34	9	941.41	0.29
3.2.4 R2	35.9	17.22	11.06	221.14		907.55	0.31
3.2.5	-	ND	ND	ND	-	-	-
3.2.6	-	ND	ND	ND	-	-	-
3.2.7 R1	36.4	20.88	15.53	194.74	5	1037.51	0.24
3.2.7 R2	36.7	20.88	17.22	134.32		779.32	0.22
3.2.8a R1	36.3	26.15	17.84	301.65	5	943.80	0.41
3.2.8a R2	36.1	26.15	19.3	247.29		680.12	0.47
						Average:	0.30
						Average excluding Periods 3.1.6 & 3.2.8a:	0.26

Table 3.16: Comparison of P fractionation data between Test and Control units during alum dosing periods (see also Fig. 3.7).

Date, Unit	Period	Alum dose Low = 5 mg/ℓ High = 9 mg/ℓ as Al based on Influent	PCA Complex P mgP/gVSS	RES Complex P estimate * mgP/gVSS	Sum of PCA and RES Complex P fractions mgP/gVSS (#)	PCA ortho P fraction mgP/gVSS	VSS during fractionation g/ℓ	Sum of PCA and RES Complex P fractions mgP/ℓ ##	PCA ortho P fraction mgP/ℓ
		see Table 3.3 (zone dosed)	"Biological"	"Biological"	Total "Biological"	"Chemical"		Total "Biological"	"Chemical"
16/8/94, R1	**3.2.1**	**None**	**89.47**	**0**	**89.47 (87%)**	**13.88 (13%)**	**2.366**	**211.68 -5%**	**32.84**
16/8/94, R2		-	91.29	0	91.29 (87%)	13.47 (13%)	2.452	223.84 -	33.03
28/8/94, R1	**3.2.1**	**None**	**112.70**	**4.69**	**117.39 (87%)**	**18.15 (13%)**	**2.698**	**316.72 +18%**	**48.97**
28/8/94, R2		-	108.94	0	108.94 (86%)	17.89 (14%)	2.459	267.88 -	43.99
1/11/94, R1	**3.2.3**	**Low, AE1**	**123.61**	**7.40**	**131.01 (72%)**	**49.83 (28%)**	**2.569**	**336.57 -12%**	**128.01**
1/11/94, R2		-	147.48	0	147.48 (89%)	18.18 (11%)	2.582	380.79 -	46.94
19/12/94, R1	**3.2.4**	**Low, AN**	**122.55**	**11.36**	**133.91 (71%)**	**54.97 (29%)**	**2.338**	**313.08 -13%**	**128.52**
19/12/94, R2		-	160.30	0	160.30 (89%)	19.42 (11%)	2.256	361.64 -	43.81
8/1/95, R1	**3.2.5**	**High, AN**	**106.14**	**29.60**	**135.74 (63%)**	**80.04 (37%)**	**2.049**	**278.13 -15%**	**164.00**
8/1/95, R2		-	177.15	0	177.15 (91%)	16.56 (9%)	1.836	325.25 -	30.40
22/1/95, R1	**3.2.6**	**High, AE1**	**117.16**	**23.40**	**140.56 (61%)**	**89.61 (39%)**	**2.224**	**312.65 -17%**	**199.29**
22/1/95, R2		-	185.16	0	185.16 (89%)	22.65 (11%)	2.034	376.62 -	46.07
23/3/95, R1	**3.2.8a**	**High, AE1**	**55.04**	**14.68**	**69.72 ** (44%)**	**90.11 (56%)**	**2.358**	**164.40 ** N/A**	**212.48**
23/3/95, R2		-	58.97	0	58.97 ** (66%)	30.97 (33%)	2.131	125.67 -	66.00
26/4/95, R1	**3.2.8b**	**High. AE1**	**101.97**	**7.73**	**109.7 (52%)**	**102.38 (48%)**	**1.994**	**218.74 -19%**	**204.15**
26/4/95, R2			144.24	0	144.24 (88%)	19.63 (12%)	1.865	269.00 -	36.61

* Estimate based on P release from RES fraction during batch tests

** New enhanced culture developed in Period 3.2.7; biological mechanism not fully developed in Period 3.2.8a.

#: (%) Percentages in parentheses refer to % sum of "Total Biological" and "Chemical"

##: Percentages e.g. -5% refer to percent inhibition of R1 "Total Biological" (mg/ℓ), relative to R2

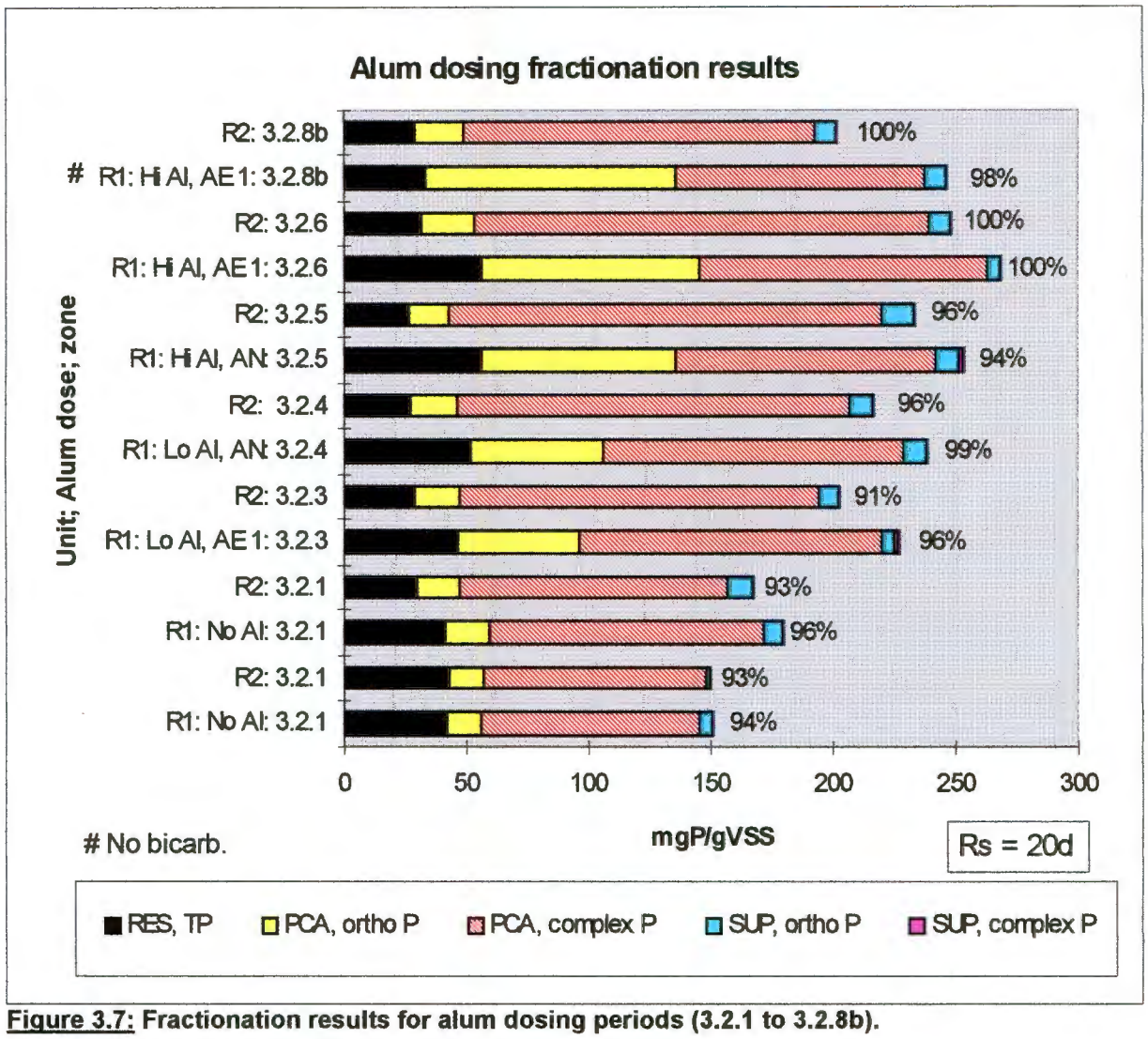


Figure 3.7: Fractionation results for alum dosing periods (3.2.1 to 3.2.8b).

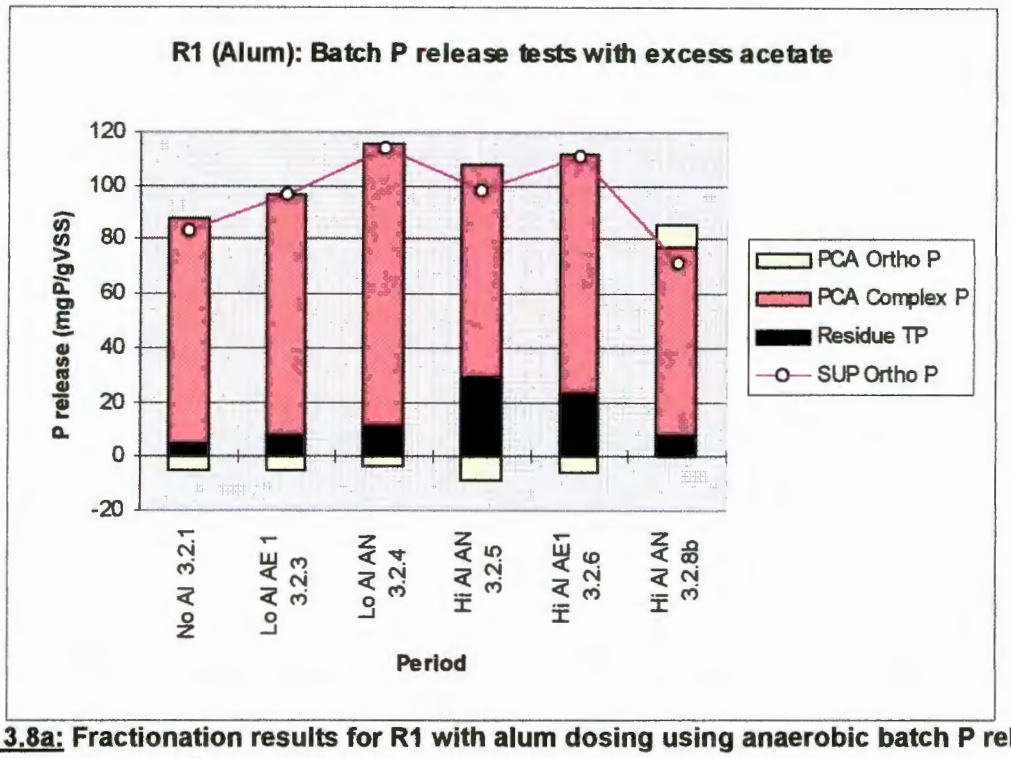


Figure 3.8a: **Fractionation results for R1 with alum dosing using anaerobic batch P release test in the presence of excess acetate.**

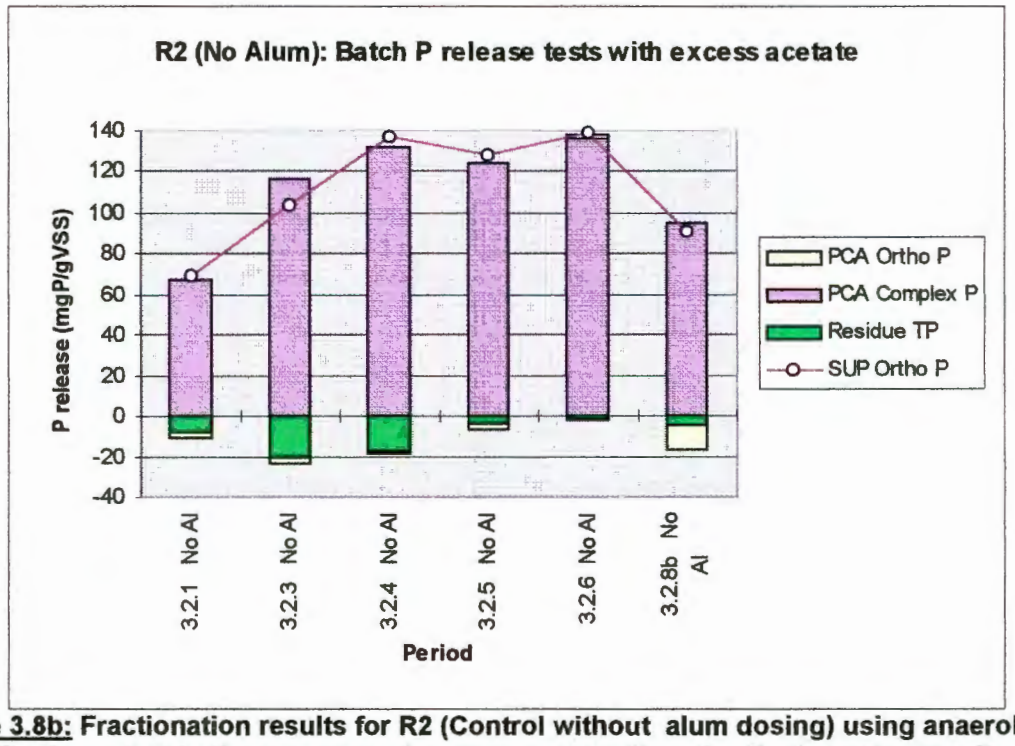


Figure 3.8b: **Fractionation results for R2 (Control without alum dosing) using anaerobic batch P release test in the presence of excess acetate. Negative P release implies P uptake in the residue during batch test.**

3.3.6 Sludge production

In Table 3.12, TSS and VSS data are given for the experimental periods with alum dosing to the pilot plants. Since the two units (R1, alum dosed; R2, Control) were operated in an identical manner with exception of alum dosing, the VSS data in Table 3.12 suggests that the low alum dose (5 mg/ℓ as Al, based on influent) resulted in an increase in VSS production of approx. 5%, while the higher alum dose (10 mg/ℓ as Al, based on influent) gave an increase in VSS of approx. 12%. However, variance in the solids data reduce the confidence in these estimates, particularly since the difference in VSS between the two units was small in comparison to the absolute values and standard deviation. Assuming the observed VSS results are valid, the increase in VSS would presumably be due to complexation/ coagulation of organic material by alum. This would reduce the efficiency of phosphate precipitation, and may partly explain why the observed chemical P removal was usually less than stoichiometric (i.e. <1 mol $P_{removed}$/ mol Al_{dosed} ; see below).

From the data in Table 3.12, the inorganic suspended solids (ISS) may be calculated :

$$ISS = TSS - VSS$$

Furthermore, the difference in ISS (ΔISS) between the two units (R1 and R2) can be calculated. It may be expected that ΔISS would arise from the chemical precipitate due to alum dosing. Hence, it is possible to compare the observed ΔISS with estimates of precipitate formation based on the additional P removal in R1 ($\Delta Pt_{rem} = Pt_{rem,R1} - Pt_{rem,R2}$). In order to do this, the stoichiometry of the precipitate must either be assumed or estimated. A suitable estimate may be obtained from taking the molar ratio of alum dosed to ΔPt_{rem} (Table 3.14), on the assumption that all the metal is removed through precipitation reactions and becomes bound in the mixed liquor matrix. From a review of the literature (see Chapter 7, section 7.1), ideally the precipitation of phosphate with aluminium would be stoichiometric in the form of $AlPO_4$ (i.e. 1 mol Al/ mol P). If the observed precipitation is not stoichiometric (i.e. > 1 mol Al_{dosed}/ mol $P_{removed}$) then it may be assumed that some mixture of aluminium phosphate and aluminium hydroxide precipitation is probably taking place[7]. A convenient chemical formula for the hypothetical precipitate aluminium hydroxy-phosphate may be written as:

$$Al_r\ PO_4\ OH_{(3r-3)}$$

where r = stoichiometry of Al:P (mol Al/ mol P).

Furthermore, it should be noted that upon ashing (during VSS determination, at 550 °C), aluminium hydroxide will be converted to aluminium oxide (Power *et al.*, 1992). On a similar basis to the typical conversion of $Al(OH)_3$ to Al_2O_3, the above-mentioned hypothetical formula for aluminium hydroxy-phosphate converts to the following formula for hypothetical aluminium phosphate oxide:

$$Al_r\ PO_4\ O_{(1.5r-1.5)}$$

where r = stoichiometry of Al:P (mol Al/ mol P).

Using the approach described above and the hypothetical formulae for precipitate before and after ashing, the data in Table 3.17 were calculated.

From Table 3.17 it can be seen that the estimates of ΔISS from precipitation stoichiometry were of the same order of magnitude as the observed ΔISS. For some experimental periods, the recovery of estimated and observed ΔISS was in the range 77 to 119%. For the remainder of the experimental periods, the observed ΔISS vales were smaller than the estimated values. This probably indicates that the experimental systems were not operating suitably close to steady-state during these periods. The TSS and VSS (and hence ISS) in the systems can be expected to take

[7] In this case, it may be valid to use the observed stoichiometry taken from the difference in system P removal between the two units (see section 3.3.3.3), for the reason that the ISS changes will include those resulting from changes in the biologically stored phosphorus.

several sludge ages to reach steady-state. Since the sludge age of the systems during alum dosing was 20 days, changes in the operational state of the unit(s) during the following periods may have influenced the results in Table 3.17:

- Period 3.1.6: Alum dosing to R1 commenced for the very first time at the start of the experimental period, implying that ISS results would be expected to increase for approximately the first 40 days (two sludge ages). By taking the observed ISS results for the final 20 days of Period 3.1.6, the agreement with estimated ISS improved to some extent but the P removal was substantially weaker during the latter period (see Fig. 3.3), which weakens confidence in the observed stoichiometry of precipitation;
- Period 3.2.5: The alum dose to R1 was doubled at the start of this period and the period was short (14d, less than one sludge age). Although this period was sufficiently long to note the immediate response in terms of additional (chemical) P removal, it was not sufficiently long to observe the new steady state ISS in R1.
- Period 3.2.6: This period followed immediately on from Period 3.2.5 with a change of alum dosing point and was also of short duration (14d).

Summarising, the data in Table 3.17 suggest that increase in ISS due to chemical dosing may be estimated with reasonable certainty using the above-mentioned hypothetical chemical formulae and the observed stoichiometry of aluminium dosed : additional P removal. The ISS data will be re-examined in Chapter 7 (sections 7.2.2.2 and 7.2.4.2) in the light of predictions using the IAWQ ASM2 model, which incorporates a simple precipitation model.

Finally, it is worth noting from section 3.4 below that observations of actual alkalinity losses attributable to alum dosing (see Table 3.11) suggested that the average formula for chemical precipitate from alum could be involve another (unknown) cation in a theoretical average formula of :

$$Al_{1.33}(X^{2+})\,PO_4\,(OH)_3$$

In the absence of further substantive evidence for this proposal, the use of the former generalised precipitate formula $Al_rPO_4OH_{(3r-3)}$ appeared to be acceptable for the purposes of ISS (or TSS) estimation.

...../ Table 3.17

Table 3.17: Comparison of observed ISS and that predicted from chemical P removal for alum dosing periods.

For all experimental periods, sludge age (R_s) = 20 d.

ISS = TSS - VSS (see Table 3.12 for TSS and VSS data)

Al~P~OH : hypothetical metal hydroxy-phosphate, $Al_r PO_4 OH_{(3r-3)}$

Al~P~O : hypothetical metal phosphate oxide, $Al_r PO_4 O_{(1.5r-1.5)}$

	ISS Table 3.12	ISS Table 3.12	**Δ ISS**	ΔM Pt_{rem} Table 3.14	Stoichiometry Observed Table 3.14	*Stoichiometry Observed*	Estimate from *Stoichiometry Observed*	**Estimated ΔISS from *Stoichiometry Observed***	Estimate/ Observed
Period (Duration) Alum dose	mg/ℓ	mg/ℓ	**mg/ℓ**	mg P/d	mol P_{rem}: mol Al $_{dosed}$	mol Al $_{dosed}$: mol P_{rem}	*Al~P~OH*	***Al~P~O***	***Al~P~O/*** Δ ISS
Unit:	R1	R2	**R1-R2**	R1-R2	P:Al	*Al:P*	mg/ℓ	**mg/ℓ**	%
3.1.6 (50 d) 5 mg/ℓ Al, AE1	1829	1578	**251**	206.6	1.08	*0.93*	484	**493**	196%
3.2.2 (26 d) 5 mg/ℓ Al, AE1	2036	1529	**507**	135.0	0.70	*1.43*	423	**392**	77%
3.2.3 (40 d) 5 mg/ℓ Al, AE1	2190	1900	**290**	65.6	0.34	*2.94*	362	**292**	101%
3.2.4 (49 d) 5 mg/ℓ Al, AN	2232	1931	**301**	33.9	0.18	*5.56*	326	**242**	80%
3.2.5 (14 d) 9 mg/ℓ Al, AN	2088	1708	**380**	216.8	0.57	*1.75*	790	**701**	185%
3.2.6 (14 d) 9 mg/ℓ, AE1	2192	1798	**394**	238.8	0.62	*1.61*	817	**738**	187%
3.2.7 (31 d) 9 mg/ℓ Al, AE1	1827	1210	**617**	237.1	0.62	*1.61*	812	**733**	119%
3.2.8a (22 d) 9 mg/ℓ Al, AE1	2218	1302	**916**	263.7	0.69	*1.45*	835	**770**	84%

AN = Anaerobic zone; AE1 = First aerobic zone

3.4 P REMOVAL IN DARVILL FULL-SCALE PLANT USING ALUM DOSING

Since the pilot-scale experiments reported in this chapter were always conducted under conditions in which excess P was present in the influent, the question arises of whether the biological mechanism would be able to "compete" as effectively with the chemical mechanism in the presence of alum dosing under P-limiting conditions. This aspect was addressed by examining the results for alum dosing in the Darvill full-scale plant.

The Darvill full-scale activated sludge plant is described in detail in Chapter 6. Briefly, it consists of a conventional aerobic activated sludge plant with three parallel aeration basins sharing mixed liquor and sludge recirculation from five secondary sedimentation tanks. There are no formal partitions in the aeration basins, but an informal anoxic zone was created by the removal of the first row surface aerators and replacement with paddle mixers. If necessary, additional informal anoxic "zones" can be created by turning off one or more rows of aerators. In 1993-4, the plant was retrofitted with a formal anaerobic basin preceding the informal anoxic zone, along with other major upgrades, such as flow balancing and the provision of fermented primary sludge supernatant (see Chapter 6, section 6.2).

Figure 3.9a shows the history of P removal at Darvill WWW prior to the introduction of chemical dosing. Noting the scale of this graph, it is clear that the influent phosphate concentration was frequently >10 mgP/ℓ TP (>8 mgP/ℓ), which is high for this Works (see Table 6.2, Chapter 6). This was caused by trade effluent interference, as discussed in Chapter 6, and contributed to the failure of the Works to achieve the 1 mgP/ℓ dissolved effluent ortho P standard. The other factors limiting the biological P removal performance at that time were the absence of a formal anaerobic zone, the lack (or inconsistency) of fermented primary sludge supernatant supply fermentation and a tendency to under-aerate in order to maximize "simultaneous" denitrification in the aeration basins. The effect of the latter is evident from the ammonia and nitrate profiles (Fig. 3.9b). The alkalinity profile (Fig. 3a) followed the effluent ammonia profile (Fig. 3b), as expected from less alkalinity consumption for nitrification. Interestingly, the secondary effluent pH (which may be expected to reflect the aerobic reactor pH) showed a decrease; this was probably also resulted in a lower pH in the informal "anaerobic/anoxic" zone (not measured). A lower pH in the latter would be counter-productive to BEPR (Smolders *et al.*, 1994).

Figure 3.9c shows the early history of simultaneous alum addition at Darvill WWW for P removal. Comparing Figs. 3.9a and 3.9c for the period Sep.- Oct. 1992, and noting the respective scales, it is clear that alum addition (ca. 30 to 45 mg/l as $Al_2(SO_4)_3.14H_2O$ had the expected effect of reducing the system alkalinity by approx. 15 to 25 mg/ℓ). Initial attempts were made to compensate for this by dosing lime (approx. 20 mg/l as $CaCO_3$) into the influent (raw) sewage. The secondary effluent (or activated sludge reactor) pH fell into the range 6 to 7 during this period. Control of aeration, and nitrification-denitrification performance were also poor during this period. Turbid effluents with elevated COD resulted. A combination of these factors led to poor P removal performance in spite of alum addition. Lime dosing to the raw sewage was judged to be only partially effective since a major part of the lime could be sedimented in the primary sedimentation tanks (PSTs). Therefore, an attempt was made to dose lime into the return activated sludge (RAS), where good mixing was achievable through the RAS pumps. However, this had the effect of inhibiting denitrification (probably due to resultant high anoxic zone pH) as seen from the increased effluent nitrate concentrations (Fig. 3.9d) [8]. As expected, the increased nitrate concentrations had a negative effect BEPR and this negated any benefit from alum addition, even at a dose of 60 mg/ℓ (Fig. 3.9c). In the second week of November 1992, lime dosing was to a channel conveying settled sewage via the main pump-station to the activated sludge plant. This resulted in a rapid improvement in system P removal performance (Fig. 3.9d). Effluent nitrate concentrations dropped into the range 2 to 6 mgN/ℓ and effluent alkalinity stabilised in the range ca. 80 to 120 mg/ℓ as $CaCO_3$. Effluent (reactor) pH tended toward the range ca. 6.5 to 7.4.

[8] From the available data it is impossible to say whether this was due to nitrite accumulation in the form of incompete nitrification or denitrification since the nitrate results in Figs. 3b & d were actually nitrate + nitrite (due to the analytical method applied at that time).

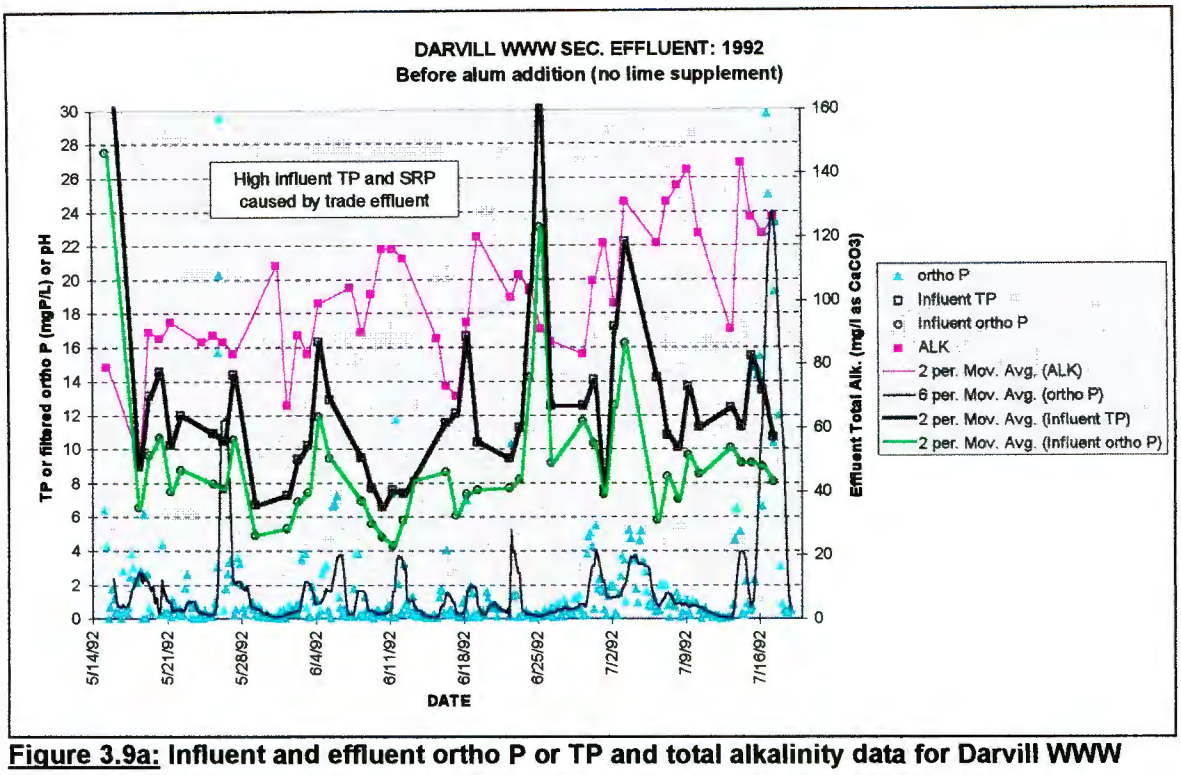


Figure 3.9a: Influent and effluent ortho P or TP and total alkalinity data for Darvill WWW full-scale activated sludge plant prior to alum dosing (May to July 1992).

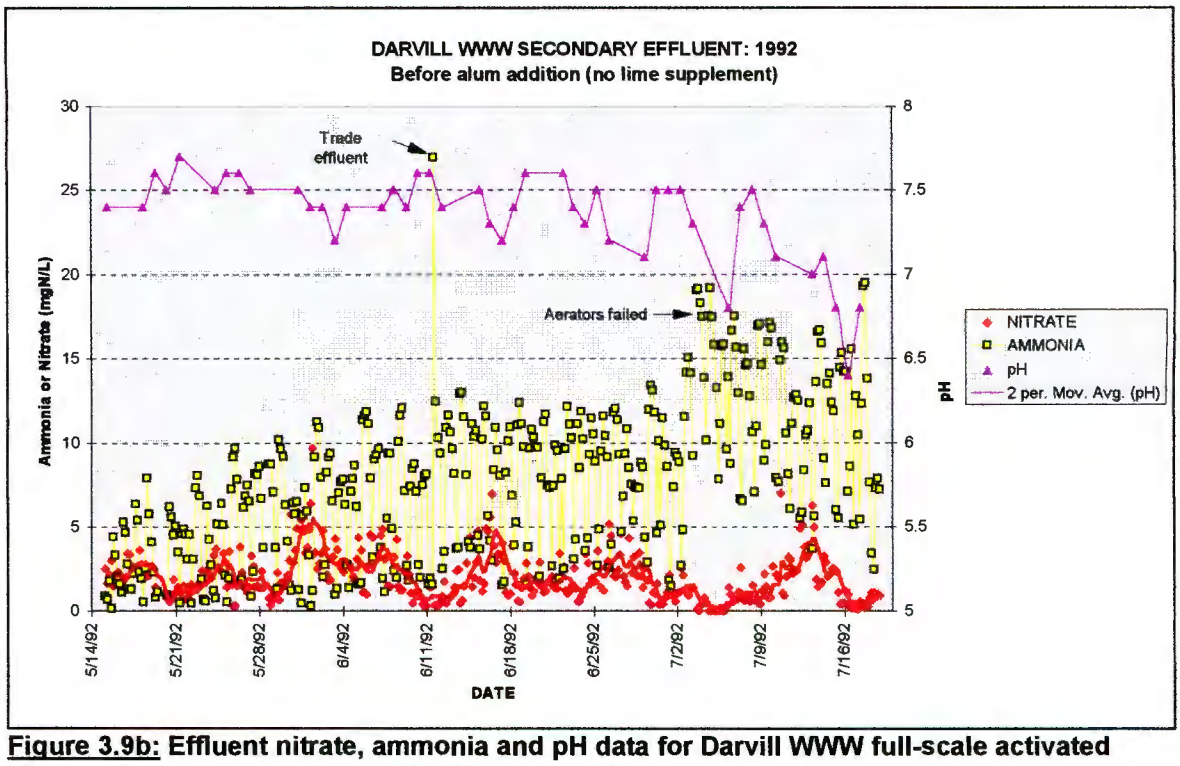


Figure 3.9b: Effluent nitrate, ammonia and pH data for Darvill WWW full-scale activated sludge plant prior to alum dosing (May to July 1992).

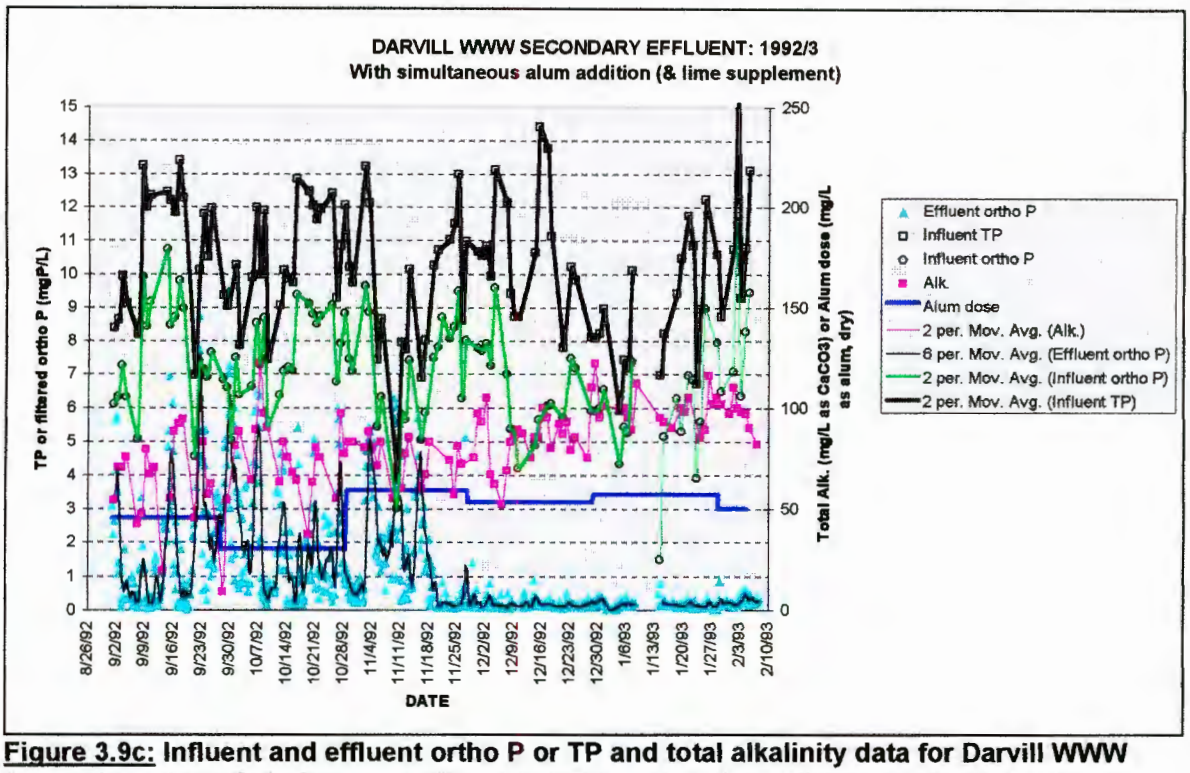


Figure 3.9c: Influent and effluent ortho P or TP and total alkalinity data for Darvill WWW full-scale activated sludge plant after the introduction of simultaneous alum addition (August 1992 to February 1993).

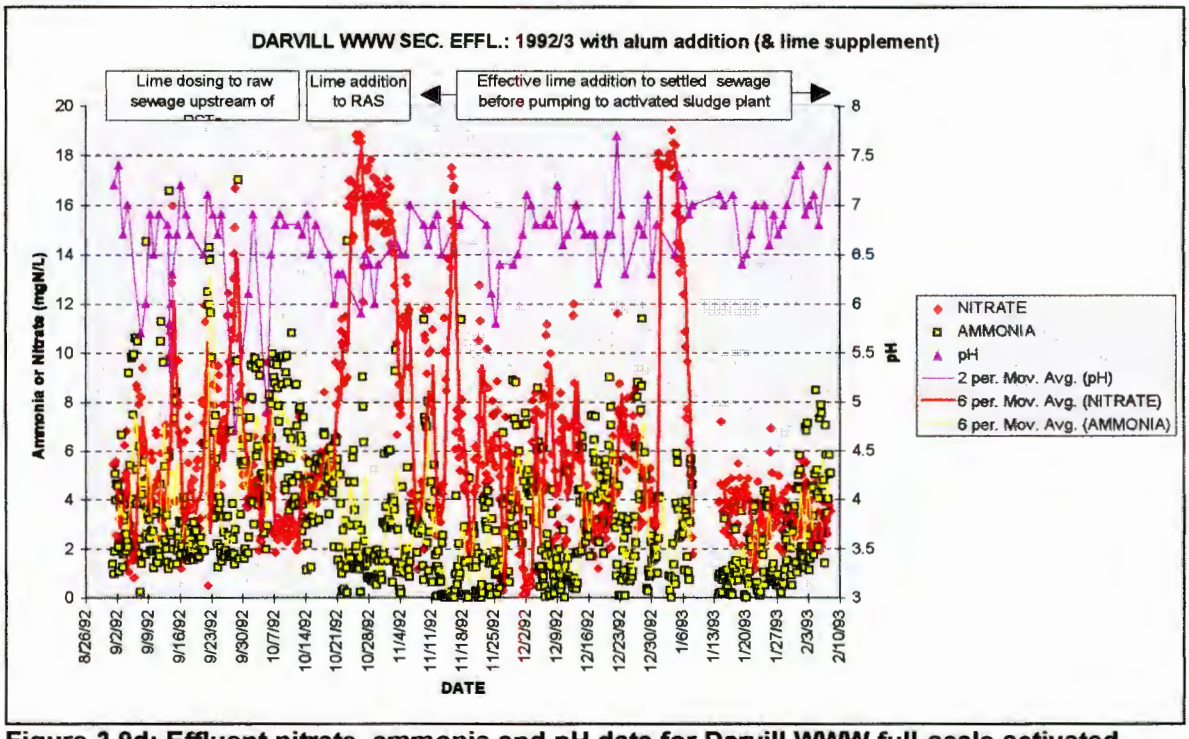


Figure 3.9d: Effluent nitrate, ammonia and pH data for Darvill WWW full-scale activated sludge plant after the introduction of simultaneous alum addition (August 1992 to February 1993).

Summarising, the early full-scale experience at Darvill WWW showed that simultaneous alum dosing in the absence of suitable alkalinity correction and control of aeration (for "simultaneous" nitrification-denitrification) is unlikely to produce improved system P removal in a BNR/ BEPR plant. With these control measures in place, low effluent P concentrations (<0.5 mgP/ℓ) were frequently achieved (Fig. 3.9d). During this period, with an alum dose of approx. 60 mg/ℓ as alum (5.5 mg/ℓ as Al), chemical P removal of approximately 4 mgP/ℓ may be expected for a stoichiometry of 0.6 to 0.7 mol $P_{removed}$ / mol Al_{dosed} (refer to Tables 3.14 and 3.18). For a system P removal of approximately 10 mgP/ℓ (Fig. 3.9d [9]) on this plant, it may be deduced that approx. 60% removal was achieved by biological means. However, during the holiday period (ca. 22 Dec.1992 to 6 Jan. 1993), dilute sewage with a high influent nitrate concentration (6 to 20 mgN/ℓ) was received. High effluent nitrate concentrations resulted (Fig. 3.9d), which would be expected to weaken BEPR. However effluent ortho P concentrations remained low (Fig. 3.9c) during the holiday period, probably because influent P concentrations had also dropped (ca. 4.3 to 7.5 mgP/ℓ), suggesting that chemical P removal was dominant during that period.

As discussed in Chapter 7 (see Fig. 7.3a), from chemical equilibrium considerations it can be shown that limiting total chemical equilibrium soluble (ortho) phosphate residual concentrations of between 0.3 and 1.1 mgP/ℓ may be expected for alum precipitation in the pH range 7.0 to 7.5.

Figure 3.10a shows that during the period January 1994 to July 1996, the *average* monthly secondary effluent ortho P concentration of the Darvill activated sludge plant was generally <1 mgP/ℓ. The same was true for the period July 1997 to April 1998, as shown in Fig. 3.10c[10]. The alum dose required to achieve this varied with the season and the influent P concentrations, but was usually in the range 22 to 50 mg/ℓ as alum (2.0 to 4.5 mg/ℓ as Al). This is somewhat lower than the low dose (5 mg/ℓ as Al) tested in the pilot plants. However, the degree of compliance with the 1 mgP/ℓ (ortho P) standard averaged 88%, ranging from 47% to 100%[11] (see Fig. 6.4 in Chapter 6). Hence, in order to evaluate the extent to which the activated sludge plant may have been operating under P limiting conditions, it is necessary to look at the effluent ortho P data in more detail.

Figures 3.10b and 3.10d show the effluent ortho P concentrations for grab samples taken at 4 hourly intervals by the operators at Darvill WWW in the 1995-6 and 1997 respectively. The large volume of data in Fig. 3.10b shows that the effluent ortho P actually varied widely and frequently exceeded 1 mgP/ℓ, often reaching concentrations >3 mgP/ℓ [12]. There were a few periods (e.g. 31/1/96 to 9/3/96; 11/4/96 to 17/5/96; 24/8/97 to 16/9/97; 25/8/97 to 10/10/97; 12/10/97 to 25/10/97) during which the effluent ortho P concentrations remained *consistently* <0.5 mgP/ℓ (usually <0.3 mgP/ℓ) for between one and five weeks. However, *between* these periods, effluent ortho P concentrations often exceeded 1 mgP/ℓ. Due to the changes in influent composition from the full-scale plant (i.e. lack of steady state), it is not possible to state conclusively that inhibition of the biological P removal mechanism by alum addition was the underlying cause of this variable P removal performance in the activated sludge plant. Nevertheless, it can be concluded that, despite moderately low *average* effluent ortho P concentrations (ca. 0.5 to 1.0 mgP/ℓ) (see summary statistics at the bottom of Tables 3.10b & d), the Darvill activated sludge plant generally did not operate under P limiting conditions. Frequent excursions of effluent ortho P concentrations to >1 mgP/ℓ prevented strictly limiting P conditions (e.g. <1 mgP/ℓ) from developing in the reactor for extended periods (e.g. > 5 weeks).

In summary, although simultaneous alum dosing has been crucial to the achievement of the 1 mgP/ℓ ortho P standard for this plant, it is possible that partial inhibition of the biological P removal

[9] Subtracting effluent ortho P from influent TP in Fig. 3.10d for the period ca. 20 Nov. to 20 Dec. 1992.

[10] The period November 1996 to June 1997 was characterised by severe trade effluent problems, related mainly to the illegal discharge of vegetable oil & grease waste to sewer. Some of these are discussed in Chapter 6 (section 6.4) in the context of the ferrous-ferric plant trial conducted in the period Aug. to Nov. 1996.

[11] Excluding the period Nov. 1996 to Jun. 1997 (see footnote 11 above).

[12] The very high peaks (> 3 mgP/ℓ) were probably caused by high influent P concentrations, as a result of trade effluent problems at Darvill WWW and were not plotted in Fig. 3.9.2. These high influent concentrations are not fully reflected in the influent TP or ortho P data (Figs. 3.9a & c), which stem from two grab samples per day. The impact of trade effluent of P removal performance at Darvill WWW is discussed in Chapter 6.

mechanism may weaken the overall performance of the plant. Consistently low effluent P concentrations may not be achieved and the biological P removal *potential* may not be optimally exploited. In this regard, chemical dosing ahead of the primary settling tanks (i.e. pre-precipitation) may serve to reduce the P load to the activated sludge plant, while minimising the risk of inhibiting part of the biological P removal potential. However, with pre-precipitation there is still the risk of limiting the supply of phosphate to the biological process downstream. Hence, only post-precipitation methods offer the possibility of excluding the risk of sacrificing biological P removal potential due to P limitation in the interests of achieving very low effluent P concentrations.

...../ Figures 3.10a to d

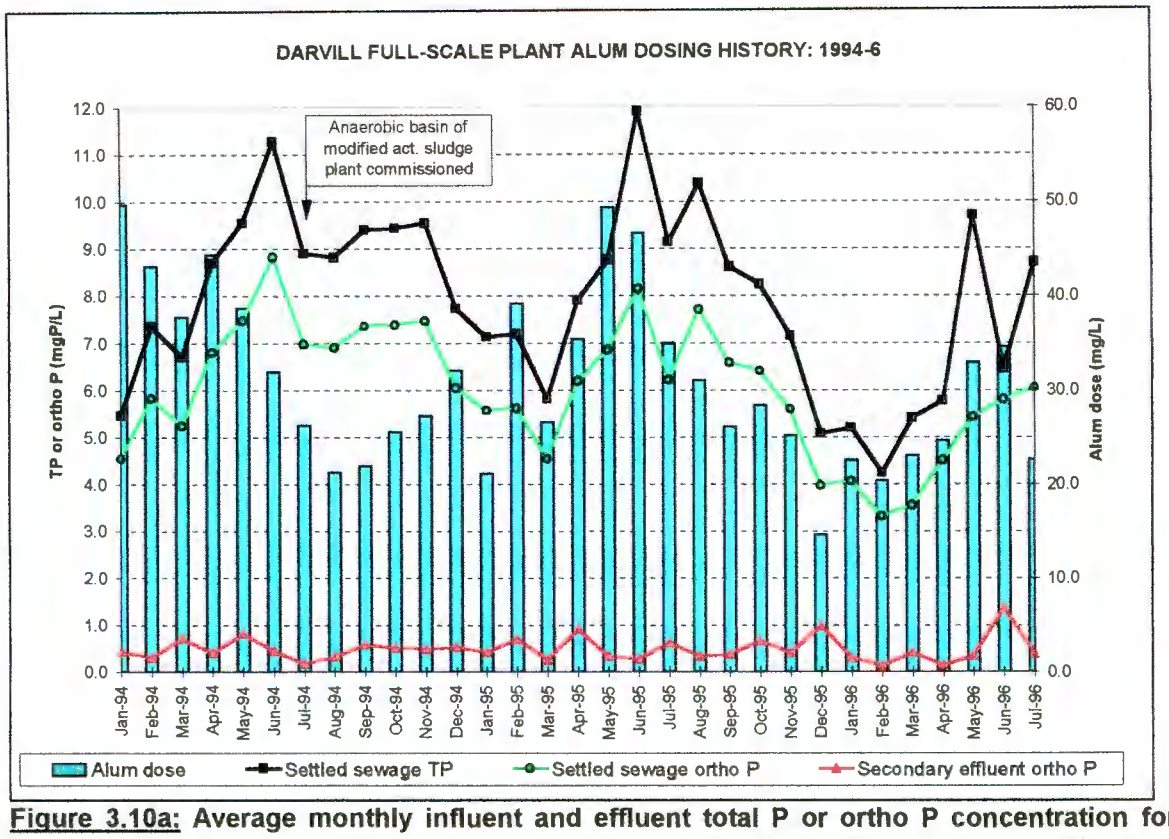


Figure 3.10a: **Average monthly influent and effluent total P or ortho P concentration for Darvill full-scale activated sludge system in the period 1994-6, with average monthly alum dose.**

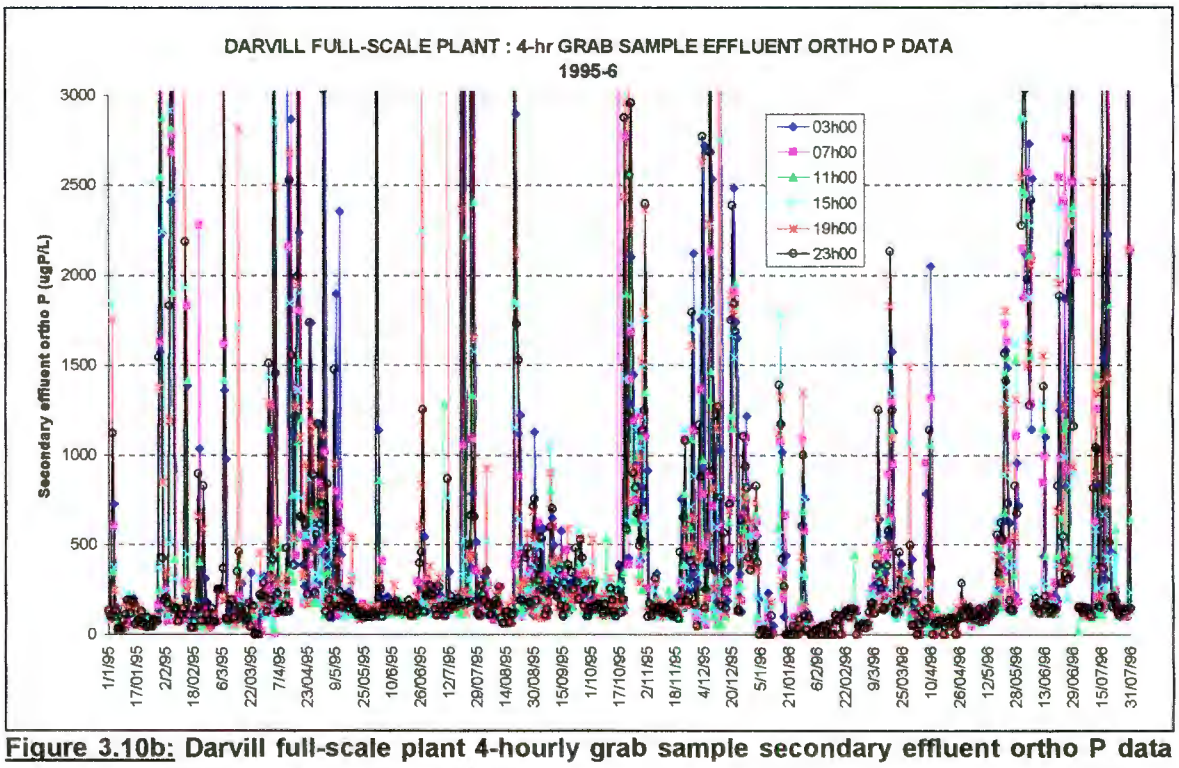


Figure 3.10b: **Darvill full-scale plant 4-hourly grab sample secondary effluent ortho P data for the year 1996. *Note scale in μg P/ℓ.* Summary statistics:**

	03h00	07h00	11h00	15h00	19h00	23h00		03h00	07h00	11h00	15h00	19h00	23h00
MEAN	477	414	366	425	515	514	S.D.	894	824	1078	1114	1175	1093

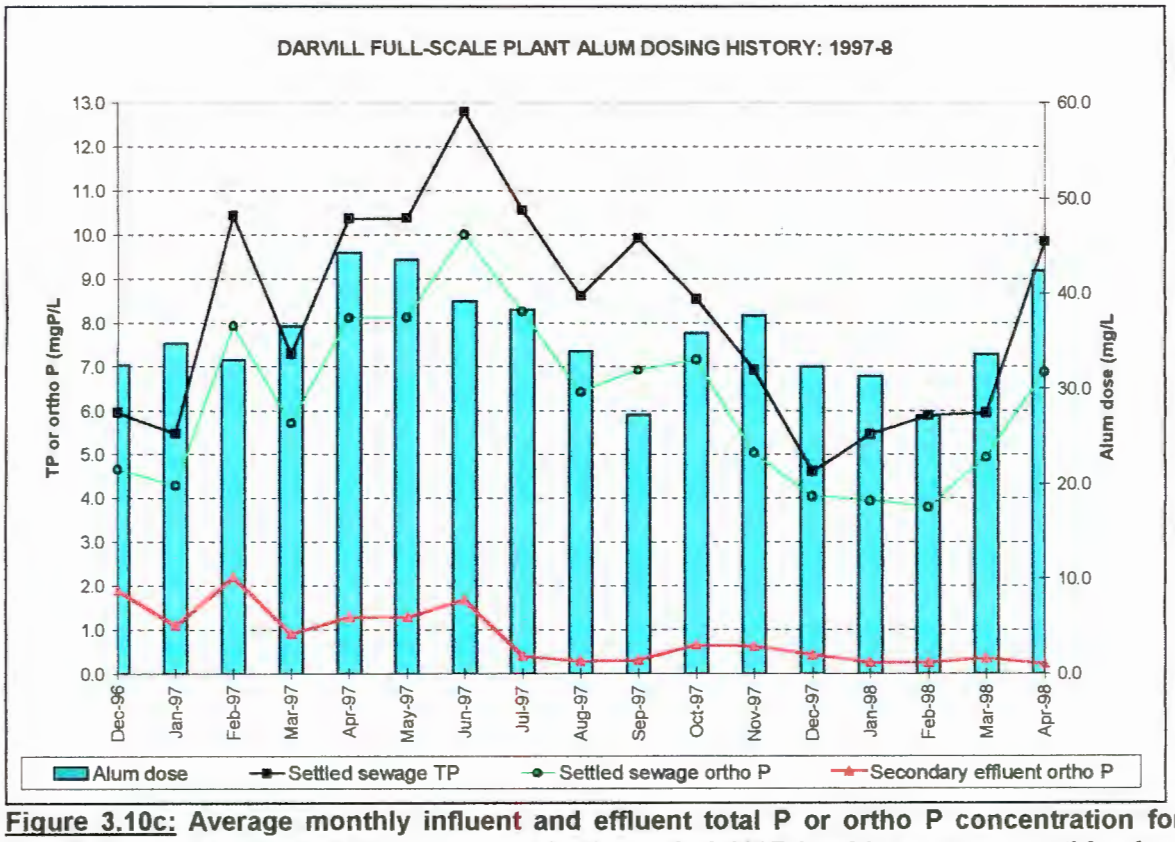


Figure 3.10c: **Average monthly influent and effluent total P or ortho P concentration for Darvill full-scale activated sludge system in the period 1997-8, with average monthly alum dose.** ***Note: Ferrous-ferric chloride plant trial conducted in the period (Aug. to Nov. 1996).***

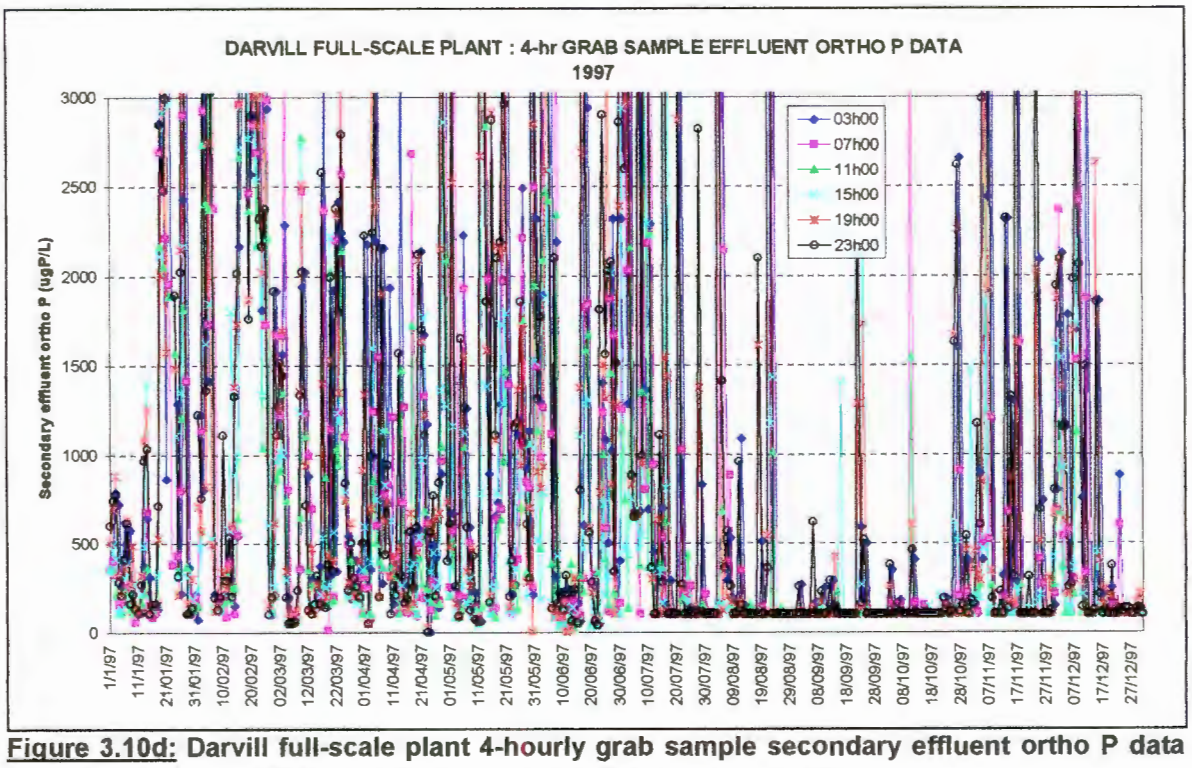


Figure 3.10d: **Darvill full-scale plant 4-hourly grab sample secondary effluent ortho P data for the period year 1997.** ***Note scale in μg P/ℓ.*** **Summary statistics :**

	03h00	07h00	11h00	15h00	19h00	23h00		03h00	07h00	11h00	15h00	19h00	23h00
MEAN	1009	840	650	691	889	1073	S.D.	1648	1336	1224	1161	1303	1720

3.5 CONCLUSIONS

From the experimental investigation with simultaneous alum dosing to an activated sludge system exhibiting the BEPR phenomenon, the following conclusions can be drawn:

1. Under conditions in which P was never limiting, simultaneous alum dosing always resulted in additional (chemical) P removal in the presence of a strong biological P removal mechanism using semi-enhanced cultures over a period of up to 2.5 sludge ages. However, evidence of partial inhibition of the biological mechanism emerged. This evidence may be summarised as follows:

   - Mass balance considerations showed that, compared to the Control (R2), the average mass of P release in the anaerobic reactor of the Test unit (R1) may have been initially stimulated by a low dose of alum (e.g. 5 mg/ℓ as Al, based on influent, dosed to the aerobic reactor), but in subsequent experimental periods, this effect disappeared and was followed by a degree of inhibition of P release in the anaerobic reactor. This was particularly evident with alum dosing to the anaerobic reactor, where a low alum dose (5 mg/ℓ as Al, based on influent) produced an average of 15% inhibition of P release and a high alum dose (9 mg/ℓ Al on the same basis) produced an average of 25% inhibition.

   - Relative to the Control, fractionation studies showed that the PCA-extracted complex P (poly P) fraction decreased in the Test unit when dosed alum. At a low alum dose (5 mg/ℓ as Al), this decrease was 16% when the aerobic zone was dosed, and more pronounced (24%) when the anaerobic zone was dosed. At high alum dose (9 mg/ℓ as Al) the decrease was very pronounced (37 to 40%). However, concomitant with the decrease in the PCA complex P fraction, there was an increase in the residue total P fraction. Batch P release tests showed the increased residue fraction was biologically active. Hence, taking the combined results of estimated Complex P (PCA extract + residue) as representing the "total biological P" (including poly P) stored by the cells, the fractionation results showed that the degree of inhibition of the biological mechanism was: 11% for the low alum dose to the aerobic zone; 16% for a low alum dose to the anaerobic zone; and 23-24% for a high alum dose to either the aerobic or anaerobic zone.

2. The magnitude of P release in anaerobic batch tests (with excess acetate present) for mixed liquor from for the Test unit (alum dosed) was compared to that from the Control unit. It was found that P release for the samples from the Test unit was depressed by 7 to 17% for the periods with low alum dose (5 mg/ℓ as Al) and by 20 to 23% for the periods with high alum dose (9 mg/ℓ as Al).

3. It is surprising to find observations of a significant degree of inhibition of the biological P removal mechanism under conditions where a large excess of ortho P was present in the effluent of the Test (and Control) system[13]. It may be concluded that the biological mechanism begins to function less well in the presence of the simultaneous precipitation mechanism and that the ortho P concentration in the bulk liquid phase of the mixed liquor may not be representative of the *localised* ortho P concentration in close proximity to the sludge floc when combined with chemical precipitate.

4. Fractionation results showed that there was a tendency for alum to increase the sludge ortho P fraction, which may be explained as increased formation of chemical precipitate. The increase in this fraction was between approximately 3 times (at low alum dose) and 5 times (at high alum dose). The largest differences in the ortho P sludge fraction of the Test and Control units were found for the periods which showed the greatest inhibition (or depression) of the biological (complex P) fractions (see above). This suggests that the chemical precipitation

[13] The above-mentioned fractionation results may be influenced to a limited extent by the slightly higher VSS production in the Test system (see point 13 of this section). However, close inspection of the fractionation data (Table 3.16) shows that, even when the results are expressed on a volume (mgP/ℓ) basis, 12 to 19% inhibition of the biological fractions was found in the Test unit with alum dosing, relative to the Control.

mechanism is antagonistic toward the biological mechanism, even under conditions when phosphate concentrations were not limiting.

5. Circumstantial evidence suggested that bicarbonate alkalinity and/or reactor pH influences both the interaction between the biological and chemical removal mechanisms. Relatively small changes in reactor pH may be critical to an understanding of the interaction between the chemical and biological P removal mechanisms. For example, of the periods in which the influent alkalinity was supplemented, a high alum dose (9 mg/ℓ as Al) to the anaerobic reactor resulted in the largest inhibition of the biological mechanism (ca. 25%). Despite the addition of bicarbonate alkalinity (150 mg/ℓ as $CaCO_3$) to the influent, the median pH in the anaerobic zone during this period was slightly below 7.0 and occasionally fell to 6.8. Similarly, one experimental period showed a virtual complete *loss* of *additional* P removal in the presence of a high alum dose after the influent bicarbonate alkalinity supplement was withdrawn. However, this effect was only manifest approximately one month (i.e. at least one sludge age) after the withdrawal of the alkalinity supplement. The median reactor pH showed a significant decrease during the first month after withdrawal of the alkalinity supplement (ca. 0.3 to 0.4 pH units) to a median pH of approximately 7.1 at the point of alum dosing to the first aerobic zone. During the first month after alkalinity supplementation was stopped, the additional P removal of Test unit showed an *increase*, relative to the Control. This suggests that the efficiency of chemical precipitation with alum increases when the pH at the point of dosing is very close to neutral (rather than in the range ca. 7.3 to 7.6), and that the biological mechanism is most sensitive to inhibition when the chemical precipitation mechanism is most efficient. This could imply that P limitation to cells within the sludge flocs is caused by the chemical adsorption/ precipitation mechanism, despite higher soluble P concentrations in the bulk liquid.

6. In summary, the data pertaining to the effect of alkalinity and/or reactor pH indicated the following:

   - The addition of bicarbonate *appeared* to reduce the efficiency of chemical P removal due to alum, as judged by a smaller gain in *system P removal* for the Test unit relative to the Control. However, inhibition of the biological mechanism in the Test unit as a result of alum addition could be misinterpreted as reduced chemical "precipitation efficiency" if only the system P removal is considered.

   - The change in reactor pH at the point of dosing as a result of the increased influent alkalinity was small (an increase of between 0.1 and 0.3 pH units to a median pH of between ca 7.2 and 7.6) but may nevertheless be significant. Inhibition of the bio-P removal mechanism in the presence of simultaneous alum addition appears to be more pronounced under conditions where the reactor pH (at the point of dosing) is $\leq$ pH 7.2. Under such conditions, the bio-P removal mechanism may deteriorate to such an extent that the benefit of adding alum is lost in terms of the system (i.e. total) P removal. The bio-P removal mechanism need not disappear entirely for the loss of benefit from chemical dosing to be noticed in terms of system P removal, relative to a Control without chemical dosing.

   - With a reactor pH in the range ca. 7.3 to 7.6 at the point of alum dosing, the biological mechanism appeared to be significantly less inhibited, although inhibition was still detectable. Under these conditions, and without P limitation, it was possible to obtain a sustained benefit from alum dosing over two to three sludge ages at low alum doses (e.g. 5 mg Al/ℓ) in terms of greater system P removal, relative to a Control without alum.

   - The average stoichiometry of chemical precipitation (as estimated from fractionation data rather than system P removal) does not appear to be significantly affected by system alkalinity (in the operating range ca. 70 to 200 mg/ℓ as $CaCO_3$ bicarbonate alkalinity).

7. No major differences in chemical precipitation efficiency were found between alum dosing to the anaerobic zone compared to the aerobic zone. There was some evidence that dosing to the anaerobic zone may be slightly less efficient than dosing to the aerobic zone. This may be due to metal complexation/ coagulation of soluble organic matter being present in the anaerobic zone to a greater degree than the aerobic zone.

8. Strictly speaking, the P:Al stoichiometry of simultaneous chemical precipitation cannot be estimated by taking the difference between the system P removal of a Test unit (alum dosed) versus a Control unit (not chemically dosed) systems where the biological mechanism in the Test unit may be partially inhibited by the chemical mechanism. Nevertheless, this method does provide an estimate of the overall "precipitation efficiency". Phosphorus fractionation provided an alternative means of estimating the stoichiometry of precipitation from chemical dosing, on the assumption that the ortho P content of the cold PCA fraction originates (principally) from chemical precipitate. Allowance needs to be made for background levels of precipitates present in the Control system as a result of natural processes for a given sewage. On this basis, the average estimated stoichiometry of the precipitate from alum was found to be between ca. 0.5 and 0.73 mol P/ mol Al (Table 3.18). This is somewhat less than the stoichiometric amount of 1 mol P/ mol Al for the "ideal" precipitate $AlPO_4$.

9. The fractionation results may be compared to the results of the IAWQ Activated Sludge Model No. 2 (ASM2) which includes a simplistic model for simultaneous chemical precipitation (refer to Chapter 7, sections 7.1.5 and 7.2). In ASM2, it is assumed that all the metal precipitant is dosed in the influent in the form of metal hydroxide (i.e. $Al(OH)_3$ in the case of alum) and that precipitation of phosphate takes place in an "ideal" manner (i.e. that $AlPO_4$ is formed in the case of alum). Hence, in terms of ASM2, the metal hydroxide which does not react to form metal phosphate, accumulates in the mixed liquor solids. In Chapter 7 (section 7.2.3.2.1) it was found that the stoichiometry of precipitation needed to be adjusted in order to account for the observed difference in P removal between the Test and Control units. (Part of this adjustment may be ascribable to the degree of inhibition of the biological P removal mechanism in the presence of alum dosing). Accepting the stoichiometry which gave satisfactory model results (usually 0.60 to 0.75 P:Al), it is possible to compare the model predictions of metal phosphate with the observed PCA ortho P estimates for chemical precipitate from fractionation results (where available). This comparison is given in Table 3.19. From this table it can be seen that the fractionation results gave metal phosphate predictions of 89% to 105% of that from the model results for the four experimental periods where comparative data was available. This implies that the calibration of the model is acceptable (see Chapter 7, section 7.2.2.2) and that there is fairly good consistency between the fractionation data and the precipitation theory upon which the model is based. The fact that the stoichiometry which fitted the IAWQ model was sometimes slightly greater than that found from fractionation data suggests that not all the chemical precipitate was solubilised in cold PCA. This effect was more pronounced for periods with iron dosing, even with a NaOH step included after the PCA step in the fractionation procedure (refer to Chapters 4 and 5, sections 4.3.6 and 5.3.5.4, respectively).

10. Bicarbonate alkalinity consumption due to chemical dosing (based on the difference in effluent bicarbonate alkalinity between the Test and the Control units) was approximately 2.24 mmol Alk./ mmol Al dosed (or approx. 0.189 mg as $CaCO_3$ / mg as $Al_2SO_4.14H_2O$ dosed), which is lower than the theoretical value of 0.253 on the same basis for the precipitation of pure $Al(OH)_3$ (Loewenthal *et al.*, 1986). This suggests that the aluminium precipitate formed involved fewer than 3 mol OH/ mol Al. When combined with the observed average P:Al stoichiometry (see above), these data suggest that an average approximate formula for the aluminium-hydroxy-phosphate complex formed could lie in the following range :

$$Al_2 (X^{2+}) PO_4 (OH)_5$$

$$Al_{1.66} (X^{2+}) PO_4 (OH)_4 \text{ (average)}$$

$$Al_{1.33} (X^{2+}) PO_4 (OH)_3$$

where X^{2+} is some unknown (possibly divalent) cation (e.g. Mg^{2+} or Ca^{2+}) (c.f. Arvin, 1985).

This compares with the generalised formula (used by Luedecke *et al.* , 1989; Briggs, 1996) of :

$$Al_rPO_4 (OH)_{(3r-3)}$$

which will predict less alkalinity loss per mol Al.

11. Magnesium removal data suggested that magnesium may be co-precipitated with alum under some circumstances. More magnesium was removed when the chemical precipitation was

apparently most efficient and the biological mechanism relatively depressed. Alternatively, the cation uptake for neutralising poly P charge may be linked to the (bi)carbonate weak acid/base sub-system. Overall, a larger molar ratio of $Mg_{removed}/P_{removed}$ was observed under conditions when the system was either dosed with acid or no bicarbonate supplement was added to the influent, compared to periods in which the influent was supplemented with bicarbonate alkalinity. In the case of the latter, a comparison of the average molar ratio of $Mg_{removed}/P_{removed}$ between the Test and Control units suggested that the biological mechanism was not inhibited by more than 15%.

12. No discernible inhibition of nitrification-denitrification mechanisms as a result of alum addition was observed. For the Test and Control units, average effluent ammonia and nitrate concentrations were similar throughout. Effluent ammonia concentrations increased slightly in Period 3.2.8b (for both units), which was probably related to the withdrawal of bicarbonate alkalinity supplement to the influent and the drop in pH in all the reactors.

13. Sludge production showed a small increase in VSS in the Test unit relative to the Control, with average increases of 5% and 12% for the low and high alum dose respectively. TSS production showed larger increases (11 to 25%) with alum dosing. The increased TSS may be expected from the additional mass of chemical precipitate (i.e. ISS) present in the mixed liquor as a result of alum addition. The mixed liquor solids fractions tended to reach steady state slowly or imperfectly, with relatively large standard deviations in the data from the experimental units. However, as a practical approximation, the increase in ISS due to chemical precipitate could be predicted on the basis of the additional system P removal and the observed stoichiometry for a known alum dose.

14. Full-scale data for Darvill WWW suggested that although moderately low monthly *average* effluent ortho P concentrations (< 1mgP/ℓ were usually achieved at an alum dose of ca. 2 to 5 mg/ℓ as Al (based on influent), regular (4 hourly) samples showed large variations in effluent ortho P concentrations. Many results exceeded 1 mgP/ℓ and only comparatively short periods (maximum of approximately 5 weeks) showed results of consistently less than 0.5 mgP/ℓ. It was not possible to separate out the possible effects of a variable influent composition on P removal, but it was clear from the historical data that the Darvill activated sludge plant did not operate under strictly limiting P conditions for extended periods. Although simultaneous alum dosing was useful in achieving low average effluent P concentrations, it is possible that partial inhibition of the biological P removal mechanism weakened the overall performance of the plant in terms of consistency and its BEPR potential. This aspect will be further examined in Chapter 8 when the overall conclusions from this study are drawn.

Table 3.18: Estimation of molar ratio of additional P removed as chemical precipitate (PCA extract ortho P) versus alum dosed in pilot plants.

UNIT/ ALUM Period	DATE	PCA, ortho P mgP/gVSS	Ave. VSS for Period g/ℓ	VSS wasted g/d	PCA ortho P wasted mgP/d	Difference R1-R2 PCA ortho P wasted mgP/d	Al dosed mmol/d	mol P /mol Al	mol P /mol Al Table 3.14
R1: No Al: 3.1.6	30/6/94	31.40	2.720	4.352	136.65	100.3	6.2	0.52	1.08
R2: 3.1.6	30/6/94	8.76	2.595	4.152	36.4				
R1: No Al: 3.2.1	28/8/94	18.15	2.734	4.374	79.40	11.77	0	-	-
R2: 3.2.1	28/8/94	17.79	2.376	3.802	67.63				
R1: Low Al, AE 1, 3.2.3	1/11/94	49.83	2.756	4.410	219.73	139.77	6.2	0.73	0.34 #
R2: 3.2.3	1/11/94	18.18	2.749	4.398	79.96				
R1: Low Al, AN, 3.2.4	19/12/94	54.97	2.422	3.875	213.02	138.88	6.2	0.72	0.18 #
R2: 3.2.4	19/12/94	19.42	2.386	3.818	74.14				
R1: High Al, AN, 3.2.5	8/1/95	80.04	2.11	3.376	270.22	219.58	12.4	0.58	0.57
R2: 3.2.5	8/1/95	16.56	1.911	3.058	50.63				
R1: High Al, AE 1, 3.2.6	22/1/95	89.61	2.105	3.368	301.81	232.77	12.4	0.61	0.62
R2: 3.2.6	22/1/95	22.65	1.905	3.048	69.04				
R1: High Al, AE 1, 3.2.8a	23/3/95	90.11	2.069	3.310	298.26	204.85	12.4	0.53	0.69
R2: 3.2.8a	23/3/95	30.97	1.885	3.016	93.41				
R1: High Al, AE 1, 3.2.8b	26/4/95	102.38	2.006	3.2096	328.60	271.53	12.4	0.71	0.07
R2: 3.2.8b	26/4/95	19.63	1.817	2.9072	57.07				

#: Partial inhibition of bio-P removal mechanism suspected and/or conditions not close to steady state

Table 3.19: Comparison of metal phosphate (MeP) predictions from fractionation results (PCA ortho P fraction) and those from the IAWQ model (refer to section 7.2 of Chapter 7).

PERIOD/ UNIT	DATE	PCA ortho P mg P/g VSS	Ave. VSS Period g/ℓ	PCA ortho P Period mg P/ℓ	Difference R1-R2 mg P/ℓ	PCA ortho P * MeP, mg/ℓ	Frac. Stoich mol P/ mol Al P/Al	IAWQ Model Stoich. mol P/mol Al P/Al	IAWQ Model MeP, mg/ℓ	PCA/ Model %
3.2.3, R1	11/1/94	49.83	2.756	137.33	87.355	425	0.73	0.75	452	94%
3.2.3, R2	11/1/94	18.18	2.749	49.98						
3.2.4, R1	12/19/94	54.97	2.422	133.14	86.801	427	0.72	0.75	452	95%
3.2.4, R2	12/19/94	19.42	2.386	46.34						
3.2.5, R1	1/8/95	80.04	2.11	168.88	137.238	790	0.58	0.60	750	105%
3.2.5, R2	1/8/95	16.56	1.911	31.65						
3.2.6, R1	1/22/95	89.61	2.105	188.63	145.481	819	0.61	-	Not modelled	-
3.2.6, R2	1/22/95	22.65	1.905	43.15						
3.2.8a, R1	23/3/95	90.11	2.069	186.43	128.05	790	0.53	0.75	814	89%
3.2.8a, R2	23/3/95	30.97	1.885	58.38						

* Taking stoichiometry from fractionation data (Table 3.18) and assuming precipitate formula is: $Me_r PO_4(OH)_{3r-3}$

DW Ba Nova
Exhibit 2

REFERENCES

Arvin, E. (1985) Biological removal of phosphorus from wastewater. *CRC Critical Reviews in Environmental Control* 15, 25 - 64.

Briggs, TA. (1996) *Dynamic modelling of chemical phosphorus removal in the activated sludge process.* M. Eng. Thesis, School of Graduate Studies, McMaster University, Hamilton, Ontario, Canada.

Brown, MJ and Lester, JN. (1979) Metal removal in activated sludge: the role of bacterial extracellular polymers. *Water Res.*, 13, 817-837.

Burke, RA, Dold, PL and Marais, GvR. (1986) *Biological excess phosphorus removal in short sludge age activated sludge systems.* Report No. W58. University of Cape Town, Depts. of Chemical Engineering and Civil Engineering, December 1986.

Clayton, JA, Ekama, GA, Wentzel MC, and Marais, GvR. (1989) Denitrification kinetics in biological nitrogen and phosphorus removal activated sludge systems. Research Report W63, Dept. of Civil Eng., Univ. of Cape Town, Rondebosch, Cape Town.

De Haas, DW. (1989) Chemical fractionation of activated sludge with special reference to enhanced biological phosphate removal. MSc. Thesis, Dept. of Biochemistry, Rand Afrikaans University, Johannesburg., November 1989.

Ekama, GA and Marais, GvR. (1984) Two improved activated sludge settleability parameters. *IMIESA*, June 1984, 20-25.

Gerber, A, de Villiers, RH, Mostert, ES and van Riet, CJJ. (1987) The phenomenon of simultaneous phosphate uptake and release, and its importance in biological nutrient removal., *In: Advances in Water Pollution Control: Biological phosphate removal from wastewaters.*, (Ramadori, R, ed.), Pergamon, Oxford, 123-134.

He, QH, Leppard, G, Paige, CR and Snodgrass, WJ. (1996) Transmission electron microscopy of a phosphate effect on the colloid structure of iron hydroxide. *Water. Res.*, 30 (6), 1345-1352.

Jenkins, D, Richard, MG and Daigger, GT. (1984) *Manual on the causes and control of activated sludge bulking and foaming.* Report prepared for Water Research Commission, PO Box 824, Pretoria, South Africa.

Loewenthal, RE Wiechers, HNS and Marais, GvR. (1986) *Softening and stabilization of municipal waters*. Water Research Commission, Pretoria, June 1986.

Lötter, LH. (1991) Combined chemical and biological removal in activated sludge plants. *Water Sci. Technol.*, 23 (Kyoto), 611-621.

Luedecke, C, Hermanowicz, SH and Jenkins, D. (1989) Precipitation of ferric phosphate in activated sludge: a chemical model and its verification. *Water Sci. Technol.* 21 (Brighton), 325-327.

Mamais, D, Jenkins , D and Pitt, P. (1993) A rapid physico-chemical method for determination of readily biodegradable soluble COD in municipal wastewater. *Water Res.* 27 (1), 195-197.

Meiring & Barnard. (1990) *First Interim Report on Upgrading of Darvill Wastewater Treatment Plant*. Report to City Engineers Dept., Pietermaritzburg by Wates Meiring Barnard (formerly Meiring & Barnard), Midrand, Johannesburg, South Africa.

Power, SPB, Ekama, GA, Wentzel, MC and Marais, GvR. (1992) *Chemical phosphorus removal from municipal wastewater by the addition of waste alum sludge to the activated sludge system.* Research Report No. W66, University of Cape Town, Dept. of Civil Engineering, September 1992.

Randall , EW, Wilkinson, A and Ekama, GA. (1991) An instrument for the direct determination of oxygen utilisation rate. *Water SA* 17 (1), 11-18.

Slatter, NP and Alborough, H (1990) Chemical oxygen demand using microwave digestion: A tentative new method. *Water SA* 18 (3), 145-148.

Smolders, GJF, van der Meijm J, van Loosdrecht, MCM and Heijnen, JJ. (1994) Model of the anaerobic metabolism of the biological phosphorus removal process; stoichiometry and pH influence. *Biotechnology and Bioengineering.* 43, 461-470.

Standard Methods for the Examination of Water and Wastewater (16th edn.) (1985). American Public Health Association, Washington DC.

Wentzel, MC, Loewenthal, RE, Ekama, GA and Marais, GvR. (1988) Enhanced polyphosphate organism cultures in activated sludge systems - Part 1: Enhanced culture development. *Water SA,* 14 (2), 81-92.

Wentzel, MC, Lötter, LH, Loewenthal, RE and Marais, GvR. (1986) Metabolic behaviour of *Acinetobacter* spp. in enhanced biological phosphorus removal - a biochemical model. *Water SA,* 12, 209-224.

Wiechers, HNS (ed.). (1987) *Guidelines for chemical phosphate removal from municipal waste waters.* Collaborative publication compiled by staff of the Town Council of Boksburg, City Council of Pretoria, National Institute of Water Research and the Water Research Commission. Water Research Commission, Pretoria, January, 1987.

Witt, PC, Grabowski, F and Hahn, HH. (1994) Interactions between biological and physico-chemical mechanisms in biological phosphate elimination. *Water Sci. Technol.,* 30 (6), 271-279.

WLPU-WMB. (1993) *Darvill Wastewater Treatment Works : Future Extensions*. Joint Report by Knight Piesold (formerly Watermeyer Legge Piesold Uhlmann,WLPU) and Wates Meiring Barnard (WMB) to Umgeni Water, November 1993. Knight Piesold, Pietermaritzburg, South Africa.

University of Cape Town

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting biological enhanced phosphate removal.

Chapter 4

Ferric chloride dosing to pilot plants

DW de Haas

CHAPTER FOUR

FERRIC CHLORIDE DOSING TO PILOT PLANTS

4.1 INTRODUCTION

A review of the literature (Chapter 1) as well as visits to major wastewater works (WWW) in the Johannesburg area which need to comply with the Special P Standard, indicated that ferric chloride is commonly used as simultaneous precipitant in activated sludge systems. Preliminary indications from chemical suppliers suggested that a cost benefit could be gained by switching from alum to ferric chloride dosing at Darvill WWW. Neglecting transport costs, which differ from area to area, the principal cost saving comes about as a result of the relatively large percentage of metal in the iron chloride salts (typically 12 to 15% m/m as Fe in the delivered product, or 2.2 to 2.7 mol Fe/ kg product) compared to aluminium sulphate (typically 4.2 to 4.4% m/m as Al in the delivered product, or approx. 1.6 mol Al/kg product). However, a report in the literature (Lötter, 1991) of ferric salts proving to be inhibitory to the biological P removal process, prompted Umgeni Water to adopt a cautious approach to changing the chemical dosed at Darvill WWW for augmentation of P removal.

In view of the experience gained from the pilot plant studies conducted at Darvill WWW to investigate the effect of alum dosing on a biological P removal system (Chapter 3), it was a logical extension to study the effect of ferric chloride in these systems. This chapter describes the outcome of these studies with ferric chloride as simultaneous precipitant.

4.2 MATERIALS AND METHODS

4.2.1 Pilot plants

Two identical pilot plant units (R1 and R2) were set up and operated in the same manner as described in Chapter 3 (see Fig. 3.1).

4.2.2 Feed supplementation for enhanced cultures

The first period of ferric chloride dosing followed on directly from the last alum dosing period (Period 3.2.8b), although an intervening period of ten days (half of one sludge age) was allowed during which no chemical dosing occurred. Accordingly, there was no need to re-develop enhanced cultures *de nova* as described in Chapter 3. A further equilibration period of ten days (half of one sludge age) was allowed from the time of commencement of ferric chloride dosing until the first period of experimental results were reported (Period 3.3.1, see Tables 4.1 and 4.3).

For the ferric chloride dosing periods, the influent composition was not changed significantly from that used in the alum dosing periods (Chapter 3). The acetate feed concentration was kept constant throughout at 150 mg/ℓ as COD, as was magnesium, potassium, phosphate and alkalinity supplementation (Table 4.1). Hence the only variation in respect of the influent composition was that of the settled sewage sampled from the full-scale Works.

Table 4.1 gives the composition of sewage supplements for the experimental periods relevant to this chapter. Each sewage batch (160 ℓ) was augmented with the following constituents:

- sodium acetate (e.g. 150 mg/ℓ as COD or 30.8 g anhydrous sodium acetate per 160 ℓ batch);
- orthophosphate (e.g. 40 mgP/ℓ as K_2HPO_4 or 80 mℓ of a concentrated stock solution containing 450 g/ℓ K_2HPO_4 per 160 ℓ batch);

- magnesium chloride (constant 84 mg Mg per g COD as acetate added e.g. for 12.6 mg Mg/ℓ required 90 mℓ of a concentrated stock solution containing 189.7 g/ℓ of $MgCl_2.6H_2O$ per 160 ℓ batch);
- sodium bicarbonate for alkalinity (usually 100 mg/ℓ as $CaCO_3$ or 26.9 g of $NaHCO_3$ per 160ℓ batch).

Table 4.1: Sewage supplement composition by experimental period.
(Refer to Table 4.3 for relevant ferric chloride dose, acid dose and sludge age).

Period Date range	No. of days	Na-acetate mg/ℓ as COD	K_2HPO_4 mgP/ℓ	$MgCl_2$ mg Mg/ℓ	K_2HPO_4 mg K/ℓ	$NaHCO_3$ mg/ℓ as $CaCO_3$
3.3.1 (Ferric) 16/5/95 to 16/7/95	62	150	40	12.6	100	100
3.3.1 (b) Sub-period of Period 3.3.1 16/6/97 to 16/7/95	31					
3.3.2 (Ferric) 17/7/95 to 19/8/95	34	150	40	12.6	100	100
3.3.3 (Ferric) 8/9/95 to 5/10/95	27	150	40	12.6	100	100
3.3.4 (Ferric) 6/10/95 to 23/10/95	18	150	40	12.6	100	100
3.3.5 (Ferric) 24/10/95 to 3/11/95	21	150	40	12.6	100	100
3.3.6 (Ferric) 14/11/95 to 3/12/95	20	150	40	12.6	100	100
New semi-enhanced culture developed (Ferric dosed)						
29/7/97 to 4/8/97	7	50	0	12.6	0	100
5/8/97 to 8/8/97	4	75	0	12.6	0	100
9/8/97 to 20/8/97	12	100	0	12.6	0	100
3.6.1 (Ferric) 21/8/97 to 4/10/97	45	100	0	12.6	0	100
3.6.2a (Ferric) 5/10/97 to 7/12/97	64	100	0	12.6	0	0
3.6.2b (Ferric) 8/12/97 to 20/12/97	13	100	20	12.6	50	0

4.2.3 Ferric chloride and acid dosing

As a point of departure, it was assumed that a molar ratio of 0.5 mol $P_{removed}$/ mol Fe_{dosed} should be achievable (Wiechers, 1987). Initial calculations were based on the supplier's minimum specification of 14% (m/m) Fe in the ferric chloride sample received. Dilutions were calculated to give a daily dose to the Test reactor of 6.2 mmol Fe/d per 25 ml diluted stock solution. Once the ferric chloride sample had been checked for true iron content by atomic absorption spectrometry, it was found to contain 14.97% (m/m) total Fe and had an S.G. of 1.46 kg/ℓ. In order to maintain consistency relative to the experimental periods already covered, it was decided to leave the dosage to the reactor unchanged, and accept the slight difference in actual molar amounts dosed (6.65 mmol Fe/d per 25 mℓ diluted stock solution).

A dilute solution of chemical precipitant was prepared according to Table 4.2 and dosed into the anaerobic (AN) or first aerobic (AE1) zone of the Test reactor (R1) at the rate of 500 mℓ/d after further dilution with tap water. It was found that a small amount of acid was required to prevent coagulation (hydroxide formation) in the diluted solutions of ferric chloride dosed. For this reason, 10 mmol/d of HCl was added to the diluted solution of ferric chloride dosed to R1, and the same amount of acid was fed in tap water only to R2, also at a rate of 500 mℓ/d[1]. The acid dose was equivalent to 14 mg/ℓ as $CaCO_3$ (based on influent flow rate of 36 ℓ/d), which was considered small in relation to the alkalinity supplement of 100 mg/ℓ as $CaCO_3$ for most periods (Tables 4.1 and 4.3). Table 4.3 gives the actual dosage rates applied for the respective experimental periods. Assuming a molar ratio of 0.5 mol $P_{removed}$/ mol Fe_{dosed} (Aspegren, 1995), an iron dose of 6.65 mmol Fe/d and 13.3 mmol Fe/d translates into an expected additional P removal of ca. 2.86 and 5.72 mgP/ℓ respectively at an influent flow rate of 36 ℓ/d. As with alum dosing (Chapter 3), this appeared to be a reasonable target for "low" and "high" ferric dosage rates on the basis of full-scale operating experience at Darvill WWW.

4.2.4 Parameters measured

All parameters measured were in accordance with: Standard Methods (1985), or methods described in Chapter 2, or Appendices 1 to 4. The only exceptions were: OUR, which was measured according to Randall *et al.* (1991); DSVI, which was measured according to Ekama and Marais (1984); and COD, which was measured by the open reflux and manual titration method in Standard Methods (1985), as well as a microwave digestion method followed automated potentiometric titration (Slatter and Alborough, 1990).
In the case of COD, it was found that the open reflux method gave poor recoveries (56 to 66%) of sodium acetate COD, both from pure solutions and in admixture with settled sewage, possibly due to the reflux condenser length (50 cm) being inadequate (refer to Chapter 2, section 2.5). Better recoveries (90 to 105%) were obtained by the microwave method which uses closed reflux in Teflon pressure vessels. Accordingly, the microwave method was always used for influent samples. The open reflux method was used for effluent samples. In summary, the parameters routinely measured were:

- COD (influent, effluents): see above
- TKN (influent, effluents): Appendix 1
- Total P (influent, effluents, mixed liquors, filtered AN, AX, AE1 and AE2 zones): Chapter 2 (2.2)
- Soluble reactive P or SRP (effluents): Chapter 2 (2.3)
- Soluble ammonia (effluents): Appendix 1
- Soluble nitrate (effluents, filtered AN, AX, AE1, AE2 zones): Appendix 2a & b
- MLSS, VSS (mixed liquor sample taken from AE2 zone): Standard Methods (1985)
- DSVI (mixed liquors): Ekama and Marais (1984)
- pH (in AN, AX, AE1, AE2 zones): Standard Methods (1985)
- OUR (AE2 zone): Randall *et al.* (1991)
- Total Mg (influent, effluents): Appendix 4.
- Bicarbonate alkalinity : Moosbrugger *et. al.* (1993).
- Influent readily biodegradable COD was measured during three experimental periods (3.6.1, 3.6.2a and 3.6.2b), using the physical-chemical method described by Mamais *et al.* (1993).

4.2.5 Chemical fractionation of sludge samples

Fractionation and P release batch tests was carried out according to the procedure described in Table 2.11 (Chapter 2).

[1] In later experimental periods (see Table 4.3), it was found that the amount of acid required to prevent coagulation of the diluted ferric chloride could be greatly reduced. Accordingly for Periods 3.6.1 and 3.6.2, the only acid dosed was 0.5 to 1.0 mmol/d in the form of HCl (2 mℓ/ℓ) added to the ferric chloride working stock solution (Tables 4.2 and 4.3).

Table 4.2: Ferric chloride dosing protocol for UCT pilot plant R1.

Chemical (Source)	% m/m S.G. (kg/ℓ)	First dilution for working stock	Daily feed Volume diluted to 500 mℓ/d with tap water	Expected dose based on Q_i (ℓ/d)		
Ferric chloride $FeCl_3$ MW = 162.4 g/mol *(NCP Ultrafloc)*	14.97 % m/m as Fe 1.46 kg/ℓ [218.6 g/ℓ as Fe]	68 mℓ/ℓ [14.9 g/ℓ as Fe]	**25 mℓ (6.65 mmol/d Fe)** [372 mg/d Fe]	36 ℓ/d	10.3 mg/ℓ as Fe	30 mg/ℓ as $FeCl_3$
			50 mℓ (13.3 mmol/d Fe) [742 mg/d Fe)	36 ℓ/d	20.6 mg/ℓ as Fe	60 mg/ℓ as $FeCl_3$

Table 4.3: Experimental periods of ferric chloride and acid dosing to UCT pilot plants.

PERIOD NAME Date range Comments	No. of days	Ferric dose to R1 (Test) reactor (mmol/d as Fe)	Zone dosed with ferric/ acid	Acid (HCl) dose (mmol/d)	Sludge age Rs (d)
3.3.1: Low ferric 16/5/95 to 16/7/95	62	Ferric: 6.65 as Fe	AE1	Yes: 10	20
3.3.1 (b) Sub-period of 3.3.1 16/6/95 to 16/7/95	31				
3.3.2: High ferric 17/7/95 to 19/8/95 Settling problems develop in R1	34	Ferric: 13.3 as Fe	AE1	Yes: 10	20
20/8/95 to 29/8/95 Settling problems in R1 worsen	9	Ferric: 13.3 as Fe	AN	Yes: 10	20
29/8/95: **R1 mixed liquor discarded due to settling problems. Re-seeded R1 with half of mixed liquor from R2.** Recommenced ferric dosing 3/9/95.	5	Ferric: 6.65 as Fe	AN	Yes: 10	20
3.3.3: Low ferric 8/9/95 to 5/10/95 Settling problems re-emerge in R1	27	Ferric: 6.65 as Fe	AN	Yes: 10	20
3.3.4: Low ferric 6/10/95 to 23/10/95	18	Ferric: 6.65 as Fe	AN	Yes: 10	10
3.3.5: High ferric 24/10/95 to 13/11/95	21	Ferric: 13.3 as Fe	AN	Yes: 10	10
3.3.6: High ferric 14/11/95 to 3/12/95	20	Ferric: 13.3 as Fe	AE1	Yes: 10	10
New semi-enhanced culture developed, with low ferric dose 29/7/97 to 20/8/97	23	Ferric: 6.65	AE1	Yes: 0.5	10
3.6.1 Low ferric 21/8/97 to 4/10/97	45	Ferric: 6.65 as Fe	AE1	Yes: 0.5	10
3.6.2a Low ferric 5/10/97 to 7/12/97	64	Ferric: 6.65 as Fe	AE1	Yes: 0.5	10
3.6.2b Low ferric 8/12/97 to 19/12/97	12	Ferric: 6.65 as Fe	AE1	Yes: 0.5	10

Table 4.4: Measured pilot plant results for ferric chloride dosing periods 3.3.1 to 3.3.6.

Results are averages with sample standard deviations in parentheses. N.D. = Not determined. See Appendix 8 for definition of symbols.

The double horizontal line between experimental periods indicates an major change in operational set-up for the units (see Tables 4.1 & 4.3).

Period Unit	Days Fe dose, mg/ℓ Fe	Sti mgO/ℓ	Ste mgO/ℓ	Nti mgN/ℓ	Nte mgN/ℓ	Nae mgN/ℓ	No3e mgN/ℓ	Pti mgP/ℓ	Pte mgP/ℓ	Pt_{rem} mgP/ℓ	P/VSS mgP /gVSS	TSS mg/ℓ	VSS mg/ℓ	% VSS	DSVI ml/g	fPt,a mgP/ℓ	fPt,d mgP/ℓ	fPt,b1 mgP/ℓ	fPt,b2 mgP/ℓ
3.3.1 R1	62 days 10 mg/ℓ, AE1	442 (82)	21 (8)	31.3 (13.0)	2.86 (1.01)	0.22 (0.14)	7.14 (2.01)	49.85 (2.18)	22.73 (6.32)	27.12 (6.52)	203.4 (16.1)	4259 (611)	2238 (333)	52.6 (2.1)	65 (9)	95.8 (8.2)	50.8 (5.1)	34.2 (5.8)	24.5 (6.2)
3.3.1 R2	62 days 0 mg/ℓ	442 (82)	20 (4)	31.3 (13.0)	2.38 (0.77)	0.19 (0.10)	5.91 (2.13)	49.85 (2.18)	26.95 (5.38)	22.90 (5.94)	185.5 (7.69)	4121 (527)	2401 (299)	58.3 (1.4)	74 (9)	105.6 (8.9)	59.4 (6.4)	41.3 (6.3)	29.7 (5.6)
3.3.1(b) R1	31 days 10 mg/ℓ, AE1	398 (64)	20 (4)	27.7 (10.1)	2.36 (0.67)	0.27 (0.13)	6.76 (2.06)	48.86 (2.23)	21.63 (6.94)	27.23 (7.59)	213.7 (15.8)	4455 (324)	2273 (210)	51.0 (1.6)	73 (6)	93.5 (7.3)	49.7 (5.5)	34.6 (7.0)	24.5 (7.0)
3.3.1(b) R2	31 days 0 mg/ℓ	398 (64)	19 (4)	27.7 (10.1)	2.34 (0.81)	0.24 (0.09)	6.26 (1.96)	48.86 (2.23)	27.65 (5.24)	21.21 (6.18)	185.8 (7.7)	4296 (208)	2490 (79)	58.0 (1.7)	80 (4)	102.3 (8.4)	60.4 (6.6)	42.2 (6.0)	30.9 (5.0)
3.3.2 R1	34 days 20 mg/ℓ, AE1	407 (67)	19 (2)	31.3 (6.2)	2.34 (0.66)	1.46 (0.81)	6.11 (2.74)	48.80 (2.91)	15.05 (4.83)	33.76 (5.34)	271.1 (19.4)	5214 (427)	2357 (141)	45.3 (1.7)	75 (3)	104.1 (13.9)	51.2 (8.6)	27.1 (5.3)	16.7 (5.0)
3.3.2 R2	34 days 0 mg/ℓ	407 (67)	20 (3)	31.3 (6.2)	2.61 (1.02)	1.19 (0.61)	5.49 (2.48)	48.80 (2.91)	26.98 (5.03)	21.83 (5.57)	215.7 (12.4)	4595 (183)	2509 (68)	54.6 (1.4)	81 (5)	112.0 (10.3)	63.8 (12.5)	43.3 (8.1)	30.2 (5.8)
3.3.3 R1	27 days 10 mg/ℓ, AN	456 (57)	26 (11)	35.0 (7.1)	3.11 (1.09)	1.24 (0.23)	6.05 (1.39)	52.64 (3.84)	23.80 (4.26)	28.84 (5.95)	211.9 (13.0)	4547 (194)	2437 (83)	53.6 (2.0)	89 (12)	101.2 (10.6)	63.6 (9.3)	36.1 (7.8)	24.1 (6.6)
3.3.3 R2	27 days 0 mg/ℓ	456 (57)	21 (3)	35.0 (7.1)	2.64 (0.80)	1.16 (0.18)	6.27 (1.60)	52.64 (3.84)	28.34 (4.98)	24.30 (6.72)	192.7 (13.7)	4155 (216)	2424 (92)	58.4 (1.4)	104 (5)	107.2 (8.8)	61.0 (8.4)	40.8 (7.1)	29.7 (7.3)
3.3.4 R1	18 days 10 mg/ℓ, AN	461 (84)	22 (3)	33.5 (4.4)	3.38 (0.65)	1.74 (0.73)	6.39 (1.35)	50.61 (2.46)	18.88 (3.27)	31.73 (2.11)	220.0 (13.7)	3869 (433)	2009 (265)	51.9 (2.6)	82 (6)	105.7 (12.3)	56.6 (6.4)	31.9 (4.7)	19.4 (4.2)
3.3.4 R2	18 days 0 mg/ℓ	461 (84)	20 (3)	33.5 (4.4)	3.21 (1.21)	1.74 (0.90)	6.04 (1.29)	50.61 (2.46)	21.27 (5.19)	29.44 (4.19)	199.4 (11.9)	3562 (362)	1987 (196)	55.8 (1.9)	92 (4)	114.2 (10.8)	60.6 (6.8)	36.3 (6.9)	23.0 (7.1)
3.3.5 R1	21 days 20 mg/ℓ, AN	398 (61)	23 (7)	30.1 (5.7)	3.12 (0.83)	1.87 (0.45)	5.69 (1.63)	50.33 (3.40)	16.03 (4.35)	34.30 (5.22)	247.4 (36.3)	3275 (207)	1581 (142)	48.4 (5.1)	72 (5)	82.2 (4.6)	50.5 (5.5)	26.7 (5.6)	14.6 (5.3)
3.3.5 R2	21 days 0 mg/ℓ	398 (61)	21 (3)	30.1 (5.7)	2.75 (0.68)	1.66 (0.41)	6.59 (1.89)	50.33 (3.40)	25.29 (4.55)	25.04 (5.12)	207.5 (20.1)	2844 (253)	1546 (101)	54.5 (1.8)	79 (6)	95.6 (6.4)	57.6 (7.0)	37.2 (3.0)	24.4 (3.2)
3.3.6 R1	20 days 20 mg/ℓ, AE1	354 (94)	21 (5)	26.7 (3.5)	2.61 (0.99)	0.64 (0.47)	4.69 (0.71)	46.03 (2.55)	15.94 (4.08)	30.13 (5.55)	246.8 (9.6)	3205 (268)	1510 (146)	47.1 (1.3)	66 (3)	79.1 (14.5)	46.3 (6.0)	22.5 (6.2)	18.8 (5.0)
3.3.6 R2	20 days 0 mg/ℓ	354 (94)	21 (3)	26.7 (3.5)	2.48 (0.74)	0.64 (0.50)	6.16 (0.96)	46.03 (2.55)	21.64 (4.62)	24.42 (6.39)	224.6 (15.7)	2416 (192)	1319 (115)	54.6 (2.6)	84 (4)	93.9 (17.2)	36.7 (0.5)	28.7 (3.4)	22.8 (5.6)

f = filtered; a = anaerobic; d = anoxic; b1 = 1st aerobic; b2 = 2nd aerobic reactors of 3-stage Phoredox system (see Fig. 3.1, Chapter 3).

Table 4.5: Mass balances for ferric chloride dosing periods 3.3.1 to 3.3.6.

Results are averages with sample standard deviations in parentheses. Figures in red indicate estimates where spurious actual values were recorded. The double horizontal line between experimental periods indicates an major change in operational set-up for the units (see Tables 4.1 & 4.3).

Period Unit	Days Fe dose, mg/ℓ Fe	Flow Q, l/d	VSS mg/ℓ	No3a mgN/ℓ	No3d mgN/ℓ	No3b2 mgN/ℓ	Nte mgN/ℓ	No3e mgN/ℓ	Nti mgN/ℓ	% N Bal.	Ot mgO/ℓ.h	Sti mgO/ℓ	Ste mgO/ℓ	% COD Bal.	Pt_{rem} mgP/ℓ	P/VSS mgP /gVSS	% P Bal.
3.3.1 R1	62 days 10 mg/ℓ, AE1	36.0	2238 (333)	0.06 (0.04)	3.34 (1.82)	6.68 (2.12)	2.86 (1.01)	7.14 (2.01)	31.3 (13.0)	**96%**	16.77 (1.80)	442 (82)	21 (8)	**77%**	27.12 (6.52)	203.4 (16.1)	**75%**
3.3.1 R2	62 days 0 mg/ℓ	36.2	2401 (299)	0.08 (0.05)	2.38 (1.82)	5.74 (2.14)	2.38 (0.77)	5.91 (2.13)	31.3 (13.0)	**96%**	17.98 (3.26)	442 (82)	20 (4)	**84%**	22.90 (5.94)	185.5 (7.69)	**86%**
3.3.1(b) R1	31 days 10 mg/ℓ, AE1	35.7	2273 (210)	0.08 (0.03)	3.75 (2.12)	6.48 (2.19)	2.36 (0.67)	6.76 (2.06)	27.7 (10.1)	**96%**	16.12 (1.44)	398 (64)	20 (4)	**87%**	27.23 (7.59)	213.7 (15.8)	**80%**
3.3.1(b) R2	31 days 0 mg/ℓ	35.9	2490 (79)	0.11 (0.05)	3.11 (1.74)	6.13 (1.96)	2.34 (0.81)	6.26 (1.96)	27.7 (10.1)	**103%**	16.23 (1.90)	398 (64)	19 (4)	**90%**	21.21 (6.18)	185.8 (7.7)	**97%**
3.3.2 R1	34 days 20 mg/ℓ, AE1	35.8	2357 (141)	0.11 (0.14)	1.10 (0.54)	5.15 (1.78)	2.34 (0.66)	6.11 (2.74)	31.3 (6.2)	**109%**	14.92 (1.64)	407 (67)	19 (2)	**79%**	33.76 (5.34)	271.1 (19.4)	**85%**
3.3.2 R2	34 days 0 mg/ℓ	36.0	2509 (68)	0.11 (0.14)	1.58 (2.70)	4.44 (2.72)	2.61 (1.02)	5.49 (2.48)	31.3 (6.2)	**93%**	18.16 (2.68)	407 (67)	20 (3)	**95%**	21.83 (5.57)	215.7 (12.4)	**106%**
3.3.3 R1	27 days 10 mg/ℓ, AN	36.0	2437 (83)	0.08 (0.03)	1.30 (0.72)	7.07 (0.66)	3.11 (1.09)	6.05 (1.39)	35.0 (7.1)	**119%**	14.48 (1.49)	456 (57)	26 (11)	**70%**	28.84 (5.95)	211.9 (13.0)	**80%**
3.3.3 R2	27 days 0 mg/ℓ	35.8	2424 (92)	0.15 (0.09)	2.78 (1.45)	6.94 (0.80)	2.64 (0.80)	6.27 (1.60)	35.0 (7.1)	**96%**	15.54 (2.66)	456 (57)	21 (3)	**75%**	24.30 (6.72)	192.7 (13.7)	**86%**
3.3.4 R1	18 days 10 mg/ℓ, AN	36.0	2009 (265)	0.07 (0.04)	1.56 (0.73)	6.18 (1.49)	3.38 (0.65)	6.39 (1.35)	33.5? 41.9	133% **106%**	14.03 (1.02)	461 (84)	22 (3)	**89%**	31.73 (2.11)	220.0 (13.7)	**125%**
3.3.4 R2	18 days 0 mg/ℓ	36.2	1987 (196)	0.10 (0.01)	1.86 (0.69)	5.98 (1.35)	3.21 (1.21)	6.04 (1.29)	33.5? 41.9	124% **99%**	13.89 (0.96)	461 (84)	20 (3)	**89%**	29.44 (4.19)	199.4 (11.9)	**119%**
3.3.5 R1	21 days 20 mg/ℓ, AN	36.4	1581 (142)	0.05 (0.03)	0.80 (0.46)	6.80 (1.39)	3.12 (0.83)	5.69 (1.63)	30.1? 37.6	143% **122%**	12.44 (1.75)	398 (61)	23 (7)	**82%**	34.30 (5.22)	247.4 (36.3)	**100%**
3.3.5 R2	21 days 0 mg/ℓ	36.1	1546 (101)	0.07 (0.02)	2.48 (0.94)	7.44 (0.95)	2.75 (0.68)	6.59 (1.89)	30.1? 37.6	134% **107%**	12.83 (1.24)	398 (61)	21 (3)	**84%**	25.04 (5.12)	207.5 (20.1)	**114%**
3.3.6 R1	20 days 20 mg/ℓ, AE1	36.3	1510 (146)	0.07 (0.03)	1.18 (1.05)	4.92 (0.53)	2.61 (0.99)	4.69 (0.71)	26.7? 33.4	129% **103%**	11.76 (2.57)	354 (94)	21 (5)	**93%**	29.27 (6.64)	246.8 (9.6)	**112%**
3.3.6 R2	20 days 0 mg/ℓ	36.6	1319 (115)	0.05 (0.02)	4.69 ? 2.20	5.94 (0.86)	2.48 (0.74)	6.16 (0.96)	26.7? 33.4	61% **99%**	14.72 (1.69)	354 (94)	21 (3)	**101%**	24.05 (6.66)	224.6 (15.7)	**108%**
									Mean (excl. 3.3.1):	104%			Mean (excl. 3.3.1):	**86%**		Mean (excl. 3.3.1):	**101%**
									S.D.:	9%			S.D.:	**9%**		S.D.:	**16%**

Table 4.6: **Summary: P removal due to ferric chloride measured in pilot plants.**
Pt_{rem} implies TP removal (Influent - Effluent) : **(1)** = R1 (Ferric); **(2)** = R2 (Control).
Note: Effluent P was limiting (<1 mgP/ℓ) in R1 during much of Periods 3.6.1 and 3.6.2a.
Refer to discussion (4.3.12) on P addition during Period 3.6.2b.

Period	Fe dose, R1 mmol/d ; zone; duration (days)	Rs (days)	Δ Pt_{rem} ($Pt_{rem,R1}$ - $Pt_{rem,R2}$) mgP/ℓ	M(Δ Pt_{rem}) mgP/d	mol $P_{removed}$ /mol Fe_{dosed}
3.3.1	6.65 ; AE1 (62d)	20	4.22	147.34	0.72
3.3.1(b)	6.65 ; AE1 (31d)	20	6.02	210.67	1.02
3.3.2	13.3; AE1 (34d)	20	11.93	422.73	1.03
3.3.3	6.65; AN (27d)	20	4.54	168.30	0.82
3.3.4	6.65; AN (18d)	10	2.29	76.55	0.37
3.3.5	13.3; AN (21d)	10	9.26	329.50	0.80
3.3.6	13.3; AE1 (20d)	10	5.71	213.40	0.52
3.6.1	6.65, AE1 (45d)	10	-0.16	-5.73	-0.03
3.6.2a	6.65, AE1 (64d)	10	0.11	8.15	0.04

4.3 RESULTS AND DISCUSSION

4.3.1 Overall results for ferric chloride dosing periods (with influent phosphate and alkalinity supplements)

4.3.1.1 Low ferric chloride dosing

A summary of the results for the ferric chloride dosing periods is given in Table 4.4. The removal of Total P for Periods 3.3.1, 3.3.3 and 3.3.4 (low ferric chloride dosing, i.e. 10 mgFe/ℓ based on influent) is plotted as a time series in Figure 4.1a, and as a normal probability plot in Fig. 4.1b.

It can be seen from Fig. 4.1a that, with relatively few exceptions, Total P removal was greater in R1 (ferric dosed) than R2 (Control). The differences are also evident from the normal probability plots (Fig. 4.1b). Table 4.4 shows that the mean Total P removal (Pt_{rem}) was always greater for R1 relative to R2 during Periods 3.3.1, 3.3.3 and 3.3.4, although the data showed considerable variance, judging from the standard deviations. Analysis of the variance in the data (e.g. Student's t-test) was not attempted since the two sample sets (R1 and R2) were not independent due to the experimental units having the same influent source.

In spite of the variance in the data, it can be confidently concluded that ferric chloride did produce a net improvement in total P removal at the low dose used in Periods 3.3.1, 3.3.3 and 3.3.4 (10 mg Fe/ℓ based on influent).

4.3.1.2 High ferric chloride dosing

A summary of the results for the ferric chloride dosing periods is given in Table 4.4. The removal of Total P for Periods 3.3.2, 3.3.5 and 3.3.6 (high ferric chloride dosing, i.e. 20 mgFe/ℓ based on influent) is plotted as a time series in Figure 4.2a, and as a normal probability plot in Fig. 4.2b.

It can be seen from Fig. 4.2a that, Total P removal was always greater in R1 (ferric dosed) than R2 (Control). The differences are also evident from the normal probability plots (Fig. 4.2b). Table 4.4 shows that the mean Total P removal (Pt_{rem}) was always greater for R1 relative to R2 during Periods 3.3.1, 3.3.3 and 3.3.4, although the data showed considerable variance, judging from the standard deviations. Analysis of the variance in the data (e.g. Student's t-test) was not attempted for the same reason as that given under 4.3.1.1 above. However, it can be confidently concluded

that ferric chloride produced a significant improvement in total P removal at the high dose used in Periods 3.3.2, 3.3.5 and 3.3.6 (20 mgFe/ℓ, based on influent).

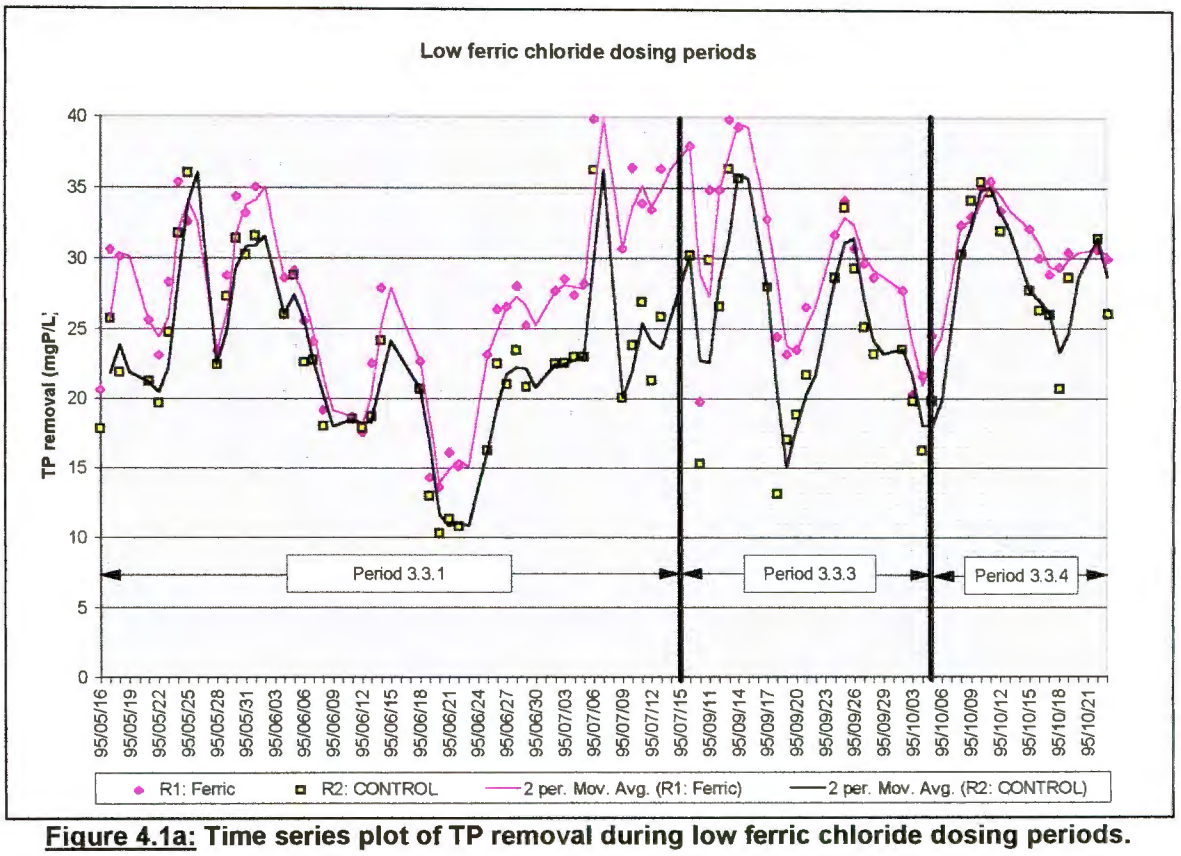


Figure 4.1a: Time series plot of TP removal during low ferric chloride dosing periods.

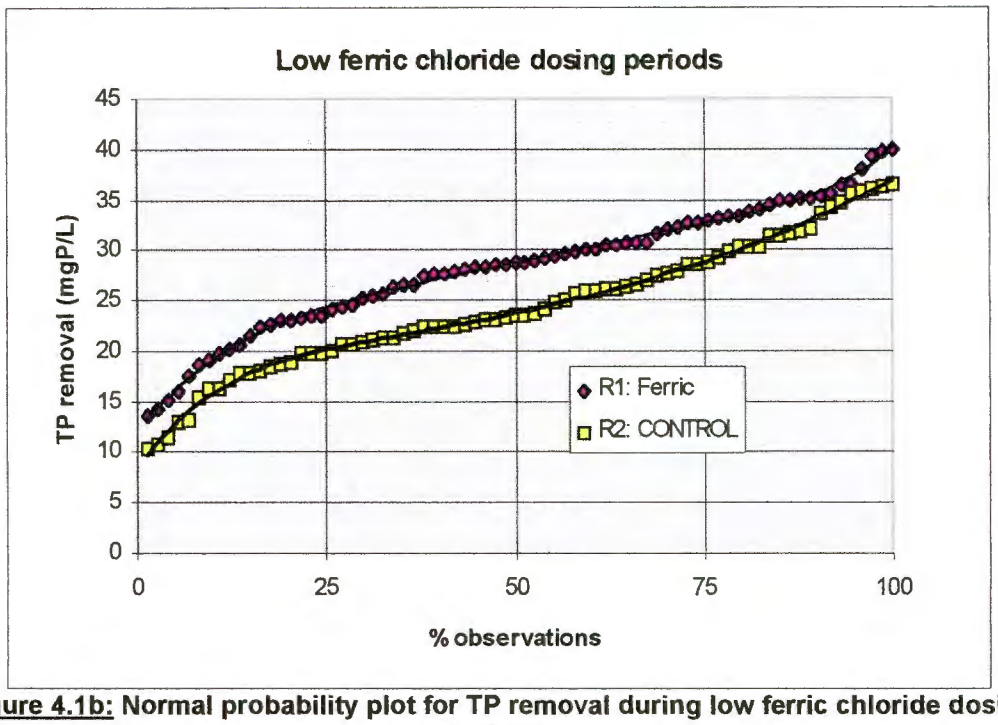


Figure 4.1b: Normal probability plot for TP removal during low ferric chloride dosing periods.

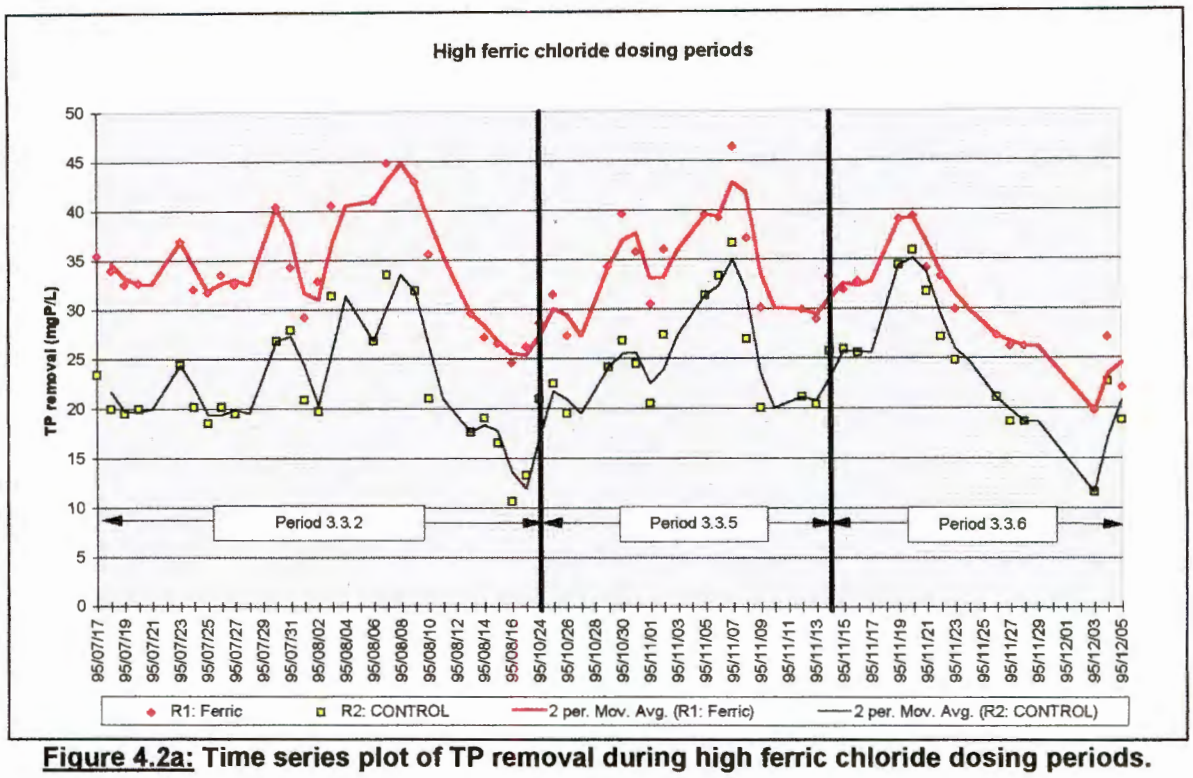


Figure 4.2a: Time series plot of TP removal during high ferric chloride dosing periods.

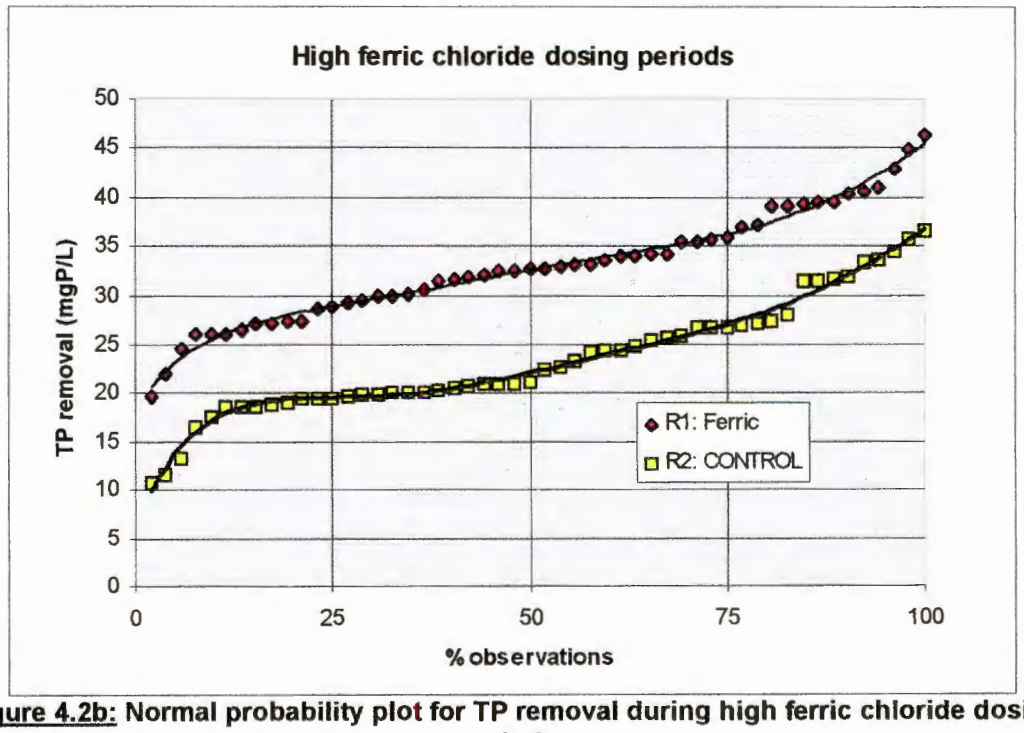


Figure 4.2b: Normal probability plot for TP removal during high ferric chloride dosing periods.

4.3.2 Mass Balances

4.3.2.1 Overall mass balances for COD, N and P

The overall mass balances (Table 4.5.1), whilst good or satisfactory for most periods, showed certain inconsistencies, the causes of which are not obvious. It appears that a cumulative effect of several sampling or measurement problems contributed to the inconsistent mass balances. For example, in Period 3.3.3, COD mass balances were relatively poor. This may have been partly due to the settling problems experienced during this period, particularly with unit R1 (see below) and sampling error from the effluent bucket may have caused a failure to fully detect the increase in effluent suspended solids as increased COD (refer to Table 4.4). However, since the effluent COD is numerically small and exerts only a small effect on the overall COD recovery, the oxygen uptake rate (O_t) would need to be 33% greater in order to increase COD recovery to 85% for the mass balance of Period 3.3.3. It is worth noting that a summary by Barker and Dold (1995) of results from a large number of pilot or laboratory-scale experimental systems suggests that activated sludge systems incorporating anaerobic zones (typical BEPR systems) tend to exhibit low COD mass balances (ca. <80%). Barker and Dold (1995) suggested that this "loss" of COD may be either the direct result of fermentation processes in the anaerobic zone (e.g. generation of gas which evolves during the fermentation process) or an indirect result thereof (e.g. production of volatile fermentation products which are released from the system during subsequent aeration). However, experimental evidence to support these proposals needs to be found. Fluctuation of the influent COD concentration (as in this study) tends to weaken confidence in COD mass balance calculations for the reason that changes in sludge production (VSS) occur slowly and require several sludge ages to reach steady state, whereas changes in parameters such as influent COD and O_t are observed more quickly.

Specifically in the case of nitrogen, the mass balances for Periods 3.3.4 through 3.3.6 appeared to be consistently greater than 100%, ranging from 118 to 153%. This observation may have been linked to the reduction in sludge age for these periods relative to those preceding. On the other hand, the problem may have stemmed from under-recovery of influent TKN (possibly due to incomplete digestion). By adjusting all the influent TKN data upwards by 25% (figures in red in Table 4.5.1), recoveries improved into the range 94 to 122%. An alternative explanation for the nitrogen mass balance problems may be the sensitivity of the balance to the nitrate results obtained, particularly for the anoxic reactor. For example, one set of results (Period 3.3.6, R2, anoxic zone nitrate) was not consistent at 4.7 mgN/ℓ, compared to an average of 2.2 mgN/ℓ for the preceding two periods; when this result was assumed to be 2.2 mgN/ℓ the mass balance improved from 61% to 99%. A discussion of the extent of denitrification in relation to P uptake in the anoxic zone is presented in Chapter 7 (section 7.2.4.3).

4.3.2.2 P mass balance around the anaerobic reactor

Using the measured data given in Table 4.4 (for P_{ti}, P_{te} and $fP_{t,a}$) and Table 4.5 (Q_i) and accepting $Q_i = Q_s$ (i.e. return sludge recycle ratio = 1:1, see Figure 3.1), from mass balance considerations around the anaerobic reactor it can be shown that:

$$M(P_{rel}) = [(Q_i + Q_s).\, fP_{t,a}] - [Q_i.P_{ti} + Q_s.P_{te}] \qquad \text{..... Eqn. 4.1}$$

where $M(P_{rel})$ is the mass of P released to the (filtered) supernatant in the anaerobic zone.

Using Eqn. 4.1 and the data as outlined above, P release in the anaerobic zone of the Test unit (R1), when expressed as a percentage of that in the Control unit was calculated to be as follows:

- Period 3.3.1 : 88% (10 mg Fe/ℓ, aerobic zone, R_s = 20d)
- Period 3.3.2 : 97% (20 mg Fe/ℓ, aerobic zone, R_s = 20d)
- Period 3.3.3 : 95% (10 mg Fe/ℓ, anaerobic zone, R_s = 20d)
- Period 3.3.4 : 90% (New culture; 10 mg Fe/ℓ, anaerobic zone, R_s = 10d)
- Period 3.3.5 : 86% (20 mg Fe/ℓ, anaerobic zone, R_s = 10d)
- Period 3.3.6 : 79% (20 mg Fe/ℓ, aerobic zone, R_s = 10d)

These data suggest that P release in the anaerobic zone of the Test unit was inhibited to a significant degree by the dosing of ferric chloride. The average degree of inhibition was 11%, which was also that found for the first experimental period (Period 3.3.1) at low alum dose (10 mgFe/ℓ based on influent). During Period 3.3.2, it appeared that the doubling of ferric chloride dose (to 20 mgFe/ℓ based on influent) resulted in less inhibition of P release. This observation may be linked to that for alum dosing (see Chapter 3, section 3.3.3.2) in which a high alum dose *initially* appeared to stimulate the biological P removal mechanism, as measured by the mass of P released in the anaerobic reactor. However, as with alum, continuous ferric chloride dosing (particularly at the high ferric chloride dose), showed greater inhibition of P release in the anaerobic reactor in subsequent experimental periods. Of the experimental periods under consideration here, Period 3.3.6 showed the greatest degree of inhibition, which was surprising since ferric chloride (20 mgFe/ℓ based on influent) was dosed to the *aerobic* zone during this period. Since period 3.3.6 was the last of a series of the six experimental periods spanning a period of some 180 days (18 sludge ages) culminating in high ferric chloride doses, these data suggest that prolonged ferric chloride addition with increasing dose, may produce greater inhibition of the BEPR mechanism.

4.3.3 Molar ratios of P removed/ Fe dosed and point of dosing

Calculation of the average molar ratio of P removal/ Fe dosed in Table 4.6 is based on the assumption that the difference in P removal between R1 and R2 is *only ascribable to chemical addition*. The problem with this assumption is that effects of both chemical and biological origin are lumped; if the biological mechanism is weaker in R1 than R2, it will reflect as a lower P (removal)/ Fe molar ratio and could be confused with a weaker chemical precipitation mechanism; the latter may not be directly linked to biological causes (or vice versa). In order to further elucidate the observed stoichiometry of chemical precipitation, the pilot plant data were examined by means of the IAWQ Activated Sludge Model (No. 2). It was possible to adjust the calibration of the model to take into account changes in the biological P removal performance of the Control, and hence to investigate the stoichiometry of precipitation independently. These modelling aspects are discussed in Chapter 7 (section 7.2).

The additional P removal (i.e. Δ Pt_{rem} $=Pt_{rem,R1}$ - $Pt_{rem,R2}$) (Table 4.6) may be compared for respective periods at the same ferric chloride dose but different sludge ages (20d vs. 10d). For Periods 3.6.1 and 3.6.2a, during which P-limitation occurred in both units, the data in Table 4.6 are not valid since virtually complete P removal occurred in the Control unit[2]. Stoichiometry estimated from fractionation results may be substituted for these periods (see Table 4.10a below). The following comparisons are obtained:

- Period 3.3.1 = 0.72 mol P/mol Fe (R_s = 20d, 10 mgFe/ℓ, AE1 zone)
- Period 3.6.1/ 3.6.2a = 0.40 mol P/mol Fe (R_s = 10d, 10 mgFe/ℓ, AE1 zone, low P)
- Ratio (R_s 20d/ R_s 10d) = 0.72/ 0.57 = 1.8

- Period 3.3.1(b) = 1.02 mol P/mol Fe (R_s = 20d, 10 mgFe/ℓ, AE1 zone)
- Period 3.6.1 = 0.40 mol P/mol Fe (R_s = 10d, 10 mgFe/ℓ, AE1 zone, low effluent P)
- Ratio = 1.02/ 0.57 = 2.5

- Period 3.3.2 = 1.03 mol P/mol Fe (R_s = 20d, 20 mgFe/ℓ, AE1 zone)
- Period 3.6.6 = 0.52 mol P/mol Fe (R_s = 10d, 20 mgFe/ℓ, AE1 zone)
- Ratio = 1.03/0.52 = 2.0

(continued)...../

[2] Periods 3.6.1 and 3.6.2a are is discussed in detail in section 4.3.11 below.

- Period 3.3.3 = 0.82 mol P/mol Fe (R_s = 20d, 10 mgFe/ℓ, AN zone)
- Period 3.3.4 = 0.37 mol P/mol Fe (R_s = 10d, 10 mgFe/ℓ, AN zone)
- Ratio = 2.2

Rabinowitz and Marais (1980) proposed that the chemical P removal mechanism involves the formation of iron hydroxide for at least a part of the iron dosed, and that ion exchange between phosphate and hydroxyl ions occurs as a slow competing side reaction to the rapid direct precipitation of iron phosphate. If this hypothesis is accepted, then ferric hydroxide may be expected to accumulate in the mixed liquor, thereby producing the so-called "persistence effect" noted, amongst others, by Rabinowitz and Marais (1980). With this "persistence effect", the mixed liquor has a residual chemical P removal potential after metal dosing is stopped, or has an attenuating effect on effluent P concentrations under cyclic loading conditions despite a constant metal dosing rate. Hence, it may be expected that, for the same metal dose, chemical P removal may be more efficient (i.e. greater ratio of mol $P_{removed}$/ mol Fe_{dosed}) at a longer sludge age where the longer solids retention time may allow the PO_4^{3-}/OH^- ion exchange reaction to proceed closer to completion. The results of the paired experimental periods given above appear to support this hypothesis, with greater additional (i.e. chemical) P removal noted for the periods at a 20d sludge age, compared to a 10d sludge age. The *ratio* between the paired results was approximately 2, suggesting that the same iron dose was twice as efficient with twice the solids retention time.

Rabinowitz and Marais (1980), examined the dosing of metal salts into either the first or last *aerobic* reactor of a laboratory-scale modified Bardenpho system (anaerobic-anoxic-aerobic) having three aerobic reactors. They concluded that the point of dosing does not have a significant effect on the chemical removal in the system.

In this study, two dosing points were studied: the anaerobic reactor and the first of two aerobic reactors in a three-stage modified Bardenpho (Phoredox) configuration (Fig. 3.1, Chapter 3). The ferric chloride dosing regime (see section 4.2.3) was based on the assumption that a molar ratio of 0.5 mol $P_{removed}$/ mol Fe_{dosed} would be achieved. This was a conservative estimate knowing that the stoichiometric molar ratio for formation of $FePO_4$ is 1 mol Fe: 1mol P, which converts to a mass ratio of 1.80 mg Fe/ mg P. If it is accepted that the molar ratios of $P_{removed}$/ Fe_{dosed} calculated in Table 4.6 represent the *net* effect of chemical and biological factors influencing system P removal, it is useful to compare these data to the theoretical (ideal) stoichiometry of precipitation for the respective ferric chloride doses, points of dosing, and sludge ages studied. Table 4.6 suggests that:

- P removal approached the theoretical stoichiometric amount for precipitation of $FePO_4$ when ferric ions were dosed to the aerobic zone at a sludge age of 20 days, under conditions when P was not limiting.
- Dosing to the anaerobic zone under the same conditions, gave approximately 80% of the theoretical stoichiometric amount of P precipitation (i.e. approx. 0.8 mol $P_{removed}$/mol Fe_{dosed});
- At a sludge age of 10 days, also without P limitation, dosing to the aerobic zone gave precipitation of approximately 50 to 60% of the stoichiometric amount (i.e. approx. 0.5 to 0.6 mol $P_{removed}$/mol Fe_{dosed}).
- Dosing to the anaerobic zone at a sludge age of 10 days without P limitation appeared to be less efficient at a low dose (10 mg Fe/ℓ, based on influent), giving about 40% of the stoichiometric amount (i.e. approx. 0.4 mol $P_{removed}$/mol Fe_{dosed}), while at a higher dose (20 mg Fe/ℓ, based on influent) the precipitation efficiency was equivalent to that for the aerobic zone (i.e. 80% of the stoichiometric amount, or 0.8 mol $P_{removed}$/mol Fe_{dosed}). Presumably precipitation efficiency is reduced when dosing small amounts of ferric ions to the anaerobic zone as a result of complexation/ coagulation reactions with soluble organic matter originating from the influent. A similar observation was made for alum (see section 3.3.3.3, Chapter 3).

However, as was stated above, it may be deceptive to consider the difference in system P removal between the Test and Control units as solely indicative of precipitation stoichiometry. The "precipitation efficiency", measured as the difference in system P removal between the units, is actually a measure of the *combined* chemical and biological removal components; it will be negatively affected if the biological removal mechanism is (partially) inhibited by the chemical mechanism, relative to the Control unit. For example, at low effluent P concentrations (see section

4.3.11 below), with effluent ortho P concentrations in the range 0.24 mgP/ℓ (± 0.15 mgP/ℓ) to 0.35 (± 0.34)[3], the apparent "precipitation efficiency" is greatly reduced, to the point that the system P removal in the Test system dosed with iron is equivalent to or *less than* that of the Control. Part of the reason for this observation may be that chemical precipitation becomes "inefficient" at these low phosphate concentrations. This conclusion was reached by Rabinowitz and Marais (1980) who reported (for 20d sludge age systems) "indications that when the effluent phosphorus concentration drops to about 1.5 mgP/ℓ and below, the removal efficiency decreases". However, it under low effluent P conditions (i.e. low soluble ortho P concentrations in the aerobic reactors) that interaction between the chemical and biological mechanisms becomes crucial. Under these conditions the biological mechanism will most likely be "competing" strongly with the precipitation / ion exchange reactions for available phosphate. Rabinowitz and Marais (1980) did not operate a Control system, and did not have an accurate measure of the biological P removal component in their Test system under conditions when iron salt was being dosed (refer to discussion in Chapter 8). Furthermore, their experimental periods were generally of less than one sludge age duration. Their conclusion was based largely on observations of the system P removal in the presence of iron dosing (i.e. similar to that drawn above from Table 4.6 for Periods 3.6.1 and 3.6.2a). However, from Table 4.6 it can be seen that dosing of ferric chloride to the Test system under conditions of potential P limitation for protracted periods (more than five sludge ages) resulted in an *apparent* loss of benefit from chemical dosing which was associated with inhibition of the *biological* P removal mechanism. These results are considered in more detail in section 4.3.11 below. It follows that under conditions of (potential) P limitation (<1 mgP/ℓ as ortho P) where a major biological P removal is also expected, simultaneous precipitation with ferric chloride cannot be assumed to follow either theoretical stoichiometry (1 P:1 Fe), nor the stoichiometry observed for conditions in which phosphate was not limiting.

It is worth noting that Lötter (1991) reported data of between 2 and 2.4 mg Fe dosed/ mgP removed using iron salts for real conditions where effluent phosphate could potentially become limiting (< 1 mgP/ℓ as dissolved ortho P). This converts to between 0.23 and 0.28 mol $P_{removed}$/mol Fe_{dosed} (or 30% stoichiometric precipitation efficiency). Comparing these results to those in Table 4.6, implies that the full-scale systems described by Lötter (1991) were most probably operating close to P limiting conditions. Lötter (1991) reported anecdotal information concerning the occasional need for increased doses of ferric salts in an attempt to achieve the 1 mgP/ℓ standard in these full-scale plants, and de Haas and Greben (1991) reported fractionation studies for one of these plants (Northern Works, Johannesburg, RSA) which showed a decrease in the poly P content of mixed liquor during dosing with ferric sulphate. These findings concur with results discussed in sections 4.3.11 and 4.3.12 below, which suggest that inhibition of the biological P removal mechanism becomes very significant under low (or limiting) effluent P concentrations.

Finally it is possible to compare the observed molar ratio of $P_{removed}$/ Fe_{dosed} (i.e. the "precipitation efficiency") in Table 4.6 with that calculated from fractionation data by taking the ortho P content of the PCA fraction as being representative of chemical precipitate present in the mixed liquor. By taking the difference in the magnitude of this fraction between the Test and Control units, the stoichiometry of Fe-P precipitate formed as a result of ferric chloride addition may be estimated. The results are shown in Table 4.10a, alongside the molar ratios from Table 4.6. These results show that the PCA + NaOH ortho P fractions accounted for a major part (60 to 70%) of the overall additional P removal in the Test unit, relative to the Control (i.e. that represented by the molar ratio $P_{removed}$/ Al_{dosed} in Table 4.6). The significance of this observation is discussed in section 4.3.6 below.

4.3.4 Alkalinity and pH considerations

The acidity of ferric chloride (0.5 to 1% free acid as HCl, according to the suppliers *NCP Ultrafloc*) may be a source of concern when using this chemical in applications with low alkalinity influent wastewater. In view of the apparent importance of added alkalinity in the stable operation of the pilot plants (Chapter 3), effluent bicarbonate (H_2CO_3*) alkalinity was measured in the effluent

[3] See Appendix 5, Results for Periods 3.6.1 and 3.6.2a, or Table 4.12 of this chapter.

during the ferric dosing periods. Table 4.7 gives a summary of the pH statistics and effluent alkalinity results. From this table it can be seen that the effluent bicarbonate alkalinity in R1 (ferric dosed) was consistently lower than in R2 (Control), but the difference was always in the range 20 to 40 mg/ℓ as $CaCO_3$. This difference is small but significant for a wastewater works such as Darvill with low influent alkalinity and requiring lime dosing on a routine basis (see Chapter 6). For Period 3.3.1 through 3.3.6, alkalinity consumption due to ferric dosing (based on measurements of bicarbonate alkalinity in the pilot plant effluents - refer to Table 4.7) was approx. 0.66 mg as $CaCO_3$/ mg $FeCl_3$, which is less than the theoretical value of 0.92 on the same basis for the precipitation of ferric hydroxide (Loewenthal *et al.*, 1986). For Periods 3.6.1 and 3.6.2a (low effluent P with bicarbonate added to influent), the alkalinity consumption was approx. 0.8 to 1.17 mg as $CaCO_3$/ mg $FeCl_3$, which is closer to the theoretical value for ferric hydroxide. These data suggest that the precipitate formed always precipitated some alkalinity (Alk.), and that the molar ratio Fe_{dosed}:$Alk_{removed}$ increases as that for Fe_{dosed}: $P_{removed}$ decreases. Various empirical formulae have been put forward in the literature to describe the overall precipitation stoichiometry observed. For example, Luedecke *et al.* (1989) suggested use of a general formula for ferric hydroxy phosphate, namely:

$$Fe_rPO_4\ (OH)_{3r-3}$$

For an Fe:P molar ratio of the order of 0.6 mol P/ mol Fe dosed (for non- P limiting conditions, see section 4.3.6 and Table 4.10a below), the average formula of the precipitate according to Luedecke *et al* would be:

$$Fe_{1.66}\ PO_4\ (OH)_2$$

However, this formula predicts an alkalinity loss of only 1.2 mol / mol Fe (approx. 0.4 mg $CaCO_3$/ mg $FeCl_3$), which is less than that observed experimentally (see above). In order to be consistent with the observed alkalinity losses, the general formula for periods without P limitation could be written as:

$$Fe_{1.66}\ (X^{2+})\ PO_4\ (OH)_4$$

where X^{2+} is some unknown (possibly divalent) cation (e.g. Mg^{2+} or Ca^{2+}) (c.f. Arvin, 1985; Henze *et al.*, 1992)[4], which is the same as the average formula found in Chapter 3 for alum.

Under P limiting conditions, the average P:Fe stoichiometry estimated from fractionation data was in the range 0.32 to 0.46 mol P/ mol Fe (see section 4.3.11). Since the bicarbonate alkalinity consumption due to precipitation was approx. 3 mol Alk./ mol Fe for these periods, the average formula for ferric-hydroxy-phosphate complex formed under these conditions could lie in the following approximate range:

$$Fe_3\ (X^{2+})\ PO4\ (OH)_8 \text{ to } Fe_{2.2}\ (X^{2+})\ PO4\ (OH)_7\ .$$

Still more complex empirical formulae have been proposed, incorporating both hydroxide and bicarbonate anions in the precipitate (Henze *et al.*, 1992):

$$Ca_k\ Me_m\ (H_2PO_4)_f\ (OH)_h\ (HCO_3)_c$$

Since calcium ion and carbonate ion concentrations were not specifically measured in this study, it is not possible to comment on the applicability of this formula to the results obtained here.

Despite the benefit of supplemented influent alkalinity to the pilot plants (Table 4.1), the data in Table 4.7 show that the pH in the anaerobic zone did not remain consistently above 7.0. However, there was little statistical difference between the behaviour of R1 compared to R2 in this respect, even in Periods 3.3.3, 3.3.4 and 3.3.5 when the anaerobic zone (of R1) was dosed with ferric chloride. There was a slight tendency for the pH of the aerobic zones to be lower in R1 than R2, and more so for Periods 3.3.1, 3.3.2 and 3.3.6 when the first aerobic zone (AE1 of R1) was dosed with ferric chloride. However, this difference never exceeded 0.13 pH units on a median basis.

[4] Note: if H^+ is used to substitute for X^{2+}, then these protons removed from solution would represent a gain in alkalinity.

Periods 3.6.1 and 3.6.2 were designed to test the effect of dosing ferric chloride under low effluent P conditions, in the presence and absence of added bicarbonate alkalinity in the influent. Experience with alum dosing (section 3.3.3.3, Chapter 3) had suggested that influent alkalinity played a role in the stable operation of the pilot plants, and that the biological P removal mechanism may be inhibited to a greater degree where the reactor at the point of dosing has a pH of less than 7.2. Comparing the results for Periods 3.6.1 and 3.6.2, it appears that under low (limiting) effluent P conditions, the presence or absence of added bicarbonate in the influent did *not* significantly influence either the effluent P concentrations nor the stability of operation of the pilot plants. It should be noted from Table 4.7 that the withdrawal of the bicarbonate supplement resulted in a drop in median reactor pH by approx. 0.3 to 0.4 units in the aerobic reactors of both the Test and Control units. Although the bicarbonate alkalinity in the Test unit (with iron) was always lower than that of the Control unit, it never rose above 263 mg/ℓ as $CaCO_3$ during Period 3.6.1 and seldom (<25% of observations) fell below 80 mg/ℓ as $CaCO_3$, even in the Test unit during Period 3.6.2a. This was probably the significant factor in ensuring stable unit operation in the presence of simultaneous precipitation. As will be discussed in section 4.3.11 below, the degree of inhibition of the bio-P removal mechanism was significant under P-limiting conditions. However, little difference could be found between Periods 3.6.1 and 3.6.2a in this respect. It may therefore be assumed that effluent bicarbonate alkalinity in the range ca. 80 to 260 mg/ℓ as $CaCO_3$ did not play a role in this regard. Judging from this observation as well as the difference of only approx. 0.1 mgP/ℓ in effluent ortho P results between Periods 3.6.1 and 3.6.2a (see Table 4.12), it appears that chemical precipitation of phosphate with ferric is not very sensitive to pH in the range 7.0 to 7.5 (median pH range for Test unit aerobic reactors in Periods 3.6.1 and 3.6.2a - see Table 4.7). Iron may be different from aluminium in this respect. In Chapter 7, from theoretical chemical equilibrium considerations using the chemical model of Briggs (1995) (Figs. 7.4 and 7.5, and ignoring uncertainty to some extent in the solubility product or equilibrium constant data), it was found that the solubility of ortho P in the presence of metal-phosphate precipitate should vary in a narrow range of approx. 0.1 to 0.3 mgP/ℓ for precipitation with ferric ions in the pH range 7.0 to 7.5; for aluminium ions, the comparable variation could be from approx. 0.3 to 2 mgP/ℓ. Another difference between the iron-P and aluminium-P solubility curves (c.f. Briggs, 1995; Figs. 7.4 and 7.5) is that the iron-P curve shows a minimum at around pH 7 (approximately), while the aluminium-P curve shows lower P solubility at pH <7. Hence, with iron dosing, the lower (but less pH sensitive) equilibrium solubility of iron-P precipitate could account for the greater degree of competition for available phosphate between the chemical and biological mechanisms at low effluent P concentrations, but the relatively small effect played by influent bicarbonate alkalinity. The finding by Rabinowitz and Marais (1980) that chemical precipitation with iron salts becomes less efficient at reactor pH < 7 (approx.) is also supported by equilibrium chemistry considerations. On the other hand, with alum dosing, competition between the chemical and biological mechanisms may be less significant with higher (or supplemented) influent bicarbonate alkalinity and the attendant higher reactor pH (ca. 7.2 or above), but very low effluent ortho P ($\leq$ 0.5 mgP/ℓ) residuals may not be achieved. More "efficient" chemical precipitation and lower residual effluent P residuals are likely to occur with alum at lower influent alkalinity and lower reactor pH (approx. <7.2), but the risk of increased inhibition of the bio-P removal mechanism (or other activated sludge processes such as nitrification and flocculation) may threaten the viability of this option.

...../ Table 4.7

Table 4.7: Alkalinity and pH data for periods of ferric chloride dosing.
 # denotes mean in place of median.

Period	Unit: / Zone:	R1 AN	R2 AN	R1 AE1	R2 AE1	R1 AE2	R2 AE2	R1 H_2CO_3* Alk. mg/ℓ as $CaCO_3$ Effluent	R2 H_2CO_3* Alk. mg/ℓ as $CaCO_3$ Effluent
3.3.1	Median	7.09	6.99	7.34	7.29	7.56	7.57	211 #	230 #
	Min.	6.70	6.59	6.89	6.90	7.15	7.09	185	179
	25%-ile	7.02	6.92	7.29	7.24	7.47	7.46	-	-
	75%-ile	7.19	7.07	7.42	7.38	7.62	7.64	-	-
	Max.	7.31	7.25	7.55	7.52	7.76	7.88	259	277
3.3.2	Median	6.93	6.84	7.23	7.21	7.46	7.50	210 #	248 #
	Min.	6.85	6.48	7.02	7.03	7.22	7.24	164	202
	25%-ile	6.87	6.80	7.19	7.16	7.43	7.46	-	-
	75%-ile	6.99	6.88	7.27	7.27	7.53	7.55	-	-
	Max.	7.08	7.00	7.38	7.34	7.62	7.70	260	301
3.3.3	Median	7.00	6.99	7.42	7.41	7.66	7.65	241 #	256 #
	Min.	6.77	6.75	7.19	7.18	7.38	7.37	-	-
	25%-ile	6.91	6.89	7.36	7.33	7.57	7.58	-	-
	75%-ile	7.06	7.06	7.45	7.46	7.71	7.74	-	-
	Max.	7.30	7.29	7.63	7.88	7.91	8.43	-	-
3.3.4	Median	7.00	6.92	7.34	7.29	7.56	7.57	ND	ND
	Min.	6.70	6.48	6.89	6.90	7.15	7.09	-	-
	25%-ile	6.89	6.82	7.21	7.20	7.45	7.46	-	-
	75%-ile	7.09	7.03	7.42	7.40	7.64	7.68	-	-
	Max.	7.31	7.29	7.63	7.88	7.91	8.43	-	-
3.3.5	Median	6.88	6.91	7.34	7.38	7.54	7.61	213 #	253 #
	Min.	6.77	6.80	7.18	7.22	7.45	7.47	203	243
	25%-ile	6.83	6.85	7.28	7.33	7.48	7.54	-	-
	75%-ile	7.00	7.09	7.39	7.45	7.61	7.69	-	-
	Max.	7.07	7.21	7.66	7.59	7.97	7.87	219	269
3.3.6	Median	7.03	6.96	7.29	7.42	7.54	7.64	212 #	250 #
	Min.	6.80	6.81	7.20	7.23	7.39	7.44	182	229
	25%-ile	6.96	6.92	7.28	7.37	7.51	7.59	-	-
	75%-ile	7.05	6.99	7.33	7.46	7.60	7.64	-	-
	Max.	7.30	7.21	7.43	7.63	7.67	7.86	247	273
3.6.1	Median	7.27	7.13	7.40	7.50	7.51	7.70	201#	225#
	Min.	7.02	6.98	7.01	7.09	7.13	7.20	159	152
	25%-ile	7.02	7.02	7.12	7.26	7.24	7.45	196	217
	75%-ile	7.45	7.33	7.54	7.61	7.68	7.79	207	242
	Max.	7.64	7.52	7.67	7.70	7.78	7.87	263	252
3.6.2a	Median	7.10	7.00	7.02	7.14	7.20	7.36	97#	132#
	Min.	6.62	6.50	6.59	6.67	6.78	6.86	28	31
	25%-ile	7.02	6.95	7.00	7.05	7.15	7.27	87	126
	75%-ile	7.14	7.02	7.13	7.22	7.31	7.43	108	138
	Max.	7.31	7.11	7.35	7.43	7.52	7.61	142	199

AN = Anaerobic zone; AE1 / AE2 = First / second aerobic zone respectively

4.3.5 Magnesium removal

Table 4.8 gives the magnesium removal data obtained during the periods of ferric chloride dosing. This table shows that with the exception of Period 3.3.1, the results obtained did not appear to be consistent with those obtained previously for the alum dosing periods (Chapter 3). An unexplained decrease in the influent Mg concentration was noted. The resultant effect was an apparent decrease in Mg removal. Since the magnesium results for the alum dosing periods (see Chapter 3) had produced little new information in respect of the state of the biological mechanism in R1 relative to R2 (but only corroborated findings by other methods), the decision was taken to abandon magnesium analysis[5].

Table 4.8: Summary of magnesium data for ferric chloride dosing periods.
N.D.= Not determined ? = Spurious result

Period, Unit	Flow Q, ℓ/d	Influent mg Mg/ℓ	Effluent mg Mg/ℓ	Removal mg Mg/d	No. of results	P removal mg P/d	mol Mg removed per mol P removed
3.3.1, R1	36.0	17.7	12.63	182.5	16	976.32	0.24
3.3.1, R2	36.2	17.7	12.03	205.3		828.98	0.32
3.3.2, R1	35.8	12.1	10.1	71.6	10	1208.61	0.08
3.3.2, R2	36.0	12.1	10.0	75.6		785.88	0.12
3.3.3, R1	36.0	11.0 ?	11.8	<0 ?	7	-	-
3.3.3, R2	35.8	11.0 ?	11.7	<0 ?		-	-
3.3.4, R1	36.0	10.3	10.0	10.8	5	1142.28	0.01
3.3.4, R2	36.2	10.3	9.6	25.3		1065.73	0.03
3.3.5, R1	36.4	N.D.	N.D	N.D	0	-	-
3.3.5, R2	36.1	N.D.	N.D	N.D		-	-
3.3.6, R1	36.3	N.D.	N.D	N.D	0	-	-
3.3.6, R2	36.6	N.D.	N.D	N.D		-	-

4.3.6 Fractionation studies

Fractionation studies (Figure 4.3) for Periods 3.3.1 through 3.3.3 showed that ferric chloride, like alum, increased the ortho P ("chemical precipitate") fraction of the sludge by three to four-fold such that it came to represent about 26% of the sludge total P at the low ferric dose, and by 4.3 fold at the high ferric dose to constitute 31% of the total P. With ferric dosing, the acid extractable (PCA) complex P fraction decreased in size (by 18 to 39% at low ferric doses) but the residue (or alkaline extractable) complex P fraction increased[6]. Most of this residue (or "non cold PCA-extractable" complex P) was in fact alkaline-extractable complex P (Fig. 4.3). The increased size of this fraction was particularly noticeable at high ferric doses when, for the first time, it predominated. The possible significance of the relative sizes of the PCA versus NaOH complex P fractions may be examined by summarising the fractionation results and relating these to model predictions (from section 7.3.2, Chapter 7).

The fractionation results are summarised in Table 4.9a. In Chapter 2 (section 2.4.2) it was shown that certainly the PCA extract complex P is very largely of biological origin, since this fraction in particular increases in response to the emergence of the BEPR phenomenon. In section 2.4.4 of Chapter 2, the need for inclusion of a NaOH extraction step in the fractionation procedure was illustrated in a batch test by adding ferric chloride to a sample of mixed liquor from a Control unit which received influent supplemented with acetate but not dosed with metal precipitant. Ferric

[5] The Mg analyses were performed by an outside laboratory geared to analysing large numbers of potable water samples. Detailed examination of the methods used for the samples submitted from this study, especially in respect of sample digestion, would have been required to verify that the observed decrease in Mg removal was real. Since the control reactor appeared to function normally in terms of biological P removal throughout this study (refer to modelling results, section 7.2.3, Chapter 7), and since a stoichiometric excess of magnesium was always added to the influent relative to phosphorus, the possibility of magnesium limitation of P removal was remote. Detailed examination of the analytical method for magnesium was therefore not adequately justified.

[6] It was the increase in the residue TP fraction which prompted introduction of the alkaline (NaOH) extraction step (Chapter 2).

chloride addition in this manner appeared to change the fractionation pattern, shifting the solubility of complex P from the PCA extract to the NaOH extract after only a matter of minutes in the batch test. In Chapter 2 (section 2.4.7) it was found that the same shift in fractionation pattern was produced by the addition of ferric ions *in vitro* during the fractionation experiment (i.e. by adding ferric chloride to the PCA solution used as extractant). This shift was completely artificial in that it occurred for a sample of mixed liquor from the Control unit with a mixed liquor culture which had never been dosed with iron. When a sample of mixed liquor containing significant amounts of iron precipitate (e.g. iron phosphate precipitate) is subjected to the fractionation procedure used here, the PCA extraction step would be expected to dissolve most of this precipitate (de Haas, 1989), and hence release iron (ferric) ions into solution. It was proposed that this would be equivalent to the *in vitro* addition of iron to the PCA solution. The complexes which form between iron and components arising from the disrupted mixed liquor solids can only be speculated upon, but could include complexes between poly P and macromolecules, such as proteins and polysaccharides, which tend to have poor solubility in cold PCA. It was concluded (Chapter 2, section 2.4.7) that the distribution of complex P between the PCA and NaOH extracts may be of little significance in the studying the biological P removal mechanism, and that significance should only be attached to the *sum* of the complex P fractions (acid + alkaline-extractable) as an measure of the biologically stored phosphate in the system. However, it may be useful to evaluate this conclusion in the light of the results for ferric chloride dosing to the pilot plants presented in this chapter.

Of the results in Fig. 4.3, those for R1 on 15/8/95 (i.e. Period 3.3.2 with a high ferric dose to the AE1 zone) clearly stand out: the NaOH complex P fraction was much greater than in preceding or succeeding periods at low ferric dose. However, the magnitude of this fraction at low ferric dose was nevertheless two to three times greater than in the Control. In order to determine the extent to which the NaOH complex P fraction was "biologically active", the results of the batch P release tests may be considered[7] (Figs. 4.4a & b and section 4.3.7 below). (In the results of these tests, the NaOH and RES (residue) fractions are grouped since the NaOH extraction step was only introduced to the fractionation procedure midway through Period 3.3.1). Fig. 4.4b shows that for mixed liquor from the Control unit, P release from the NaOH/RES fraction was negligible compared to that from the PCA complex P fraction. However, for the Test unit, P release from the NaOH/ RES fraction was significant and commensurate with its magnitude prior to the P release test (Figs. 4.4a and 4.3). For completeness, all the P release results from Figs. 4.4 (a&b) are given in Table 4.9b.

The data in Table 4.9b and Figs. 4.4(a&b) confirm that, for mixed liquor dosed with ferric ions, *at least part* of the complex P which is extracted with NaOH (rather than PCA) is of biological origin. If, on this basis, all the NaOH complex P is attributed to the biological mechanism in Table 4.9a, then it would appear that the biological fractions were never depressed by more than 17% relative to the Control. In some cases, the size of the biological fractions of the two units appeared to be equivalent, or even slightly larger in the Test unit dosed with ferric chloride. The sum of the biological and chemical fractions was always greater in the Test unit, compared to the Control, which is line with the observations of greater system total P removal in the Test unit (see 4.3.1). These results were obtained for ferric chloride dosing periods under non-P- limiting conditions; the fractionation results for P-limiting conditions were somewhat different and are discussed in sections 4.3.11.1 and 4.3.11.2.

Table 4.10a compares the additional P removal as chemical precipitate (estimated from the sludge ortho P fractionation data) with the metal dose, on a molar basis. It can be seen that the P removal attributable to chemical precipitate extracted in the PCA + NaOH ortho P fractions only account for about 60 to 70% of the observed molar ratio of $P_{removed}/Fe_{dosed}$ for periods in which P limiting conditions did not occur (from section 4.3.3 above and Table 4.6 above). Yet, the PCA + NaOH ortho P fractions accounted almost fully (90 to 96%) for the metal (hydroxy) phosphate ("MeP") predicted by the IAWQ chemical precipitation model[8] (see Table 4.10b; and refer to Chapter 7 and Table 7.10). The P:Fe stoichiometry fitted for the IAWQ model[9] was greater than

[7] The method for the batch P release tests is described in the full fractionation procedure in Table 2.11 of Chapter 2.
[8] A margin of error arises in these comparisons from the failure of the model to *exactly* predict the observed effluent P concentrations of the Test unit. The problem stems the accuracy to which the biological model can be calibrated (given the assumptions made in influent characterisation) as well as variance in both the observed influent and effluent data.
[9] These results are discussed in greater detail in Chapter 7 (sections 7.2.2.2 and 7.2.4.2).

that found by fractionation for periods where P was not limiting[10]. It is possible that a proportion of the observed additional (i.e. chemical) P removal in the Test unit (R1), versus the Control (R2), is due to the formation of chemical complexes which are either not extracted with cold PCA or NaOH, or if extracted, were not reactive in the ortho P test applied to the extracts. In general the fractionation procedure used here lacked the sophistication necessary to distinguish between different forms of chemically bound ortho P. However, if the hypothesis of Rabinowitz and Marais (1980) is accepted, then iron dosing (e.g. ferric chloride) may give rise not only to ferric phosphate precipitate directly, but also to ferric hydroxide as an ancillary precipitate, which also has chemical P removal potential (due to ion exchange). Most likely, this ferric hydroxide exists in colloidal/ amorphous form and may be bound to components ("microfibrils") of the biomass such as extracellular polysaccharide (Brown and Lester, 1979; He *et al.*, 1996). If the ferric-hydroxy-phosphate colloid is bound in some manner to biomass particles and not fully solubilised with cold PCA or NaOH, this could account for the failure of the fractionation method to completely recover the chemical phosphate fraction. It is worth noting that evidence of a "reserve" chemical precipitation potential (or so-called "persistence effect" ascribed to ferric hydroxide by Rabinowitz and Marais, 1980) was found in the batch tests with samples of mixed liquor from the Test unit which had either been exposed to a relatively high dose of ferric chloride (e.g. Period 3.3.2), or to ferric chloride dosing for a protracted time (Period 3.3.3). Comparing the fractionation patterns before and after the batch P release test, it was observed that a net *increase* in the PCA ortho P fraction had occurred. This suggests that a portion of the colloidal iron (from the ferric hydroxide "reserve" in the mixed liquor) reacted with P released biologically from the cells to form ferric phosphate precipitate. These results are considered in more detail in section 4.3.7.

4.3.7 Batch tests in association with fractionation studies

Figures 4.4a and 4.4b depict the release of phosphate according to fractions defined by the fractionation procedure. The ortho P released to the supernatant (SUP) is also shown. Where uptake (i.e. increase in size of a given fraction) occurred in the batch test when compared with the state before the batch test, this is depicted as *negative release.* In theory, within the bounds of experimental error, the sum of the release from the various sludge fractions (minus uptake in any fractions, if present) should equate to the net release observed for the SUP ortho P. In order to construct Figs. 4.4a & 4.4b such that fractionation results which included the NaOH extraction step could be compared to those which did not, the NaOH extract ortho P and complex P fractions were lumped with the residue TP.

Figure 4.4a shows that ferric chloride resulted in markedly less P release occurring from the PCA complex P of the R1 and more from the alkaline (NaOH) extract, particularly during high ferric dosing (20 mg/ℓ as Fe, based on influent) to the aerobic zone (Fig. 4.4a). The same phenomenon occurred to a lesser degree with alum (Fig. 3.8a) and generally did not occur in the *Control* (R2) (Fig. 4.4b and Fig. 3.8b). The one occasion where P release was noted from the "residue TP" (i.e. NaOH complex P fraction) of the Control (R2) was on 5/10/95 with ferric dosing to the anaerobic zone. On this occasion, apparent release from the residue fraction of the Control was small (12 mgP/gVSS) out of a total observed release of ca. 120 mgP/gVSS as ortho P to the supernatant, and the sum of release from the respective fractions exceeded that to the supernatant by a similar margin. It is likely that this is within the range of experimental error stemming from the analytical difficulty of ensuring 100% recovery of phosphate during the fractionation procedure, particularly where dilutions are necessitated.

The above-mentioned observation of P release from the alkaline-extractable complex P fraction is in line with the shift toward its increasing size in the presence of metal salt dosing (ferric chloride in this case). In view of the finding that ferric ions appear to introduce a change in acid-solubility versus alkaline-solubility of the complex P fractions (see above and Chapter 2, section 2.4.7), little

[10] This comment is only valid for periods in which P was not limiting. For P-limiting periods (Periods 3.6.1 and 3.6.2a), the model stoichiometry was adjusted downwards in line with the fractionation data in attempt to match predicted and observed ortho effluent P concentrations, which were close to zero. The fact that the model over-estimated precipitate for these periods suggests that model calibration could have been still further refined. However, the absolute difference in metal (hydroxy) phosphate ("MeP") between the predicted and observed (fractionation) results was small (approx. 70 mg/ℓ) and would be negligible for design and operational purposes.

can be said of the biological significance of release patterns observed for the PCA versus NaOH fractions. The formation of complexes between ferric ions or ferric hydroxides and poly P or other biological polymers (e.g. polysaccharides or proteins) is certainly possible (Brown and Lester, 1979; He *et al.*, 1996; refer to Chapter 1). It is most likely that such complexation occurs when the chemical precipitates are dissolved and cell structure disrupted in perchloric acid, thereby altering the solubility of poly P in either the PCA or subsequent NaOH step. Whether metal-poly P (with or without other biopolymers) form naturally at or near the cell surface (e.g. in the periplasmic space) and whether such complexes would be biologically active remains a matter for speculation.

It is worth noting that the batch test produced a small (but possibly significant) increase in the sludge ortho P fraction (PCA-extractable) for two samples from the Test unit (R1). These samples were taken from the Test unit at a time when either a high dose was fed to the aerobic zone, or a low dose fed to the anaerobic zone. This observation suggests that if "surplus" ferric hydroxide (or a similar form of iron "available" for phosphate adsorption/ precipitation) is present in the sludge matrix, it may bind phosphate which is released biologically but will not be measured as ortho P released to the supernatant. The batch test used here represents an extreme case of biological release with excess acetate present over an extended period. Nevertheless, dynamic interactions between the biological and chemical mechanisms would be expected to take place continually in the alternating aerobic/anaerobic sequences of a BEPR activated sludge system, and observations in respect of minor changes in the sludge ortho P fraction during the batch test seem to illustrate such interaction. It implies that the two P removal mechanisms do not operate entirely independently. This aspect will be examined further from a modelling point of view in Chapter 7.

In summary, batch tests (Figs. 4.4a and 4.4b) showed that the *net* P release to the supernatant in the presence of excess acetate from the Test unit (R1) was depressed by 7 to 15% relative to the Control. Accepting the apparent uptake of P into the ortho P (chemical) fractions, the *net P change* (or sum of release and uptake) in the respective fractions implied that P release from R1 was depressed by 11 to 26%, compared to the Control. Taking account of the apparent uptake in the PCA ortho P fraction by counting it as part of the total biological P release, the *total* release of P from the sludge was never depressed by more than 7%, relative to the Control. In fact, on at least one occasion (at high ferric dose on 15/8/95), the sludge from the Test unit showed significantly more (ca. 20%) *total* release of P than the Control.

Taken together, the batch test P release data suggest that the biological mechanism was not severely inhibited (or possibly stimulated at times) by ferric chloride dosing. Similarly, P release in the anaerobic zone of the Test pilot plant itself was never depressed by more than 10% (relative to the Control unit) at a 20d sludge age, and by ≤16% at a 10d sludge age (Table 4.5.1). It may therefore be concluded that inhibition of the biological P removal mechanism by simultaneous ferric chloride dosing is limited, which confirms that the system P removal potential will be increased by chemical addition.

...../ Figure 4.3

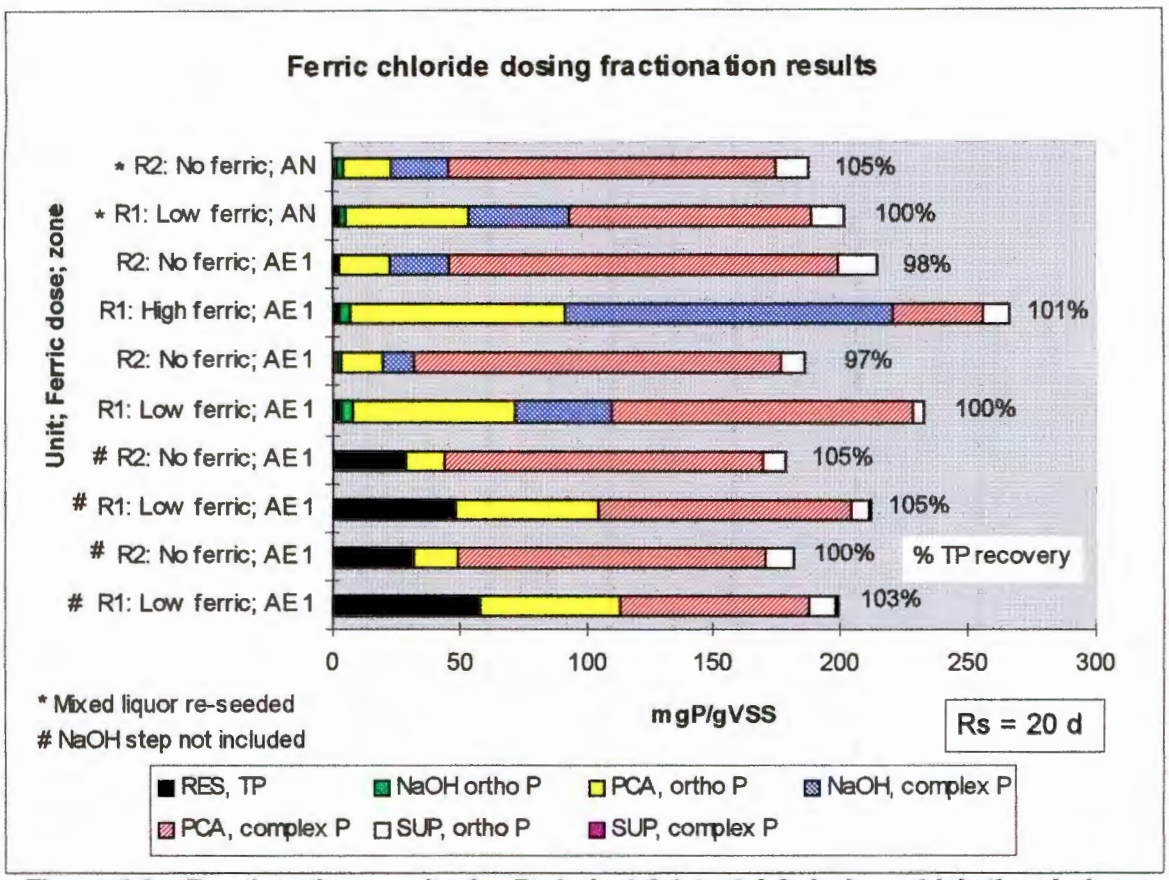


Figure 4.3: Fractionation results for Periods 3.3.1 to 3.3.3 during which the sludge age was 20d and ferric chloride was dosed to R1. Refer to Tables 4.2 and 4.3 for ferric chloride dose data. Percentage figures quoted are for % TP recovery in the fractionation procedure compared to the measured P/VSS content.

Table 4.9a: Fractionation data relating to Figure 4.3 for periods of ferric chloride dosing without P limitation. Percentages are relative contributions to total P of mixed liquor solids (i.e. sum of extracts, including residue (RES) fraction but *excluding supernatant (SUP) fraction).*

Date, Unit	Period	Ferric dose Low = 6.65 High = 13.3 mmol/d	PCA Complex P mgP/gVSS	NaOH Complex P mgP/gVSS *Italics: estimate **	Sum of PCA and NaOH Complex P fractions mgP/gVSS	Sum of PCA and NaOH ortho P fractions mgP/gVSS *Italics: estimate**	VSS during fractionation g/ℓ	Sum of PCA and NaOH Complex P fractions mgP/ℓ *Italics: estimate**	Sum of PCA and NaOH ortho P fractions mgP/ℓ *Italics: estimate**
see Fig. 4.3		see Table 4.3	"Biological"	"Biological"	Total "Biological" (#)	Total "Chemical" (#)		Total "Biological" ##	Total "Chemical"
8/6/95, R1	3.3.1	Low, AE1	74.09	*51.23*	***125.32 (67%)***	***59.62 (32%)***	**2.568**	***321.82 -20%***	***153.10***
8/6/95, R2		-	121.17	*28.46*	*149.63 (88%)*	*19.57 (12%)*	2.674	*400.11 -*	*52.33*
4/7/95, R1	3.3.1	Low, AE1	99.80	*41.56*	***141.36 (69%)***	***60.38 (30%)***	**2.396**	***338.70 -10%***	***144.67***
4/7/95, R2		-	125.37	*25.22*	*150.59 (89%)*	*17.46 (10%)*	2.499	*376.32 -*	*43.63*
18/7/95, R1	3.3.1 **	Low/ High, AE1	118.19	38.39	**156.58 (69%)**	**68.16 (30%)**	**2.184**	**346.34 -8%**	**148.86**
18/7/95, R2		-	144.30	12.05	156.35 (89%)	18.70 (11%)	2.675	418.24 -	50.02
15/8/95, R1	3.3.2	High, AE1	35.19	129.22	**164.41 (64%)**	**88.27 (35%)**	**2.577**	**423.69 -3%**	**227.47**
15/8/95, R2		-	153.59	22.98	176.57 (89%)	20.98 (11%)	2.453	433.13 -	51.46
5/10/95, R1	3.3.3	Low, AN	95.08	40.08	**135.16 (72%)**	**50.92 (27%)**	**2.360**	**318.98 -13%**	**120.17**
5/10/95, R2		-	128.37	23.27	151.74 (87%)	21.17 (12%)	2.429	368.58 -	51.42

* : Estimate (for cases where NaOH extraction had not been introduced) based on projected NaOH ortho P and Residue TP fractions (from cases where NaOH extraction had been used).
**: Transition with Period 3.3.2
#: (%) Percentages in parentheses refer to % sum of "Total Biological" and "Chemical"
##: Percentages, e.g. -5%, refer to percent inhibition of R1 "Total Biological" (mg/ℓ), relative to R2

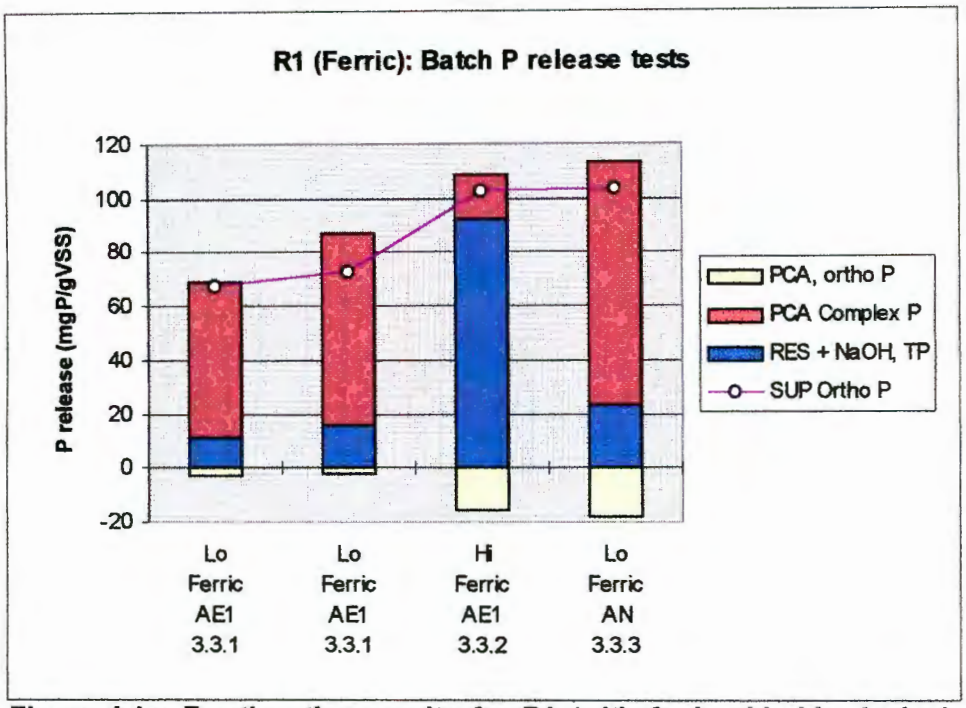


Figure 4.4a: Fractionation results for R1 (with ferric chloride dosing) using P release batch tests in the presence of excess acetate.

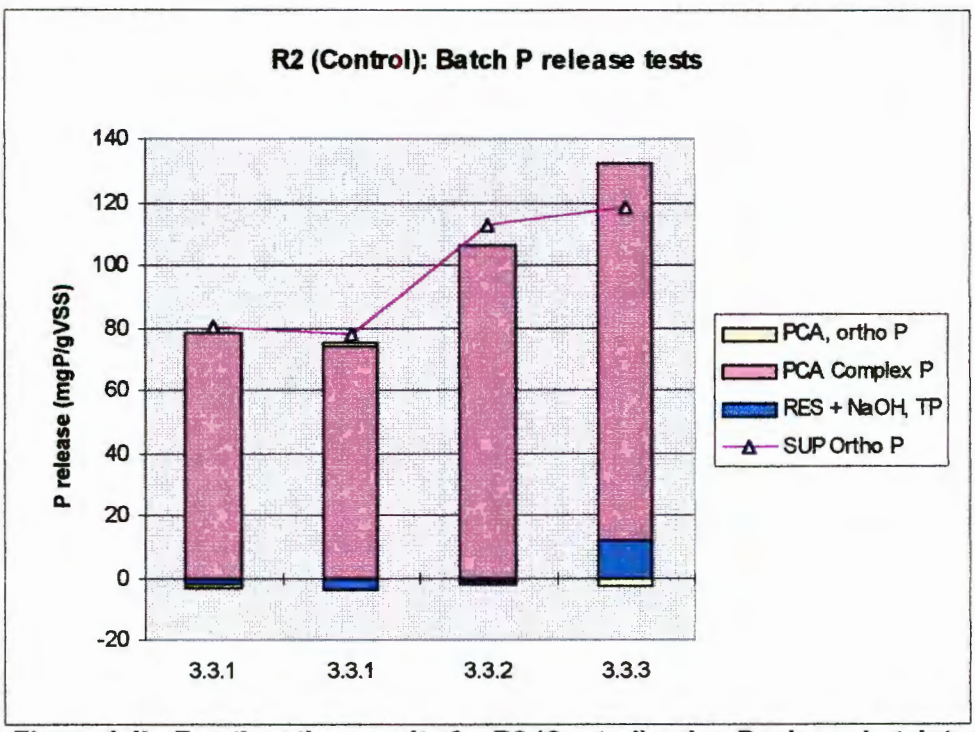


Figure 4.4b: Fractionation results for R2 (Control) using P release batch tests in the presence of excess acetate.

Table 4.9b: P release data from anaerobic batch tests for mixed liquor from the pilot plants during ferric chloride dosing periods without P limitation. Data plotted in Figs. 4.4 (a&b).

TEST UNIT (R1) Period see Fig. 4.4a	mgP/gVSS, R1 released with excess acetate RES + NaOH, TP	mgP/gVSS, R1 released with excess acetate PCA Complex P	mgP/gVSS, R1 release with PCA, ortho P excess acetate	mgP/gVSS, R1 release with SUP Ortho P excess acetate	mgP/gVSS, R1 Net P release FRACTIONS (incl. residue) and less (PCA ortho P change)	mgP/gVSS, R1 Net P release FRACTIONS (incl. residue) and less (PCA ortho P change)
Lo Ferric AE1 3.3.1	11.56	57.46	-3.102	67.87	65.92	72.12
Lo Ferric AE1 3.3.1	15.69	71.64	-2.234	72.58	85.10	89.56
Hi Ferric AE1 3.3.2	92.33	16.11	-15.503	102.79	92.94	123.94
Lo Ferric AN 3.3.3	23.55	89.88	-17.797	103.85	95.63	131.23
CONTROL (R2) Period see Fig, 4.4b	**mgP/gVSS, R2 released with excess acetate RES + NaOH, TP**	**mgP/gVSS, R2 released with excess acetate PCA Complex P**	**mgP/gVSS, R2 release with excess acetate PCA, ortho P**	**mgP/gVSS, R2 release with excess acetate SUP Ortho P**	**mgP/gVSS, R2 Net P release FRACTIONS (incl. residue) and less (PCA ortho P change)**	**mgP/gVSS, R2 Net P release FRACTIONS (incl. Residue) and less (PCA ortho P change)**
3.3.1, Control	-2.24	78.29	-1.116	80.03	74.93	77.17
3.3.1, Control	-4.36	74.23	0.712	77.97	70.58	69.16
3.3.2, Control	-1.69	106.59	-0.695	112.72	104.21	105.60
3.3.3, Control	11.88	120.58	-3.067	118.34	129.39	135.53

Table 4.10a: **Estimation of molar ratio of additional P removed as chemical precipitate (PCA and NaOH extract ortho P fractions) versus iron dosed during ferric chloride dosing periods without P limitation.**
Sludge age = 20d for experimental periods in this table.

UNIT/ FERRIC	DATE	PCA + NaOH ortho P fractions * mgP/gVSS	Ave. VSS for Period g/L	VSS wasted g/d	PCA + NaOH ortho P wasted mgP/d	Difference (R1-R2) PCA +NaOH ortho P wasted mgP/d	Fe dosed mmol/d	mol P /mol Fe	mol P /mol Fe from Table 4.6
R1: Low Fe: 3.3.1	8/6/95	*59.26*	2.238	3.5818	212.19	137.12	6.65	0.67	1.02
R2: 3.3.1	8/6/95	*19.54*	2.401	3.8426	75.06				
R1: Low Fe, AE 1: 3.3.1	4/7/95	*60.30*	2.238	3.5818	215.93	148.93	6.65	0.72	1.02
R2: 3.3.1	4/7/95	*17.44*	2.401	3.842	67.00				
R1: High Fe, AE1: 3.3.2	15/8/95	88.27	2.357	3.771	332.88	248.66	13.3	0.60	1.03
R2: 3.3.2	15/8/95	20.98	2.509	4.014	84.22				
R1: Low Fe, AN: 3.3.3	5/10/95	50.92	2.437	3.899	198.55	116.44	6.65	0.57	0.82
R2: 3.3.3	5/10/95	21.17	2.424	3.878	82.11				
R1: Low Fe, AE 1: 3.6.1	8/9/97	25.79	1.291	4.1312	106.54	66.20	6.65	0.32	-0.03
R2: 3.6.1	8/9/97	10.35	1.218	3.8976	40.34				
R1: Low Fe, AE 1: 3.6.1	29/9/97	31.62	1.291	4.1312	130.63	90.60	6.65	0.44	-0.03
R2: 3.6.1	29/9/97	10.27	1.218	3.8976	40.03				
R1: Low Fe, AE 1: 3.6.2a	31/10/97	30.32	1.223	3.9136	118.66	81.43	6.65	0.40	0.04
R2: 3.6.2a	31/10/97	9.81	1.186	3.7952	37.23				
R1: Low Fe, AE 1: 3.6.2a	4/12/97	33.14	1.223	3.9136	129.70	94.29	6.65	0.46	0.04
R2: 3.6.2a	4/12/97	9.33	1.186	3.7952	35.41				

** Italics = estimate of NaOH ortho P where this step was not carried out*

Table 4.10b: **Comparison of chemical precipitate predictions from fractionation data for PCA & NaOH ortho P extracts and IAWQ model (Chapter 7).**

Period/ Frac. Date	PCA + NaOH ortho P: R1 mgP /gVSS	Period Ave. VSS: R1 g/ℓ	PCA + NaOH ortho P: R2 mgP /gVSS	Period Ave. VSS: R2 g/ℓ	PCA + NaOH ortho P R1 - R2 mgP/ℓ	PCA + NaOH ortho P R1 - R2 mg/ℓ MeP *	Frac. Stoich. P:Fe mol P/ mol Fe	IAWQ Model P:Fe mol P/ mol Fe	IAWQ Model "MeP" mg/ℓ as MeP	(PCA + NaOH) /Model (%)
3.3.1b 4/7/95	*60.30*	2.238	*17.44*	2.401	93.1	581	0.72	1.0	601	96%
3.3.2 15/8/95	88.27	2.357	20.98	2.509	155.4	1114	0.60	1.0	1191	93%
3.3.3 5/10/95	50.92	2.437	21.17	2.424	72.78	544	0.57	1.0	603	90%
3.6.1 Ave.	28.71	1.291	10.31	1.218	24.50	257	0.38	0.4	186	138%
3.6.2 Ave.	31.73	1.223	9.57	1.186	27.46	256	0.43	0.4	183	140%

* Taking stoichiometry from fractionation data (Table 4.10a) and assuming MeP precipitate formula is: $Me_r PO_4(OH)_{3r-3}$
** Italics = estimate of NaOH ortho P where this step was not carried out*

4.3.8 Nitrification/ denitrification

Ferric chloride did not appear to inhibit nitrification-denitrification to a significant degree since the effluent ammonia and nitrate results of the Test and Control units were very comparable (Table 4.4). There was a slight tendency (<1 mgN/ℓ) for effluent ammonia concentrations to be higher in the Test unit (R1) than the Control unit (R2) under P-limiting conditions (Table 4.12). Since phosphate contributes to the total alkalinity of the system, the lower influent P concentrations may have indirectly exposed the nitrifiers to slight inhibition as a result of localised pH effects in the first aerobic zone (point of addition of the acidic ferric chloride solution).

4.3.9 Sludge production

In terms of VSS production, the Test (R1) and Control (R2) units were comparable for most experimental periods (Refer to Tables 4.3 and Table 4.4: Periods 3.3.1 to 3.3.2, spanned 96 days; followed by a change of enhanced culture; followed by Periods 3.3.3 to 3.3.6). Period 3.3.6 (20 mg/ℓ Fe dosed to aerobic zone) showed 14% more VSS in R1 than R2 (Table 4.4). Under conditions of P-limitation, Periods 3.6.1 and 3.6.2a (10 mg/ℓ Fe to aerobic zone) showed smaller VSS differences, in the range 3 to 7% more VSS in R1 than R2 (Table 4.12). Since the period of ferric chloride dosing from the time of the change of enhanced culture in R1 to the start of Period 3.3.6 was 71 days, and since a three week period of semi-enhanced culture re-development in the presence of ferric chloride dosing had led up to Periods 3.6.1 and 3.6.2 (Table 4.3), it is possible that slow changes in the behaviour of the chemical or biological mechanisms led to the observed increase in VSS for R1 relative to R2. It is not possible to say exactly what these changes were, but an accumulation of chemical precipitate with coagulant properties toward organic material seems to be suggested by the data. One possibility is that the iron (hydroxide) precipitate has properties which adsorb/ enmesh colloidal organic material in a manner which tends to make it unbiodegradable and thus contributing directly to the VSS of the system. The effect would be analogous to an increase in the influent unbiodegradable particulate COD fraction. However, differences in VSS will also arise from the relative abundance of poly P accumulating organisms in the systems. It is well known that BEPR gives increased VSS production, due to the lower death rate of these organisms (Wentzel *et al.*, 1989). Hence, potentially, as a result of partial inhibition of the BEPR mechanism in the presence of iron dosing, VSS production in the Test unit may have been *reduced*, relative to the Control. The fact that the smaller VSS differences between the units was observed under P-limiting conditions (Periods 3.6.1 and 3.6.2a) are relevant in this regard.

In terms of TSS (i.e. MLSS) the Test unit showed a significantly increase (9 to 33%) in sludge production, particularly at the shorter sludge age of 10d (refer to Table 4.4). These results must be viewed in the context of additional P removal as a result of chemical precipitation, with the chemical precipitate contributing to the inorganic suspended solids (ISS).

From the data in Tables 4.4 and 4.11, the inorganic suspended solids (ISS) may be calculated:

$$ISS = TSS - VSS$$

Furthermore, the difference in ISS (ΔISS) between the two units can be calculated. It is possible to compare the observed ΔISS with estimates of precipitate formation based on the additional P removal in R1 ($\Delta Pt_{rem} = Pt_{rem,R1} - Pt_{rem,R2}$). In order to do this, the stoichiometry of the precipitate must either be assumed or estimated. As discussed under section 4.3.6 above, for periods without P-limitation, stoichiometry estimates from fractionation results (Table 4.10a) had failed to account fully for that calculated from the additional system P removal in the presence of iron dosing (Table 4.6). For these periods, the stoichiometry from Table 4.6 was accepted (i.e. it was assumed that inhibition of the biological removal mechanism was negligible; from fractionation results this was not strictly true[11]). In the case of periods with P-limitation (Periods 3.6.1 and 3.6.2a), the P:Fe

[11] Table 4.9a shows that this is not strictly true. However, as a result of a partial inhibition of bio-P removal, possible over-estimates of ISS production due an apparently higher Fe:P (lower P:Fe) stoichiometry (i.e. estimated from $\Delta Pt_{removed}$ data), will to some extent be compensated for by a loss of ISS from reduced biological accumulation.

precipitate stoichiometry calculated by difference in system P removal (Table 4.6) was very low (i.e. the Test and Control systems both removed phosphate virtually completely and inhibition of the bio-P mechanism was much greater - see section 4.3.11). Hence, the estimates of fractionation results for estimated stoichiometry and P removal due precipitate were accepted for Periods 3.6.1 and 3.6.2a.

From a review of the literature (see Chapter 7, section 7.1), the ideal precipitation of phosphate with ferric ions would be stoichiometric in the form of $FePO_4$ (1 mol Fe/ mol P). If the observed precipitation is not stoichiometric (i.e. > 1 mol Fe_{dosed}/ mol $P_{removed}$) then it may be reasonably assumed that some mixture of iron phosphate and iron hydroxide precipitation is probably taking place. A convenient chemical formula for the hypothetical precipitate iron hydroxy-phosphate may be written as:

$$Fe_r\ PO_4\ OH_{(3r-3)}$$

where r = stoichiometry of Fe:P (mol Fe/ mol P).

It should be noted that upon ashing (during VSS determination, at 550 °C), iron hydroxide will most likely be converted to iron oxide in the same manner as assumed for aluminium precipitates by Power et al. (1992). On a similar basis to the typical conversion of $Fe(OH)_3$ to Fe_2O_3, the above-mentioned hypothetical formula for iron hydroxy-phosphate converts to the following formula for hypothetical "iron phosphate oxide":

$$Fe_r\ PO_4\ O_{(1.5r-1.5)}$$

where r = stoichiometry of Fe:P (mol Fe/ mol P).

Using the approach described above, and the hypothetical formulae for precipitate before and after ashing, the data in Table 4.11 were calculated.

From Table 4.11 it can be seen that the estimates of ΔISS from precipitation stoichiometry show a degree of similarity to the observed ΔISS. For four of the eight experimental periods examined, the recovery of estimated and observed ΔISS was in the range 76 to 127%. For the remaining four experimental periods, the observed ΔISS values were smaller than the estimated values. This probably indicates that the experimental systems were not operating suitably close to steady-state during these periods. Unlike the biological P removal processes, the TSS and VSS (and hence ISS) in the systems can be expected to take several sludge ages to reach steady-state. The first experimental period with ferric chloride dosing (Period 3.3.1) lasted for 62 days (three sludges ages), which should have allowed steady state ISS concentrations to be approached in the next period. However, the ferric dose was increased at the beginning of Period 3.3.2, which would have required further time for equilibration. Furthermore, from section 4.3.10 below, it will be seen that settling problems (pin floc sludge formation) began to emerge in Period 3.3.2, and became so problematic during that period that the mixed liquor from the Test unit (R1) had to be discarded (Table 4.3). Although an effort was made to prevent large-scale carryover of solids from the clarifier of unit R1 at these times, a "creeping" loss of very fine solids from this unit could not be prevented, particularly during Periods 3.3.2. This probably contributed to the lower-than-expected ISS slightly lower during that period. During Period 3.3.3, a process of re-equilibration of the ISS would be commenced since half of the mixed liquor from the Control unit (R2) was transferred to the Test unit (R1) and ferric dosing re-commenced within a week. Again, this would explain the relatively low ISS observed for the ensuing Period (3.3.3) which lasted for slightly longer than one sludge age. Similarly, in terms of ISS, Period 3.3.5 was probably not at steady state due to the increased ferric chloride dose at the start of this period.

In summary the data in Table 4.11 suggest that the increase in ISS due to chemical dosing may be estimated with a degree of certainty using the above-mentioned hypothetical chemical formulae and either the observed stoichiometry of iron dosed : additional P removal. In Chapter 7 (sections 7.2.2.2 and 7.2.4.2), the observed ISS data will be re-examined in the light of IAWQ ASM Model No. 2 predictions of metal phosphate and metal hydroxide precipitate formation.

Table 4.11: Comparison of observed ISS and that predicted from chemical P removal for ferric chloride dosing periods.

For all experimental periods, 3.3.1 to 3.3.3 : sludge age (R_s) = 20 d. For other experimental periods : sludge age (R_s) = 10 d.

ISS = TSS - VSS (see Tables 4.4 & 4.12 for TSS and VSS data)

Fe~P~OH : hypothetical metal hydroxy-phosphate, $Fe_r PO_4 OH_{(3r-3)}$

Fe~P~O : hypothetical metal phosphate oxide, $Fe_r PO_4 O_{(1.5r-1.5)}$

Period (Duration) Ferric chloride dose	ISS Tables 4.4 & 4.12	ISS Tables 4.4 & 4.12	**Δ ISS**	ΔM Pt_{rem} Table 4.6	Stoichiometry Observed Table 4.6	*Stoichiometry Observed*	Estimate from *Stoichiometry Observed*	**Estimated ΔISS from *Stoichiometry Observed***	Estimate/ Observed
	mg/ℓ	mg/ℓ	**mg/ℓ**	mg P/d	mol P_{rem}: mol Fe $_{dosed}$	mol Fe $_{dosed}$: mol P_{rem}	*Fe~P~OH*	***Fe~P~O***	***Fe~P~O/*** Δ ISS
Unit:	R1	R2	**R1-R2**	R1-R2	P:Fe	*Fe:P*	mg/ℓ	mg/ℓ	%
3.3.1 (62 d) 10 mg/ℓ Fe, AE1	2021	1720	301	147.3	0.72	*1.39*	572	**541**	180%
3.3.1(b) (31 d) 10 mg/ℓ Fe, AE1	2182	1806	376	210.7	1.02	*0.98*	632	**634**	169%
3.3.2 (34 d) 20 mg/ℓ Fe, AE1	2857	2086	771	422.7	1.03	*0.97*	1260	**1266**	164%
3.3.3 (27 d) 10 mg/ℓ Fe, AN	2110	1731	379	168.3	0.82	*1.22*	592	**572**	151%
3.3.4 (18 d) 10 mg/ℓ Fe, AN	1860	1575	285	76.6	0.37	*2.70*	257	**221**	78%
3.3.5 (21 d) 20 mg/ℓ Fe, AN	1694	1298	396	344.6	0.80	*1.25*	617	**594**	150%
3.3.6 (20 d) 20 mg/ℓ Fe, AE1	1695	1097	598	199.9	0.52	*1.92*	503	**453**	76%
3.6.1 (44 d) 10 mg/ℓ Fe, AE1	642	444	198	78.5*	0.38*	*2.63**	257	**223**	112%
3.6.2a (64 d) 10 mg/ℓ Fe, AE1	626	452	174	81.0*	0.40*	*2.50**	254	**221**	127%

AN = Anaerobic zone; AE1 = First aerobic zone

* Stoichiometry from fractionation data in the case of Periods 3.6.1 and 3.6.2a.

4.3.10 Sludge settleability

One area in which ferric chloride dosing appeared to have a negative influence on the operation of the pilot plant was sludge settleability. The DSVI data (Table 4.4) suggests that the settling in the Test unit dosed with ferric chloride (R1) was generally somewhat better than in the Control reactor (R2). However, this was not the observed behaviour. Floc size in R1 decreased markedly in the presence of ferric chloride dosing during Periods 3.3.1 through 3.3.6, resulting in a slower unstirred zone settling velocity (UZSV), despite a good settled volume result after 30 min. Effluent turbidity was also significantly greater for R1, compared to R2.

The observed effect on UZSV is borne out in Figure 4.5 which shows that the UZSV for R1 was significantly less than that for R2 during Periods 3.3.5 and 3.3.6. A lower DSVI result is usually expected to produce a lower UZSV (Ozinsky and Ekama, 1995). In fact, the settling in R1 was so problematic at a 20d sludge age (during which the steady state TSS in that unit reached 5214 mg/ℓ) that the clarifier was frequently overloaded with solids. For this reason the sludge age was reduced to 10d, which quickly solved the clarification problems, but the differences in UZSV (Fig. 4.5) as well as effluent turbidity nevertheless persisted.

The reasons for partial deflocculation in the presence of ferric chloride dosing were not determined. It is possible that the acidity of the chemical exerted at the point of dosing (or, alternatively its alkalinity demand in the precipitation of ferric hydroxide) exerts localised effects which are disruptive to activated sludge flocs. Poor flocculation would lead to turbidity in the form of large numbers of free bacteria (or very small flocs) in the effluent. Wuhrmann (1968, cited by Jenkins *et al.*, 1971) identified effluent turbidity as a problem with the addition of ferric chloride (30 mg Fe/ℓ) to a conventional activated sludge system but was unable to identify whether the cause was poorly flocculated ferric hydroxy-phosphate particles, or dispersed activated sludge particles due to the absence of protozoa. Rabinowitz and Marais (1980) found that effluent turbidity from anaerobic-aerobic modified activated sludge systems dosed simultaneously with ferric chloride increased when the process pH decreased below 7.2. Table 4.7 shows that the pH in the aerobic zones of *both* the Test and Control units was generally in the range 7.2 to 7.7 during Periods 3.3.1 to 3.3.6 when the turbid effluent from R1 was mainly noticed; on the other hand, the pH in the anaerobic zones of both units was usually 6.9 to 7.0, but it seems unlikely that this alone could account for the settling problems encountered. From the results of this study, it appears that the simultaneous chemical precipitation mechanism for ferric chloride may interfere negatively with the biological flocculation of activated sludge. These observations were made during experimental periods when the phosphate was added to the influent of both units (i.e. non-P-limiting conditions). Settling and turbidity problems were *not* encountered to the same degree under P-limiting conditions during Periods 3.6.1 and 3.6.2a. Settling behaviour in response to metal salt dosing was not studied in detail as part of this project, but the variable response to ferric chloride and influent composition suggests that population dynamics strongly affects settling characteristics. For example, it is possible that ferric hydroxide accumulation in the mixed liquor solids interferes with both biological floc integrity and the BEPR mechanism. In this respect, it is probably significant that iron removal (or iron hydroxide formation) in activated sludge appears to be linked to complexes formed with extracellular material such as polysaccharides which are also known to be important in biological flocculation (Brown and Lester, 1979; He *et al.* 1996).

On 4 Dec. 1995, experiments with ferrous-ferric blend dosing to R1 commenced. The DSVI of R1 improved still further and the UZSV in R1 increased. Further comparisons of UZSV were called off since the differences between R1 and R2 disappeared. At the same time, the settling velocity in R2 increased and this appeared to correlate with the onset of heavy summer rains in the catchment (data not shown). Rain produces large ingress of surface run-off and groundwater to the Pietermaritzburg sewer system, probably carrying with it clay materials which have been observed to improve the settling in the full-scale activated sludge system too (see Chapter 6).

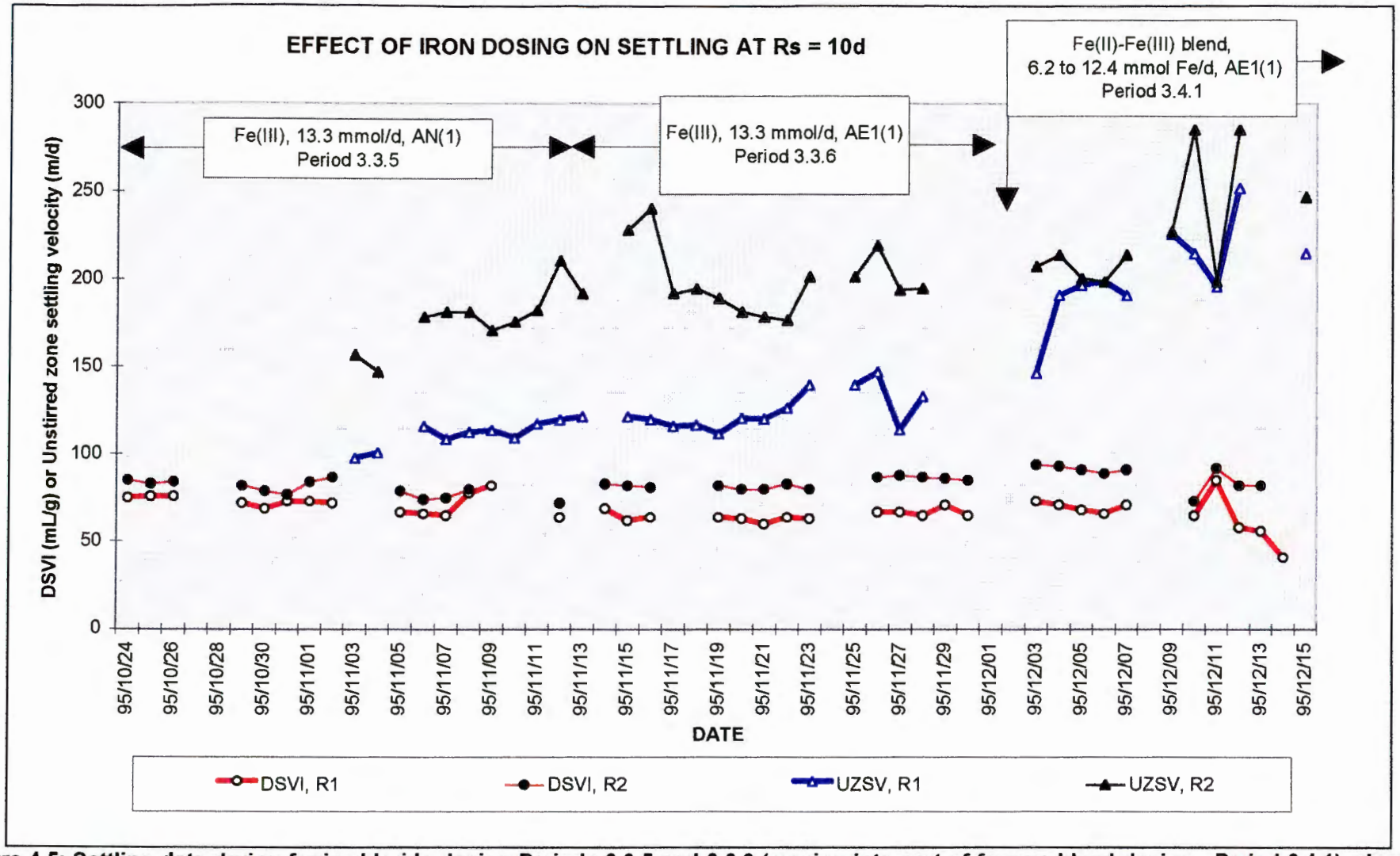


Figure 4.5: Settling data during ferric chloride dosing Periods 3.3.5 and 3.3.6 (moving into part of ferrous blend dosing - Period 3.4.1), showing effect of ferric chloride in depressing unstirred zone settling velocity (UZSV) of mixed liquor in R1, compared to R2. This effect was reversed when the ferrous chloride blend was dosed in place of ferric chloride. Taken with the effect on DSVI and visual observation of clarifier behaviour, "pin floc" sludge formation appeared to be the cause of settling problems experienced with ferric chloride - see text.

4.3.11 Ferric chloride dosing under conditions of P limitation

The results described in sections 4.3.6 and 4.3.7 above referred to experimental periods in which there was no limitation on the influent P in the units. Effluent P concentrations ranged 15 to 30 mgP/ℓ during these periods. It was hypothesised that the biological P removal mechanism may function less well in the presence of a strong chemical removal mechanism under conditions where the effluent P concentration is low and potentially limiting. Under such conditions the two mechanisms may come into "competition" for available phosphate. Moreover, such conditions would be more representative of real full-scale operating conditions where attainment of low effluent P concentrations would be the objective. Accordingly, experimental periods 3.6.1 and 3.6.2a were set up in which a moderate amount of sodium acetate (100 mg/ℓ as COD) was added to the influent along with excess magnesium ions, but no phosphate (or potassium) was added (see Table 4.1 for influent composition, and Table 4.3 for details of date ranges and ferric dose). Furthermore, in order to make conditions in the pilot plants as representative as possible of the full-scale plant, the influent was not supplemented with sodium bicarbonate during Periods 3.6.2a & b. As will be seen, this had the desired result of producing an effluent bicarbonate alkalinity very similar to that usually observed at full-scale. Finally, during Period 3.6.2b, phosphate (20 mgP/ℓ) was again added to the influent in order to observe the response of the Test unit (R1), relative to the Control (R2). It was hypothesised that if the bio-P removal mechanism was at a competitive disadvantage coming out of a sustained period of low (limiting) effluent P concentration, then the system P removal potential in the Test unit (as measured with surplus effluent P) would be temporarily weaker in the Test unit, compared to Control unit, and particularly in relation to preceding experimental periods when effluent P had never been limiting.

4.3.11.1 With influent bicarbonate supplement (Period 3.6.1)

The pilot plant units were re-started on 29/797 using 10ℓ of seed sludge in each from the full-scale activated plant. The full-scale plant was being dosed with alum at the time. In the pilot plant Test unit (R1), ferric chloride dosing commenced immediately at 6.65 mmol Fe/d (refer to Table 4.2), while R2 served as Control (no ferric dose). An equilibration period of almost three weeks (two sludge ages) was allowed before experimental data collection for Period 3.6.1 was commenced.

Figure 4.7 shows the changes in MLSS and VSS over the six week period 21/8/97 to 4/10/97 (Period 3.6.1). From Fig. 4.7 it can be seen that the MLSS was always higher in R1 than R2. However, as will be seen from Fig. 4.6 below, little additional P removal occurred in R1 (with ferric chloride addition) since R2 (Control) achieved very similar effluent P concentrations with only biological removal. Under these conditions, it would be expected that a significant portion of the iron dosed would be precipitated in the mixed liquor solids as ferric hydroxide. Nevertheless, MLSS and VSS profiles were fairly stable during Period 3.6.1 (Fig. 4.7). What variation was observed appeared to be generally related to changes in influent COD (Fig. 4.8). Figure 4.8 shows that wide variation in the influent COD occurred over the six week period under consideration. This reflects the variability of Darvill settled sewage, with the first summer rains occurring in early September 1997, and attendant ingress of rainwater to the sewer system. However, later during September and early October, dry hot weather occurred and some relatively "strong" batches of settled sewage were obtained.

Average results for Period 3.6.1 are given in Tables 4.12a and 4.12b. The overall N, COD and P mass balance results were in the range 86 to 102% (Table 4.13). Comparing the P release from mass balance considerations for the anaerobic reactors (see Equation 4.1 in section 4.3.2.2), it was found that, on average, P release in the anaerobic reactor of the Test was 57% of that in the Control unit (i.e. inhibited by 43% in R1, compared to R2). Although the iron dose was relatively low (10 mg/ℓ as Fe, based on influent) during Period 3.6.1, this degree of inhibition represents about double the maximum degree of inhibition found for ferric chloride at higher effluent P concentrations and at double the iron dose (Period 3.3.6 - see section 4.3.2.2).

Fig. 4.6 shows that low effluent P concentrations were achieved during Period 3.6.1. From Tables 4.12a and 4.12b it can be seen that both units R1 and R2 achieved average effluent ortho P = 0.2

(±0.2) mgP/ℓ and effluent total P = 0.4 (±0.4) mgP/ℓ)[12], whereas in previous ferric chloride dosing periods (Table 4.4), the effluent P concentrations were much higher (>10 mgP/ℓ as total P for R1). It follows that ferric chloride dosing to the Test unit (R1) during Period 3.6.1 would most likely have created conditions in which biological P removal mechanism would "compete" for available phosphate with the chemical P precipitation mechanism. Such P limitation (i.e. competition for available phosphate between the two mechanisms) could be interpreted as a potential cause of "inhibition" of the bio-P mechanism. This aspect is discussed further below, in the light of fractionation results for Periods 3.6.1 and 3.6.2a.

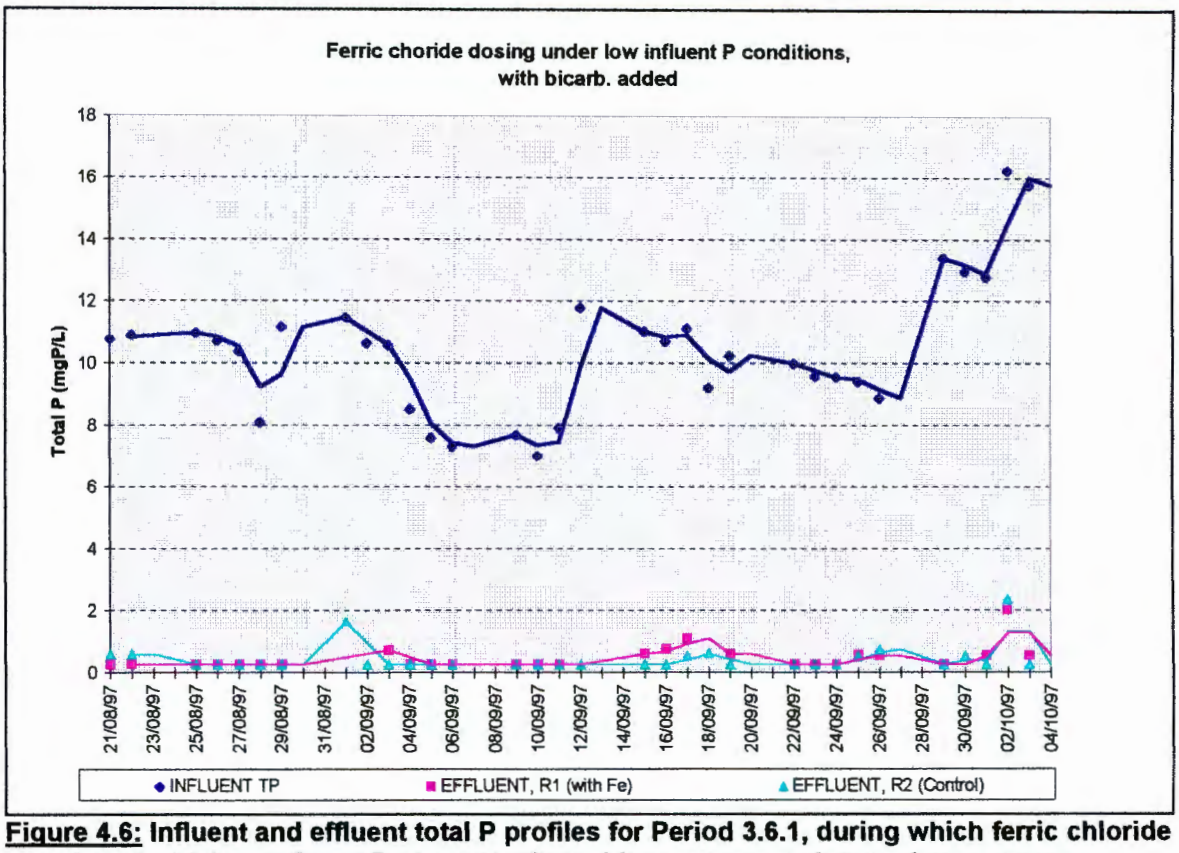


Figure 4.6: Influent and effluent total P profiles for Period 3.6.1, during which ferric chloride was dosed with low influent P concentrations. Lines are two-point moving averages.

...../ Figs. 4.7 and 4.8

[12] The detection limits of the automated molybdate-ascorbic acid methods used here were 0.1 mgP/l as ortho P and 0.5 mgP/l as total P. *Results below detection limit were reported as half the detection limit. This will have produced a low bias in the total P results.* Refer to Appendix 5. Only two of the thirty ortho P results (n=28) for R1 in this period were below detection limit, whereas sixteen of the total P results (n=27) for R1 were below detection limit. For R2, twenty of the TP results (n=32) were below detection limit, while for ortho P, eight of the results (n=32) were below detection limit.

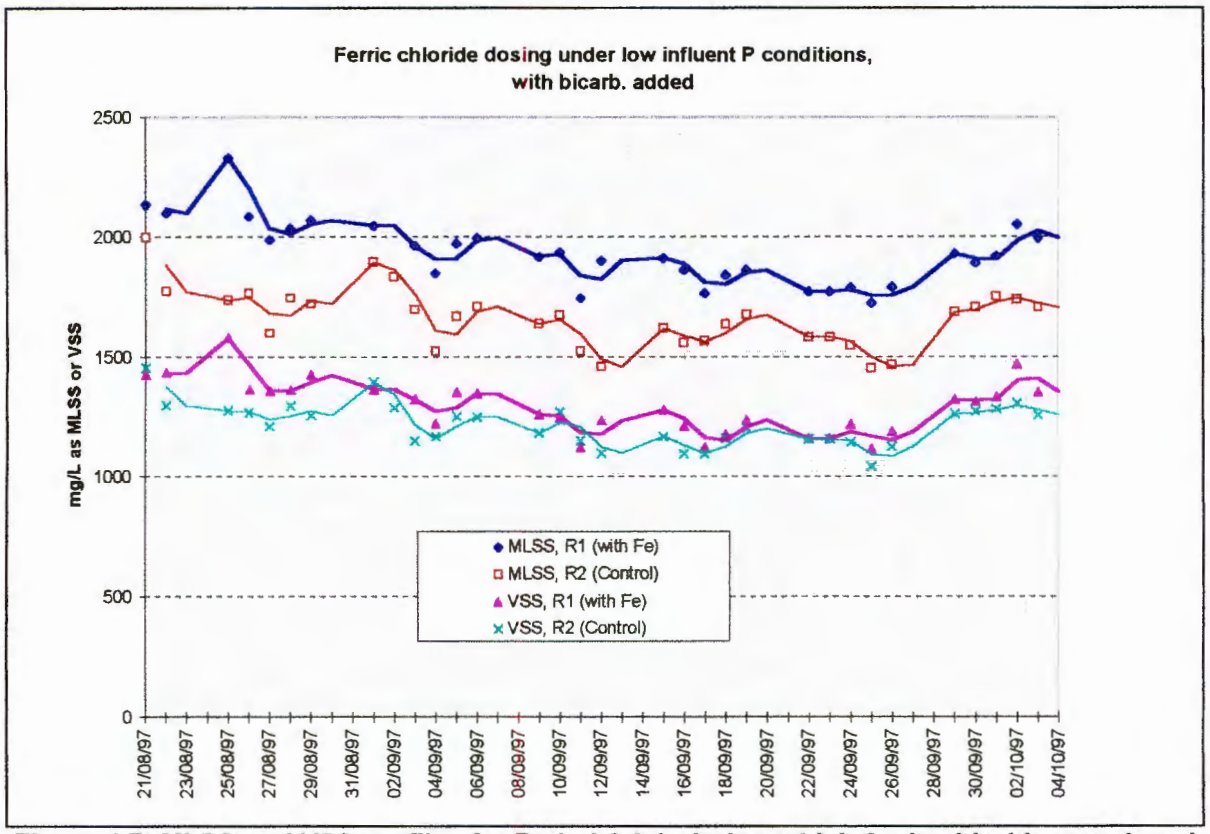


Figure 4.7: MLSS and VSS profiles for Period 3.6.1, during which ferric chloride was dosed with low influent P concentrations. Lines are two-point moving averages.

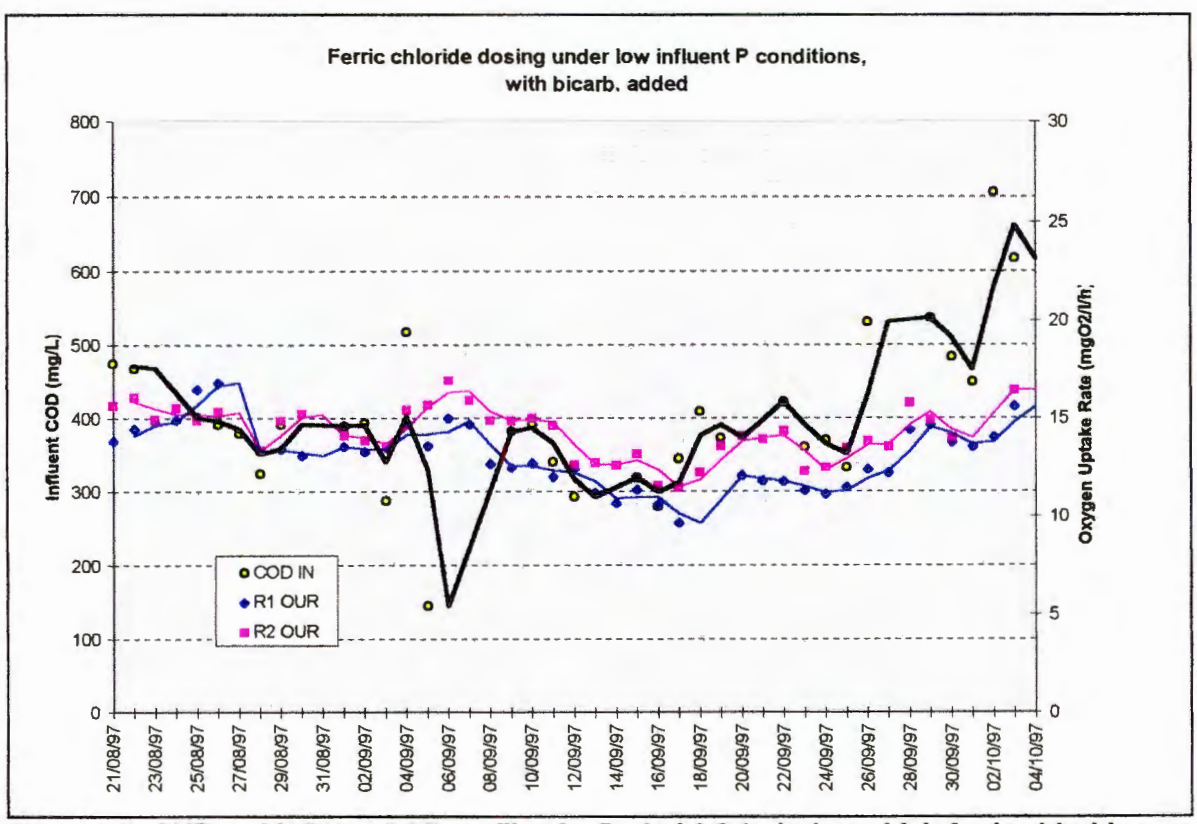


Figure 4.8: OUR and influent COD profiles for Period 3.6.1, during which ferric chloride was dosed with low influent P concentrations. Lines are two-point moving averages.

Table 4.12a: Measured pilot plant results for ferric chloride dosing periods 3.6.1 to 3.6.2 (a & b).
Results are averages with sample standard deviations in parentheses. N.D. = Not determined. See Appendix 8 for definition of symbols.
The double horizontal line between experimental periods indicates a change in influent alkalinity or phosphorus for the units (see Table 4.1).

Period Unit	Sti mgO/ℓ	Ste mgO/ℓ	Nti mgN/ℓ	Nte mgN/ℓ	Nae mgN/ℓ	No3e mgN/ℓ	Pti mgP/ℓ	Pte mgP/ℓ	Pt_{rem} mgP/ℓ	P/VSS mgP /gVSS	TSS mg/ℓ	VSS mg/ℓ	% VSS	DSVI ml/g	*f*Pt,a mgP/ℓ	*f*Pt,d mgP/ℓ	*f*Pt,b1 mgP/ℓ	*f*Pt,b2 mgP/ℓ
3.6.1 R1	403 (105)	52 (23)	31.1 (6.2)	2.4 (1.0)	1.04 (0.80)	7.08 (2.61)	10.45 (2.15)	0.45 (0.37)	9.85 (2.05)	80.10 (5.24)	1933 (133)	1291 (110)	66.8 (1.8)	64 (7)	25.38 (5.13)	7.99 (2.18)	1.27 (0.62)	0.41 (0.27)
3.6.1 R2	403 (105)	58 (20)	31.1 (6.2)	2.2 (0.6)	0.50 (0.50)	6.24 (2.60)	10.45 (2.15)	0.43 (0.43)	10.01 (2.00)	91.14 (5.68)	1291 (110)	1218 (89)	73.3 (2.0)	104 (26)	40.12 (7.35)	15.50 (3.54)	2.97 (2.09)	0.37 (0.23)
3.6.2a R1	427 (82)	44 (22)	31.8 (4.6)	2.1 (0.3)	1.13 (0.84)	5.33 (1.39)	10.46 (3.02)	0.53 (0.45)	9.93 (2.92)	89.65 (11.53)	1849 (220)	1223 (160)	66.0 (1.7)	72 (10)	25.73 (6.32)	8.44 (2.72)	1.51 (0.79)	0.41 (0.26)
3.6.2a R2	427 (82)	41 (11)	31.8 (4.6)	2.1 (0.3)	0.59 (0.52)	4.74 (1.42)	10.46 (3.02)	0.62 (0.94)	9.84 (3.25)	96.91 (9.61)	1638 (192)	1186 (121)	72.6 (2.4)	130 (10)	40.52 (8.19)	14.76 (3.04)	2.71 (1.99)	0.63 (0.77)
3.6.2b R1	324 (52)	31 (12)	25.92 (3.47)	2.0 (-)	0.66 (0.52)	4.00 (0.66)	25.85 (6.82)	10.42 (5.01)	15.43 (5.97)	123.98 (24.16)	1633 (73)	1031 (34)	63.1 (2.4)	79 (2)	38.27 (13.76)	18.52 (7.53)	13.17 (6.24)	9.35 (4.60)
3.6.2b R2	324 (52)	34 (15)	25.92 (3.47)	2.0 (-)	0.46 (0.43)	4.29 (0.70)	25.85 (6.82)	11.15 (6.16)	14.70 (7.07)	130.89 (23.24)	1328 (58)	961 (25)	72.5 (2.4)	118 (4)	53.36 (5.88)	23.40 (8.19)	15.05 (6.97)	9.42 (5.25)

f = filtered; a = anaerobic; d = anoxic; b1 = 1st aerobic; b2 = 2nd aerobic reactors of 3-stage Phoredox system (see Fig. 3.1, Chapter 3).

Table 4.12b: Additional pilot plant results measured for ferric chloride dosing periods 3.6.1 to 3.6.2 (a & b).
Results are averages with sample standard deviations in parentheses. N.D. = Not determined. See Appendix 8 for definition of symbols.
The double horizontal line between experimental periods indicates a change in influent alkalinity or phosphorus for the units (see Table 4.1).

Period Unit	Sbsi+Susi mgO/ℓ Mamais	Sbsi mgO/ℓ Mamais	Nai mgN/ℓ	PO_4i mgP/ℓ	*f*PO_4, a mgP/ℓ	*f*PO_4, d mgP/ℓ	*f*PO_4, b1 mgP/ℓ	*f*PO_4, b2 mgP/ℓ	PO_4e mgP/ℓ
3.6.1 R1	230 (88)	172 (-)	21.16 (3.80)	7.56 (1.49)	22.50 (4.37)	7.04 (1.80)	1.01 (0.50)	0.31 (0.25)	0.24 (0.15)
3.6.1 R2	230 (88)	172 (-)	21.16 (3.80)	7.56 (1.49)	37.26 (7.30)	14.31 (3.22)	2.27 (1.04)	0.34 (0.24)	0.21 (0.25)
3.6.2a R1	219 (55)	178 (-)	20.15 (3.14)	7.84 (2.54)	23.19 (5.65)	7.53 (2.43)	1.29 (0.67)	0.32 (0.24)	0.35 (0.34)
3.6.2a R2	219 (55)	178 (-)	20.15 (3.14)	7.84 (2.54)	39.11 (6.82)	13.35 (2.86)	2.44 (1.95)	0.52 (0.75)	0.44 (0.85)
3.6.2b R1	174 (40)	140 (-)	17.22 (1.18)	22.52 (6.48)	33.90 (10.66)	17.11 (6.82)	11.64 (5.28)	8.33 (3.85)	8.79 (3.86)
3.6.2b R2	174 (40)	140 (-)	17.22 (1.18)	22.52 (6.48)	45.73 (11.96)	21.89 (7.18)	13.22 (5.93)	8.94 (4.71)	9.23 (4.93)

Table 4.13: Mass balances for ferric chloride dosing periods 3.6.1 and 3.6.2 (a & b).
Results are averages with sample standard deviations in parentheses. See Appendix 8 for definition of symbols.
The double horizontal line between experimental periods indicates a change in influent alkalinity for the urits (see Table 4.1).

Period Unit	Flow Q, ℓ/d	VSS mg/ℓ	No3a mgN/ℓ	No3d mgN/ℓ	No3b2 mgN/ℓ	Nte mgN/ℓ	No3e mgN/ℓ	Nti mgN/ℓ	% N Bal.	Ot mgO/ℓ.h	Sti mgO/ℓ	Ste mgO/ℓ	% COD Bal.	Pt_{rem} mgP/ℓ	P/VSS mgP/gVSS	% P Bal.
3.6.1 R1 45 days 10 mg/ℓ Fe, AE1	35.8 (1.0)	1291 (110)	0.25 -	3.60 (1.72)	6.94 (2.63)	7.20 (2.83)	7.08 (2.61)	31.1 (6.2)	**102**	13.13 (1.61)	403 (105)	52 (23)	**86**	9.85 (2.05)	80.10 (5.24)	**94**
3.6.1 R2 Control	35.8 (0.8)	1218 (89)	0.25 -	6.94 (2.63)	6.40 (2.33)	6.68 (2.74)	7.56 (1.49)	31.1 (6.2)	**102**	14.23 (1.33)	403 (105)	58 (20)	**89**	10.01 (2.00)	91.14 (5.68)	**99**
3.6.2a R1 64 days 10 mg/ℓ Fe, AE1	35.9 (1.9)	1223 (160)	0.25 -	2.83 (0.71)	5.43 (1.38)	2.06 (0.26)	5.33 (1.39)	31.77 (4.56)	**81**	11.36 (1.57)	415 (88)	44 (22)	**77**	9.93 (2.92)	89.65 (11.53)	**98**
3.6.2a R2 Control	35.4 (2.0)	1186 (121)	0.25 -	2.31 (0.77)	4.70 (1.24)	2.09 (0.32)	4.74 (1.42)	31.77 (4.56)	**78**	12.87 (2.35)	415 (88)	41 (11)	**82**	9.84 (3.25)	96.91 (9.61)	**106**
3.6.2b R1 12 days 10 mg/ℓ Fe, AE 1	Mass balances not attempted - short experimental period (12 d) and systems not in steady state, due to addition of influent P															
3.6.2b R2 Control	Mass balances not attempted - short experimental period (12 d) and systems not in steady state, due to addition of influent P															

At the prevailing reactor pH for Period 3.6.1 (median pH 7.4 to 7.5 in the aerobic reactors - see Table 4.14), the solubility limit for ferric (hydroxy) phosphate precipitate is expected to be in the region of 0.2 to 0.4 mgP/ℓ as ortho P, due to the formation of soluble iron-P complexes (ion-pairs) (see Chapter 7, section 7.1.3.2 and Fig. 7.4). Hence, even in the presence of excess iron, it would be theoretically impossible to achieve an effluent ortho P concentration of <0.2 mgP/ℓ at a reactor pH of 7.4 to 7.5. Background iron (or other cation) concentrations in the influent sewage could set up similar equilibrium constraints in the Control reactor (median aerobic reactor pH 7.5 to 7.7), which may also make it also impossible for the biological mechanism to remove phosphate to lower residual ortho P concentrations (ca. 0.3 to 0.5 mgP/ℓ, based on Fig. 7.4 at pH 7.5 to 7.7). These equilibrium constraints appear to be borne out by the above-mentioned effluent ortho P results for Period 3.6.1 (Table 4.12b). Under such low effluent P conditions, in the presence of metal (e.g. iron) dosing, the biological mechanism would be in maximum competition with the chemical mechanism for available phosphate. Since the chemical reactions would take place outside the bacterial cells and since chemical precipitation should be much more rapid than biological P uptake, it may be hypothesised that the biological mechanism would always be at a competitive disadvantage under low reactor P concentrations. This hypothesis appears to be supported by the greater degree to which P release in the anaerobic reactor was depressed in the Test unit, relative to the Control (see above). A comparison of the size of the poly P pool in the Test and Control units (measurable by fractionation) serves as another indicator of the "strength" of the biological mechanism under these conditions.

Figures 4.9 and 4.10 as well as Table 4.15 show fractionation results for mixed liquor sampled during Period 3.6.1. Examining Fig. 4.9 and Table 4.15, and ignoring the relative contributions of acid versus alkaline soluble forms of either ortho P or complex P by taking the sum of the respective PCA and NaOH fractions, the following observations may be made:

- The total P of the mixed liquor was significantly lower (80 to 120 mgP/gVSS) during Period 3.6.1, compared to preceding ferric chloride dosing periods (Fig. 4.3), as would be expected for the lower influent acetate addition and limiting influent P concentration. For the same reasons, in absolute terms, the magnitude of the complex P (biological) fractions of both the Test and Control units was significantly lower in Period 3.6.1, compared to previous ferric chloride dosing periods.
- The total P content of the mixed liquor (sum of all fractions, based on P/VSS) was either almost equal in the two units, or slightly lower in the Test unit (dosed with ferric chloride). This is in agreement with the results for Period 3.6.1 as a whole (Table 4.12a) in which the Test unit had a lower P/VSS ratio (but slightly higher VSS) and gave a slightly lower system P removal.
- The magnitude of the complex P (biological) fractions was depressed by 26 to 37% in R1 relative to R2 (Control), which is greater than the degree of depression (max. 17%) observed for periods in which P was never limiting (see section 4.3.6), but less than that suggested from mass balance data for average P release in the anaerobic reactor of R1 compared to R2 (43%, see above).
- The magnitude of the ortho P fractions was approximately three-fold greater in R1 (ferric dosed) compared to the R2 (Control), which is similar in relative terms to the differences between R1 and R2 for non-P limiting conditions (Table 4.9a).
- In absolute terms, the magnitude of ortho P (chemical) fractions was approx. 25 to 40 mgP/gVSS (or 33 to 52 mgP/ℓ) in the Test unit (R1) and 10 mgP/gVSS (12 mgP/ℓ) in the Control (R2), which is *significantly less than that for periods of comparable flow and iron dose without P limitation* (50 to 60 mgP/gVSS, or 113 to 136 mgP/ℓ, for R1; and 20 mgP/gVSS, or 48 mgP/ℓ, for R2 - from Tables 4.9a and VSS data in Table 4.4). This implies that the chemical mechanism removed less phosphate under P limiting conditions and therefore probably does not have a large "competitive advantage" over the biological mechanism under these conditions.
- The relative percentage contributions of the chemical (ortho P) fractions and biological (complex P) fractions to the total P of the mixed liquor solids (i.e. sum of all the sludge fractions, ignoring the supernatant) were approx. 10% chemical - 84% biological (remainder unknown residue) in R2 (no ferric), and approx. (26 to) 36 % chemical[13] - (55 to) 60%

[13] A degree of uncertainty arose due to the significantly higher residue TP in R1 on 29/9/97 (Fig. 4.9).

biological in R1 (with ferric). If these results are compared to those in Table 4.9 for non-P limiting conditions, then the *relative* behaviour of the two units was little changed under P limiting conditions: in relative terms, most, the biological mechanism may have been "inhibited" (depressed) by at most 5 to 12% in the Test unit (dosed with ferric chloride), while the chemical mechanism gained by no more than this margin, under P-limiting conditions. This implies that the biological mechanism is only at a fairly small competitive disadvantage to the chemical mechanism under P-limiting conditions, when compared to non-P- limiting conditions.

- PCA-extractable complex P fractions became very minor or seemed to disappear in R1, but remained fairly significant in R2; much of the complex P was NaOH-extractable, and this was particularly noticeable in R1.These observations are linked with those reported in Chapter 2 (section 2.4.7) where the fractionation pattern for complex P was found to be at least partly an artefact induced by the availability of metal during the fractionation procedure, whether that metal was solubilised from the mixed liquor solids during the extraction procedure, or added to the test tube during the PCA step from an external source. Therefore, little significance can be attached to the relative size of the PCA and NaOH complex P fractions. Accordingly, these fractions were lumped together as "complex P" for interpretation purposes.

Summarising, it appears that the bio-P removal mechanism is at a competitive disadvantage under P limiting conditions in the presence of ferric chloride dosing, but from the fractionation data, the extent of the "inhibition" appears to be somewhat less than that suggested by mass balance data for P release around the anaerobic reactor. The latter suggested on average 43% inhibition of the bio-P mechanism in Period 3.6.1, while the magnitude of the complex P (biological) fractions suggested 26 to 37% inhibition for this period. Moreover, whereas the percentage inhibition of P release in the anaerobic reactor found by mass balance for Period 3.6.1 was *at least double* that found for periods of ferric chloride dosing in the absence of P limitation, the relative proportions of chemical to biological P fractions in the mixed liquor for Period 3.6.1 (Fig. 4.9) were only slightly shifted in favour of the chemical fractions, compared to those for ferric chloride dosing periods without P limitation (Table 4.9a).

Anaerobic batch P release tests carried out in association with the fractionation studies showed a large (50 to 65%) depression of P release to the supernatant in the Test unit (R1), compared to the Control (Fig. 4.10). Most (or all) of the P release to the supernatant could be accounted for as release from the complex (biological) P fractions. However, in the case of R1 (ferric dosed at 10 mg/ℓ as Fe), minor P *uptake* was noted in two fractions during the anaerobic batch test, namely, the supernatant complex P (slight) and PCA ortho P fractions (ca. 10 mgP/gVSS) (Fig. 4.10). The same effect was noted for R1 in batch tests for periods without P limitation either with a high ferric chloride dose (20 mg/l as Fe) to the aerobic zone, or a lower dose (10 mg/l as Fe) to the anaerobic zone. It is therefore possible that a degree of interaction occurs between the chemical and biological mechanisms in the form of ortho P that "migrates" from the biologically stored complex (poly) P fraction to the chemical (ortho P) fraction(s) during P release under anaerobic reactor conditions. Most likely, the sites of chemical precipitation (or adsorption) are located in very close physical proximity to the cell wall/ membrane of the bacteria responsible for the biological release-uptake reactions, and partial "entrapment" of phosphate in the form of a ferric (hydroxy) phosphate precipitate or adsorption to ferric hydroxide colloid seems plausible under anaerobic conditions during P release from the cells. As the experimental data suggest, this would be most likely where iron is actually dosed to the anaerobic zone, or where the iron in one of the subsequent reactors is high and a significant amount of ferric hydroxide accumulates in the mixed liquor solids, or under conditions of P limitation when "surplus" iron may be expected to accumulate as ferric hydroxide. Under aerobic conditions, when the bacterial cells take up phosphate, localised chemical equilibrium conditions may be created which lead to redissolution of some or all of this "transient" chemical precipitate (or adsorbed) ortho P[14]. A degree of migration of P between the chemical and biological fractions in this manner may explain why the degree of inhibition of the bio-P

[14] Simultaneous fractionation of both anaerobic and aerobic mixed liquor of both Test and Control units would be necessary to further examine this aspect. An attempt to observe the phenomenon in batch tests with successive anaerobic-aerobic cycles was also carried out by De Haas (1989) using mixed liquor samples from Daspoort Works (Pretoria). The results also showed increased formation of the chemical (ortho P) fraction during the anaerobic period, but a rapid increase in pH (from ca. 7.6 to 8.3) at the start of the aerobic cycle may have resulted in further precipitation of phosphate (e.g. as struvite), thus leading to the observation of a further increase in the chemical (ortho P) fraction after the aerobic cycle, as opposed to the decrease hypothesized here.

mechanism noted by fractionation of the aerobic mixed liquor appeared to be less than that found by mass balance calculation of average P release in the anaerobic reactor for Period 3.6.1.

It is possible to estimate the stoichiometry of chemical precipitation and concentration of metal phosphate accumulated in the mixed liquor from the fractionation data for Period 3.6.1 under P limiting conditions (see similar results for earlier experimental periods in Tables 4.10a and 4.10b above). From two sets of fractionation results for Period 3.6.1 (Fig. 4.9), the *difference* in PCA and NaOH ortho P fractions between the two units (i.e. R1-R2) was approx. +16 to 22 mgP/gVSS. Applying this difference in the same manner as set out in Table 4.10a for previous experimental periods, and assuming steady-state at a 10d sludge age, the average *additional* P removal via the PCA ortho P ("chemical precipitate") fraction was 66 to 91 mgP/d (or 2.1 to 2.9 mmol P/d). Since the iron dose was 6.65 mmol Fe/d, this gives an average stoichiometry of 0.32 to 0.44 mol P/mol Fe (dosed). This result is somewhat (ca. 35%) lower than the average result of 0.62 mol P/ mol Fe for non-P-limiting conditions (Table 4.10a), and is probably a reflection of P-limiting conditions leading to competition for available phosphate. The fact that the P:Fe stoichiometry of the precipitate was reduced to a similar extent to the relative magnitude of the biological (complex P) fractions between the Test and Control units implies that the chemical mechanism did not entirely "out compete" the biological mechanism for available P under the experimental conditions applied here.

Finally, alkalinity loss comparisons between the Test (R1) and Control (R2) units may be considered. From Table 4.1.4, for Period 3.6.1, the difference in mean alkalinity between the two units (R2-R1) was 24 mg/ℓ as $CaCO_3$, which equates to 0.48 mmol/ℓ, or 17.2 mmol/d for an average flow of 35.8 ℓ/d (Table 4.12a). Since the iron dose was 6.65 mmol/d as Fe, the mean alkalinity loss was 2.6 mmol $CaCO_3$/ mmol Fe dosed. This is slightly higher than the average found for ferric chloride dosing under non-P-limiting conditions and probably reflects the fact that P limitation resulted in greater residuals of ferric hydroxide precipitate in the mixed liquor, as opposed to ferric (hydroxy) phosphate.

4.3.11.2 Without influent bicarbonate supplement (Period 3.6.2a)

Since P limiting conditions appeared to emerge during 3.6.1, it was decided to perform the penultimate experiment (Period 3.6.2a) under conditions as representative as possible of the full-scale plant at Darvill WWW. To achieve this, not only should effluent P concentrations remain below 1 mgP/ℓ, but the effluent total alkalinity should be in the range approximately 60 to 120 mg/ℓ as $CaCO_3$ (see Chapter 6, Fig. 6.11). Table 4.14 shows that the average bicarbonate alkalinity for the Test unit (R1) during Period 3.6.1 was close to 200 mg/ℓ as $CaCO_3$. Since the bicarbonate makes a major contribution to the effluent total alkalinity, withdrawal of the sodium bicarbonate influent supplement (100 mg/ℓ as $CaCO_3$, see Table 4.1) was expected to have the necessary effect of reducing the pilot plant effluent total alkalinity in order to match that of the full-scale plant more closely.

On 5/10/97, influent supplementation with sodium bicarbonate was stopped. Figures 4.11, 4.12 and 4.13 show the MLSS, VSS, COD, OUR and effluent total P trends for the ensuing eleven week period (Periods 3.6.2a & b).

Figure 4.11 shows that MLSS and VSS trends were fairly stable during Period 3.6.2b, with the exception of incidents where settling problems were encountered due to malfunctioning of the clarifier scraper mechanism. The gradual decreasing trend in both VSS and MLSS is linked to the a similar trend in influent COD, with the onset of summer (Fig. 4.12). With the increase in influent P during Period 3.6.2b, the downward trend in MLSS concentrations of both units was halted or reversed, due to the increase in P uptake by the sludge organisms; VSS concentrations had shown a degree of stabilisation in the week preceding P addition, and remained in this narrow band in the last two week period at higher influent P concentrations.

With the exception of brief incidents during which settling problems occurred due to clarifier scraper malfunction, Fig. 4.13 and Tables 4.12(a & b) show that during Period 3.6.2a, both the

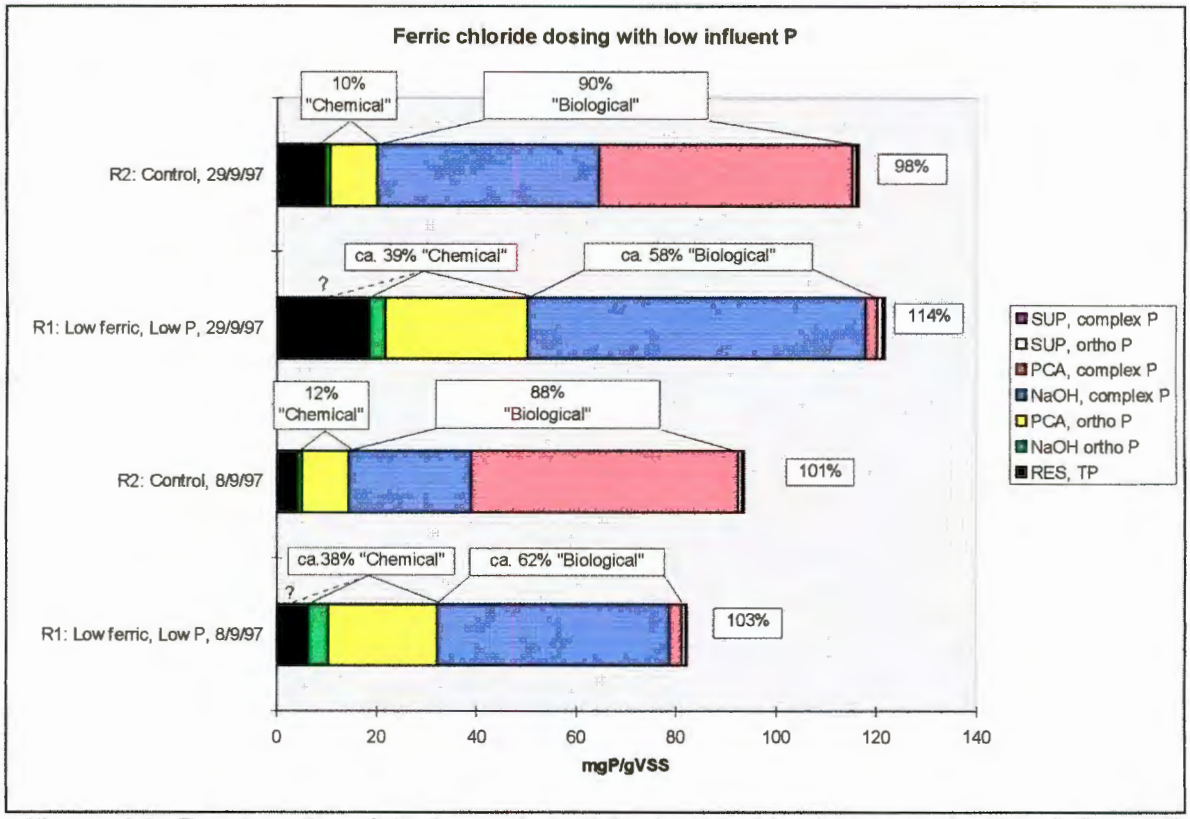


Figure 4.9: Fractionation data for period of ferric chloride dosing under low influent P conditions with bicarbonate added to influent (Period 3.6.1). Unless otherwise stated, percentage figures quoted are for % TP recovery in the fractionation procedure compared to the measured P/VSS content. "Biological" ("complex P") vs. "chemical" (ortho P) fraction contributions expressed as a percentage of the sum of fractions (including RES, but excluding SUP).

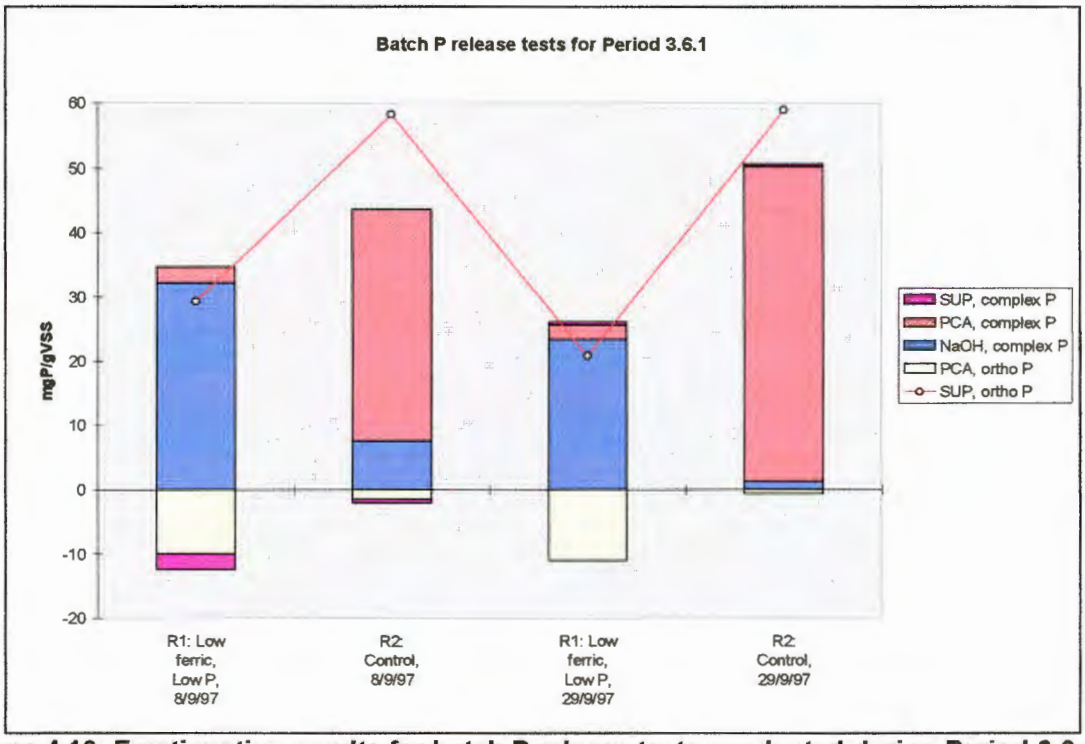


Figure 4.10: Fractionation results for batch P release tests conducted during Period 3.6.1.

Test (R1) and Control (R2) units achieved very low effluent ortho P concentrations (R1: average = 0.35 (± 0.34) mgP/ℓ; R2: average = 0.44 (± 0.85) mgP/ℓ) and total P concentrations (R1: average = 0.53 (± 0.45) mgP/ℓ; R2: average = 0.62 (± 0.94) mgP/ℓ)[15]. Table 4.14 shows that the reduction of the influent alkalinity had the effect of lowering the aerobic reactor pH in both units, with the Test unit (R1) showing a median pH = 7.0 at the point of dosing (first aerobic reactor), in comparison to a pH = 7.4 for this reactor in the previous period (3.6.1). An examination of Fig. 7.4 in Chapter 7, shows that uncertainty over the equilibrium constant for one of the iron-P ion pairs creates significant uncertainty over the theoretical equilibrium solubility limit for ortho P: a range of approx. 0.05 to 1.0 mgP/ℓ is possible at pH 7.0, and 0.09 to 0.45 mgP/ℓ at pH 7.2 (Fig. 7.4). The experimental data for ortho P during Period 3.6.2a did fit within these limits, suggesting that both systems were P-limited for most of this experimental period. As in the case for Period 3.6.1, maximum "competition" for available P between the chemical and biological P removal mechanisms would be expected under conditions of P limitation.

Average results for Period 3.6.2a are given in Tables 4.12a and 4.12b. The overall N, COD and P mass balance results were in the range 77 to 106% (Table 4.13). Comparing the P release from mass balance considerations for the anaerobic reactors (see Equation 4.1 in section 4.3.2.2) it was found that, on average, P release in the anaerobic reactor of the Test was 59% of that in the Control unit (i.e. inhibited by 41% in R1, compared to R2). This is very similar to the degree of inhibition noted by the same method for Period 3.6.1 (section 4.3.11.1 above).

Figures 4.14 and 4.15 show fractionation results for mixed liquor sampled during Period 3.6.2a. Examining Figs. 4.14 and 4.15, and ignoring the relative contributions of acid versus alkaline soluble forms of either ortho P or complex P by taking the sum of the respective PCA and NaOH fractions, the following observations may be made:

- The total P of the mixed liquor was approximately the same (80 to 110 mgP/gVSS) in Period 3.6.2a as Period 3.6.1 (Fig. 4.9), which would be expected for a very similar influent composition (Table 4.12a,b). For the same reasons, in absolute terms, the magnitude of the complex P (biological) fractions of the Test and Control units was very similar for Periods 3.6.1 and 3.6.2a.
- The total P content of the mixed liquor (sum of all fractions, based on P/VSS) was either almost equal in the two units, or slightly lower in the Test unit (dosed with ferric chloride). This is in agreement for the results of Period 3.6.2a as a whole (Table 4.12a) in which the Test unit had a lower P/VSS ratio (but slightly higher VSS) and gave a very similar system P removal to the Control unit.
- The magnitude of the complex P (biological) fractions was depressed by 33 to 35% in R1 relative to R2 (Control), which is similar to the degree of depression (26 to 37%) observed for Period 3.6.1. Furthermore, as in Period 3.6.1, this degree of depression observed from fractionation data was less than that suggested from mass balance data for average P release in the anaerobic reactor of R1 versus R2 (41%, see above).
- The magnitude of the ortho P fractions was approximately three-fold greater in R1 (ferric dosed) compared to the R2 (Control), which is similar in relative terms to the differences between R1 and R2 for non-P limiting conditions (Table 4.9a).
- In absolute terms, the magnitude of ortho P (chemical) fractions was approx. 30 to 33 mgP/gVSS (or 37 to 40 mgP/ℓ) in the Test unit (R1) and 10 mgP/gVSS (12 mgP/ℓ) in the Control (R2), but *significantly less than that for periods of comparable flow and iron dose without P limitation* (50 to 60 mgP/gVSS, or 113 to 136 mgP/ℓ, for R1; and 20 mgP/gVSS, or 48 mgP/ℓ, for R2 - from Tables 4.9a and VSS data in Table 4.4). The same conclusion was reached for Period 3.6.1 and implies that the chemical mechanism removed less phosphate under P limiting conditions and therefore probably does not have a large "competitive advantage" over the biological mechanism under these conditions.
- When expressed in stoichiometric terms based on the iron dosed, the additional P removed in the form of PCA + NaOH ortho P fractions in R1, relative compared to R2, was approx. 81 to

[15] The detection limits of the automated molybdate-ascorbic acid methods used here were 0.1 mgP/l as ortho P and 0.5 mgP/l as total P. *Results below detection limit were reported as half the detection limit. This will have produced a low bias in the total P results, with 50% (R1, n=43) to 76% (R2, n=43) of the TP results being below detection limit. during Period 3.6.2a.* In this period, none of the P results for R1 were below the ortho P detection limit, while in R2 (n=43), 35% of the results were below detection limit.

94 mgP/d, which gives a stoichiometry of about 0.40 to 0.46 mol P/mol Fe (dosed). This is similar to that observed for Period 3.6.1, and about 33% less than the average stoichiometry calculated in the same manner for periods of ferric chloride dosing without P limitation.

- The relative percentage contributions of the chemical (ortho P) fractions and biological (complex P) fractions to the total P of the mixed liquor solids (i.e. sum of all the sludge fractions, ignoring the supernatant) were approx. 10% chemical - 84% biological (remainder unknown residue) in R2 (no ferric), and approx. 33 to 39 % chemical and 54 to 62% biological in R1 (with ferric). If these results are compared to those in Table 4.9 for non-P limiting conditions, then the *relative* behaviour of the two units was little changed under P limiting conditions: at most, the biological mechanism may have been "inhibited" (depressed) by about 12% in the Test unit (dosed with ferric chloride), while the chemical mechanism gained by no more than this margin, in relative terms. This implies that the biological mechanism is only at a fairly small competitive disadvantage to the chemical mechanism under P-limiting conditions, when compared to non-P- limiting conditions.
- PCA-extractable complex P fractions became very minor in R1, but remained fairly significant in R2; much of the complex P was NaOH-extractable, and this was particularly noticeable in R1. These observations are linked with those reported in Chapter 2 (section 2.4.7) where the fractionation pattern for complex P was found to be at least partly an artefact induced by the availability of metal during the fractionation procedure, whether that metal was solubilised from the mixed liquor solids during the extraction procedure, or added to the test tube during the PCA step from an external source. As a result, little significance can be attached to the relative size of the PCA and NaOH complex P fractions. Accordingly, these fractions were lumped together as "complex P" for interpretation purposes.
- Anaerobic batch P release tests in combination with the fractionation studies (Fig. 4.15) showed that P release was depressed by 37 to 47% in mixed liquor from R1 (ferric dosed), compared to R2 (Control). For both R1 and R2, P release to the supernatant could be largely accounted for by P release from the biological (complex P) fractions, although the agreement improved if minor uptake into the PCA ortho P and supernatant complex P fractions was also taken into account. The apparent uptake into these fractions was also observed in these batch tests for Period 3.6.1, and could indicate the formation of chemical iron-P complexes (e.g. colloidal or particulate ferric-hydroxy-phosphate complexes). The formation of such complexes would be more likely where "surplus" (free or complexed) iron, with the potential to adsorb or precipitate phosphate, has accumulated in the mixed liquor. This would be most likely under P limiting conditions, such as Period 3.6.2a. The fact that this phenomenon was also observed to some extent in the batch test for mixed liquor from the Control unit suggests that settled sewage alone can contribute a significant amount of iron (or similar cation) which can give chemical P precipitation as a minor removal mechanism.

Summarising, Periods 3.6.1 and 3.6.2a represent a fifteen week experimental period (equivalent to fifteen sludge ages) during which the pilot plants operated under conditions approximating full-scale conditions with limiting effluent P concentrations, and relatively low effluent alkalinity. The Control unit (R2) achieved virtually complete P removal by biological means alone. The Test unit was dosed with ferric chloride at a constant dose of 10 mg/ℓ as Fe to the first aerobic reactor. The Test unit also achieved virtually complete P removal. Fractionation results indicated that the relative ratio of chemical to biological sludge P fractions in the mixed liquor of the Test unit was similar to that observed under conditions when effluent P was never limiting, with a small shift toward the chemical mechanism. On the one hand, the magnitude of the biological fractions was depressed ("inhibited") by about 35% in the Test unit with iron dosing, relative to the Control under P-limiting conditions; this is approximately double that found for non-P-limiting conditions. On the other hand, a comparison of the chemical fractions in the Test unit under P-limiting versus non-P-limiting conditions revealed that, for the same iron dose and operating conditions, significantly less phosphate was precipitated under P-limiting conditions. The stoichiometry of additional chemical precipitate due to iron dosing (calculated by difference from fractionation data for the Test and Control units) was approximately 30 to 35% lower under P-limiting conditions, compared to that for non-P-limiting conditions. It follows that the *both the biological and chemical P removal mechanisms are "disadvantaged" to approximately the same degree under P-limiting conditions*. This explains why the relative proportions of the chemical and biological sludge P fractions remains essentially constant under both limiting and non-P-limiting conditions. However, the chemical precipitation mechanism obviously does limit the extent to which the biological P

removal *potential* can be utilised by removing part of the phosphate in the system. This, in turn, explains why the magnitude of the biological sludge P fractions in the Test unit was depressed to a greater degree (relative to the Control unit) under P-limiting conditions, compared to non-P-limiting conditions. The extent of this depression should be mirrored by the extent to which P release in the anaerobic reactor was depressed (from mass balance considerations). The fact that the P release mass balance data (as well as anaerobic batch P release tests) tended to overestimate the degree of depression of the bio-P mechanism by a small margin (5 to 10%) may be a reflection of role played by minor changes in the chemical P fractions in the sludge. It may be speculated that degree of "exchange" of phosphate occurs between the biological and chemical mechanisms: particularly under conditions where "surplus" metal hydroxide accumulates in the mixed liquor (e.g. effluent P limiting), P release under anaerobic conditions may give rise to a transient increase in phosphorus complexed/ adsorbed/ precipitated in chemical form, followed by a reversal under aerobic (or anoxic) conditions when a reversal of these equilibrium reactions occurs due to the P uptake by the biological mechanism. Although these interactions may be comparatively minor, they may explain differences between the observed behaviour of the Test unit compared to mathematical model predictions where the model (for simplicity) assumes that the chemical and biological mechanisms operate independently of each other. As will be seen in Chapter 7, the difficulty of defining or calibrating the actual chemical equilibrium reactions which may be occurring in such systems, leads to simpler kinetic models being favoured over more complex equilibrium models.

Finally, both the Test and Control units operated in a stable manner throughout the fifteen weeks which spanned Periods 3.6.1 and 3.6.2a. The removal of the 100 mg/ℓ (as $CaCO_3$) alkalinity supplement had no noticeable effect on the systems. Sludge settleability in the Test unit (with ferric chloride) did not deteriorate significantly after the reduction in the system alkalinity. It would thus appear that a residual effluent alkalinity of approx. (75 to) 100 mg/ℓ $CaCO_3$ (Table 4.14, R1) is adequate for sustaining stable operation of a BEPR activated sludge system in the presence of simultaneous iron (ferric chloride) dosing. There was a tendency for the floc in the Test unit to be finer than that in the Control, despite a consistently lower DSVI, relative to the Control (Table 4.12a) and the effluent from the Test unit sometimes showed a tendency to turn slightly turbid. In these respects, the behaviour of the Test unit was similar to previous ferric chloride dosing periods (see section 4.3.10 above), although settleability during Periods 3.6.1 and 3.6.2a never deteriorated to the point that the zone settling velocity was lower for the Test unit, relative to the Control. Differences in this regard, compared to previous ferric chloride dosing periods cannot be explained and may be related to differences in the activated sludge population, or possibly to the higher system phosphate concentration in previous experimental periods.

Table 4.14 ...../

Table 4.14: Summary pH and alkalinity data for Periods 3.6.1 and 3.6.2a & b.
Data in italics indicate mean in place of median. n = no. of observations.

	Unit:	R1	R2	R1	R2	R1	R2	R1 H_2CO_3* /Total Alk. mg/ℓ as $CaCO_3$	R2 H_2CO_3* /Total Alk. mg/ℓ as $CaCO_3$
Period	Zone:	AN	AN	AE1	AE1	AE2	AE2	Effluent	Effluent
3.6.1	Min.	7.02	6.98	7.01	7.09	7.13	7.20	159	152
	25%-ile	7.02	7.02	7.12	7.26	7.24	7.45	196	217
	Median	7.27	7.13	7.40	7.50	7.51	7.70	*201*	*225*
	75%-ile	7.45	7.33	7.54	7.61	7.68	7.79	207	242
	Max.	7.64	7.52	7.67	7.70	7.78	7.87	263	252
3.6.2a	Min.	6.62	6.50	6.59	6.67	6.78	6.86	28	31
	25%-ile	7.02	6.95	7.00	7.05	7.15	7.27	87	126
	Median	7.10	7.00	7.02	7.14	7.20	7.36	*97*	*132*
	75%-ile	7.14	7.02	7.13	7.22	7.31	7.43	108	138
	Max.	7.31	7.11	7.35	7.43	7.52	7.61	142	199
3.6.2b	Min.	7.07	6.94	7.02	7.13	7.18	7.29	61	129
	25%-ile	7.11	6.96	7.04	7.14	7.28	7.42	104	142
	Median	7.13	7.00	7.09	7.20	7.36	7.47	*106*	*145*
	75%-ile	7.17	7.05	7.25	7.25	7.54	7.52	122	152
	Max.	7.27	7.17	7.39	7.66	7.72	8.08	123	155

AN = Anaerobic zone; AE1 / AE2 = First / second aerobic zone respectively

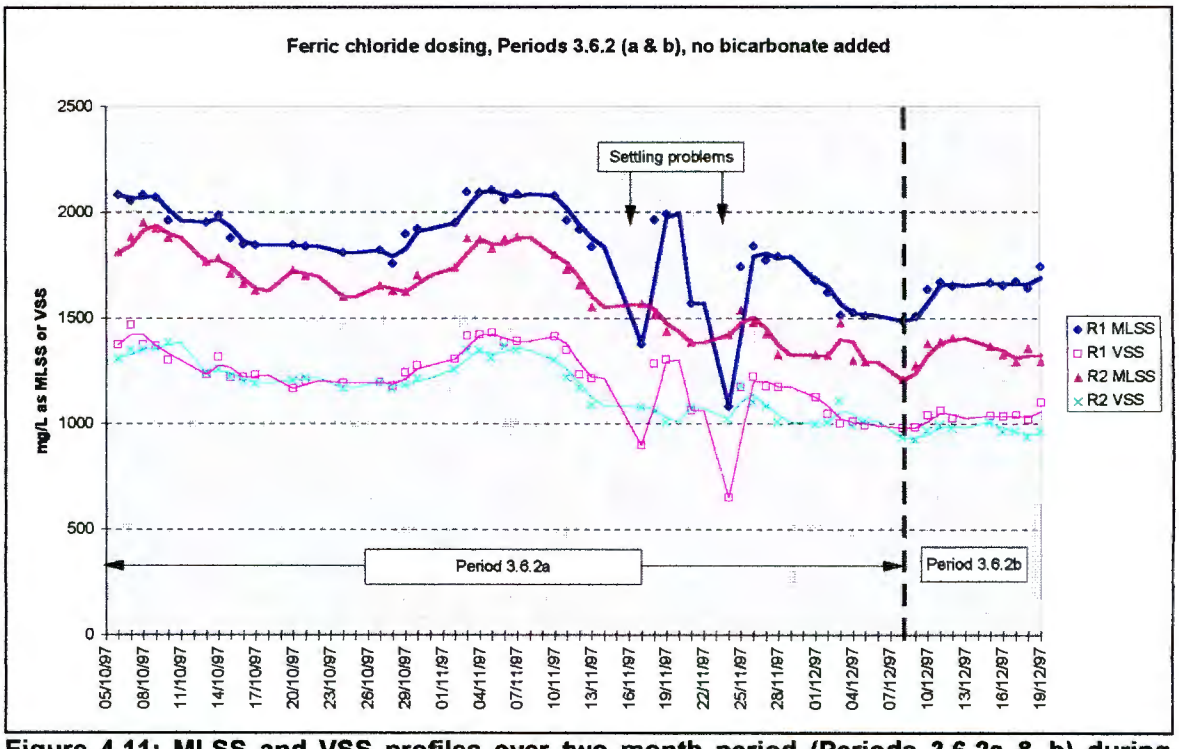


Figure 4.11: MLSS and VSS profiles over two month period (Periods 3.6.2a & b) during which ferric chloride was dosed, without bicarbonate added to the influent, and the influent P was low for nine weeks, followed by two weeks with added influent P. Lines are two-point moving averages.

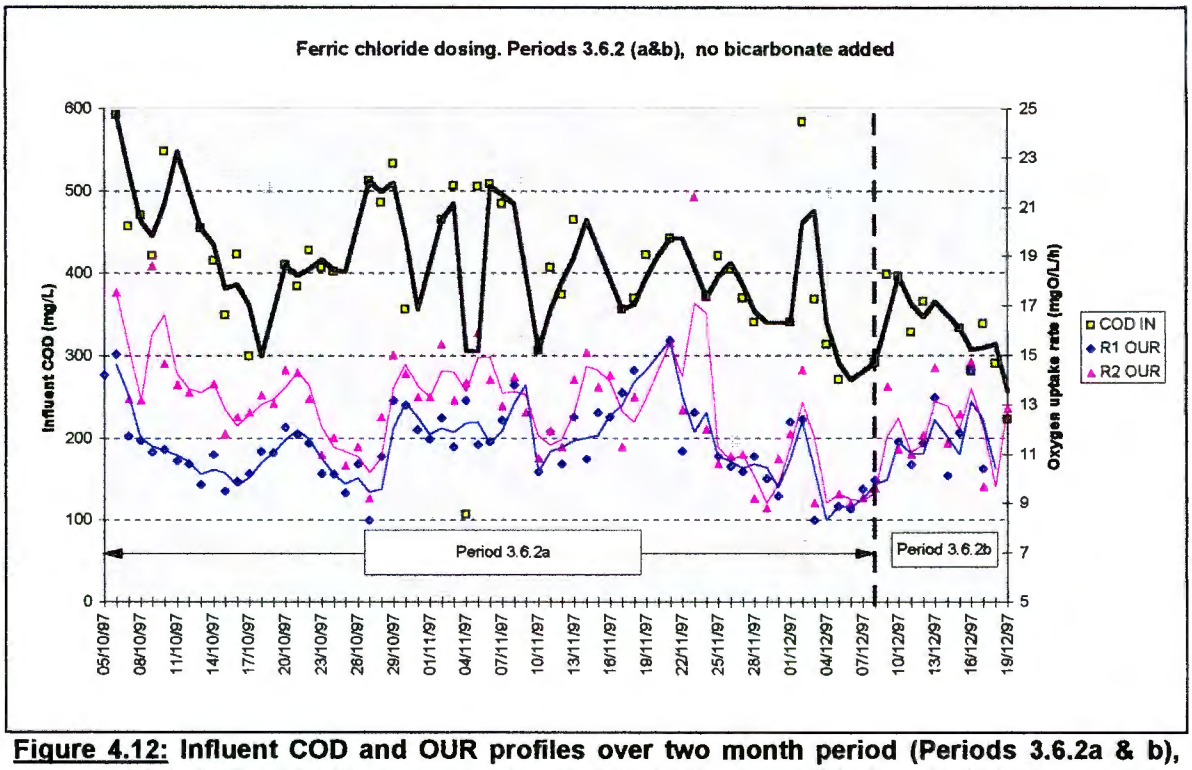


Figure 4.12: Influent COD and OUR profiles over two month period (Periods 3.6.2a & b), during which ferric chloride was dosed, without bicarbonate added to the influent, and the influent P was low for nine weeks, followed by two weeks with added influent P. Lines are two-point moving averages.

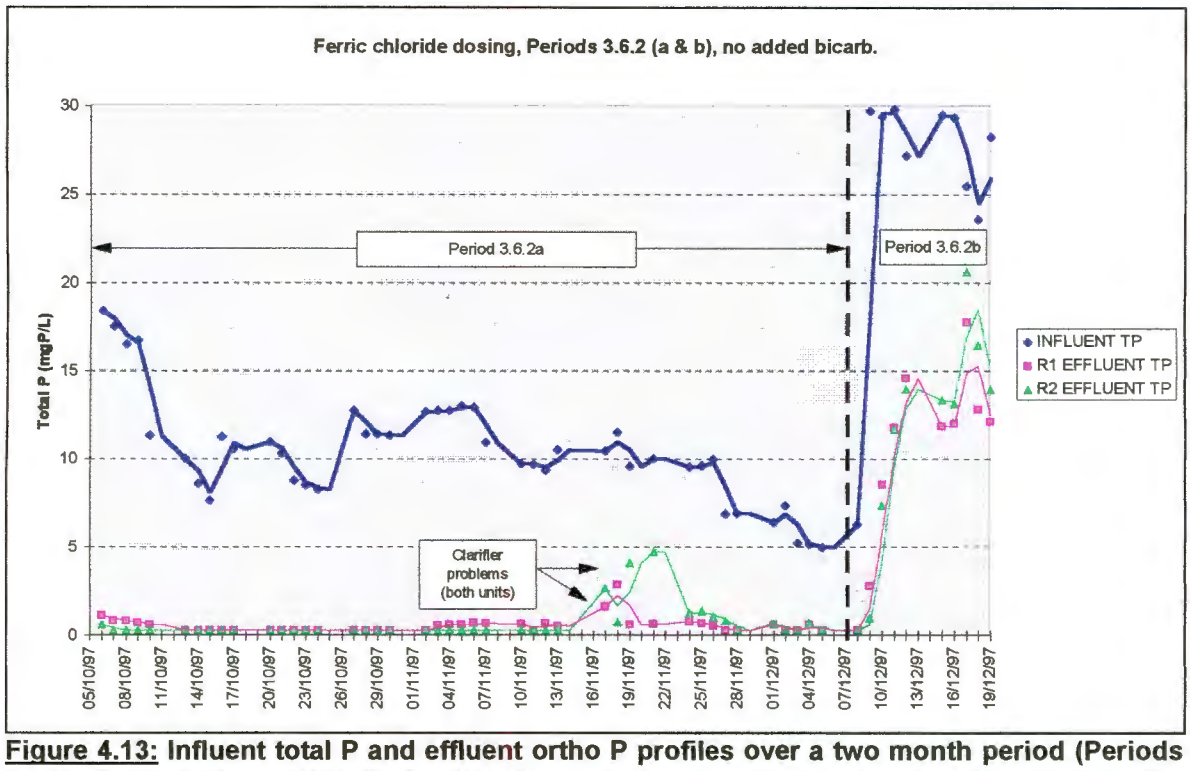


Figure 4.13: Influent total P and effluent ortho P profiles over a two month period (Periods 3.6.2a & b), during which ferric chloride was dosed, without bicarbonate added to the influent, and the influent P was low for nine weeks, followed by two weeks with added influent P. Lines are two-point moving averages.

Table 4.15: Fractionation data relating to Figs. 4.9 and 4.14 (excluding data for RES, residue and SUP, supernatant fractions).

Date, Unit Period	Ferric dose Low = 6.65 mmol/d	PCA Complex P mgP/gVSS	NaOH Complex P mgP/gVSS	Sum of PCA and NaOH Complex P fractions mgP/gVSS	Sum of PCA and NaOH ortho P fractions mgP/gVSS	Sum of PCA and NaOH Complex P fractions mgP/ℓ	Sum of PCA and NaOH ortho P fractions mgP/ℓ
see Figs. 4.9 & 4.15	see Table 4.3	"Biological"	"Biological"	Total "Biological" (#%); ##%	Total "Chemical"	Total "Biological" ##%	Total "Chemical"
8/9/97, R1 3.6.1	Low, AE1	2.46	46.61	**49.07 (66%); -37%**	**25.79 (34%)**	**65.02 -26%**	**34..17**
8/9/97, R2 3.6.1	-	53.40	24.56	77.96 (88%)	10.35 (12%)	87.86 -	11.66
29/9/97, R1 3.6.1	Low, AE1	2.31	67.78	**70.09 (69%); -26%**	**31.62 (31%)**	**84.25 -22%**	**38.01**
29/9/97, R2 3.6.1	-	50.70	44.50	95.20 (90%)	10.27 (10%)	107.96 -	11.65
30/10/97, R1 3.6.2	Low, AE1	8.35	49.03	**57.38 (65%); -35%**	**30.32 (35%)**	**69.89 -29%**	**36.93**
30/10/97, R2 3.6.2	-	67.50	20.78	88.28 (90%)	9.81 (10%)	98.17 -	10.91
4/12/97, R1 3.6.2	Low, AE1	3.79	42.09	**45.88 (58%); -33%**	**33.14 (42%)**	**47.26 -27%**	**34.13**
4/12/97, R2 3.6.2	-	43.68	24.48	68.16 (88%)	9.35 (12%)	64.82	8.89

#: Percentage figures in parentheses refer to % (sum of "total biological" and "chemical")
##: Percentage figures (e.g. -37%) refer to % inhibition of "total biological" fractions in R1 vs. R2

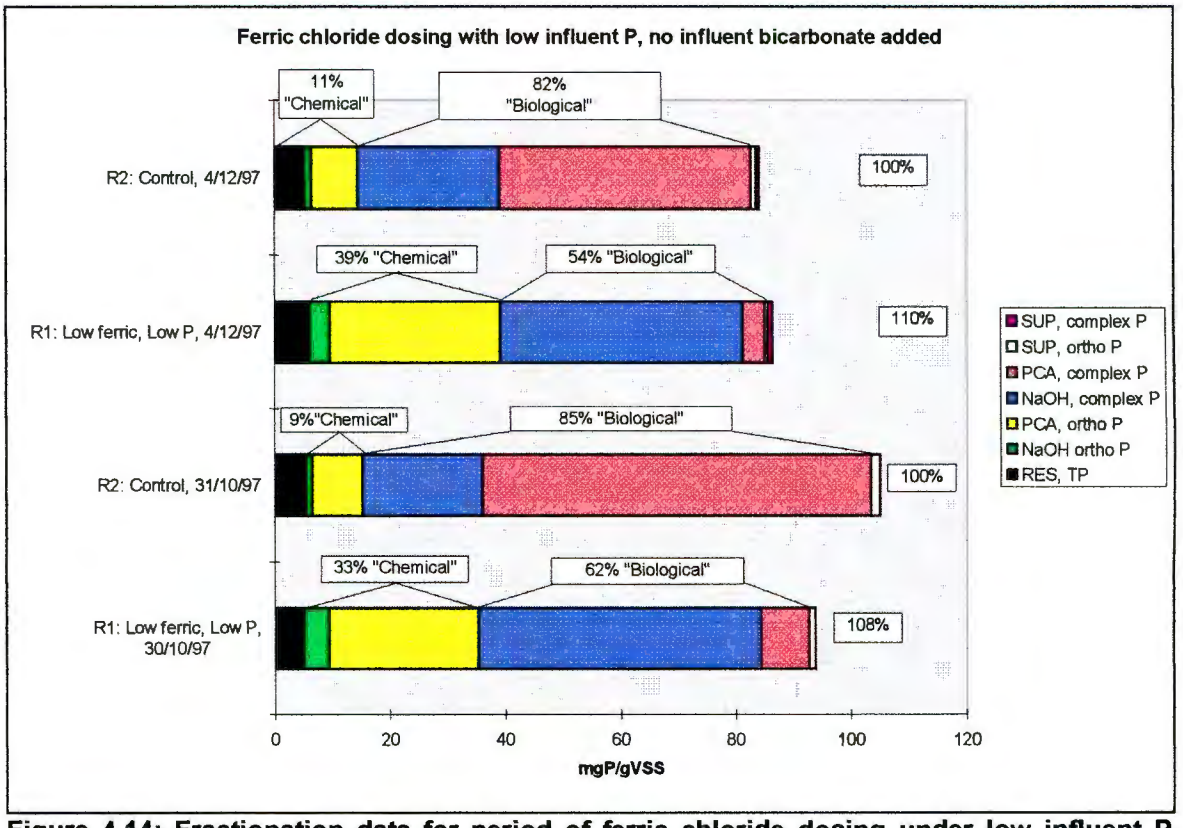


Figure 4.14: Fractionation data for period of ferric chloride dosing under low influent P conditions *without* bicarbonate added to influent (Period 3.6.2a). Unless otherwise stated, percentage figures quoted are for % TP recovery in the fractionation procedure compared to the measured P/VSS content. "Biological" ("complex P") vs. "chemical" (ortho P) fraction contributions expressed as a percentage of the sum of fractions (including RES, but excluding SUP).

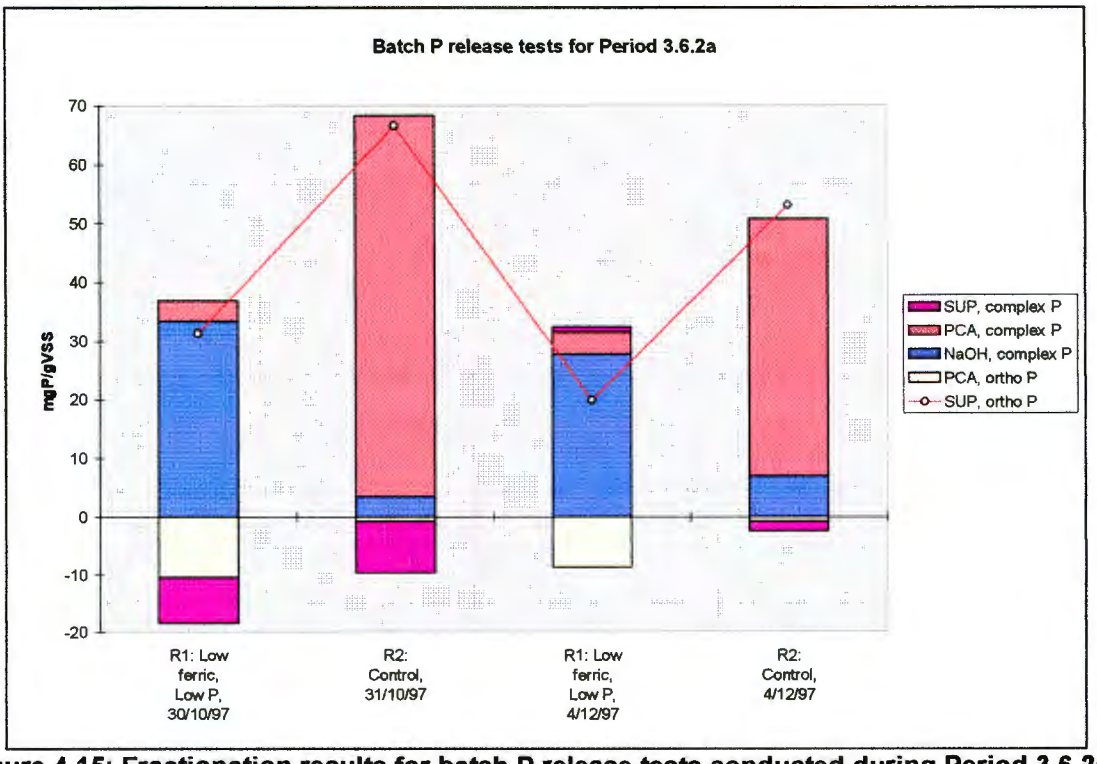


Figure 4.15: Fractionation results for batch P release tests conducted during Period 3.6.2a.

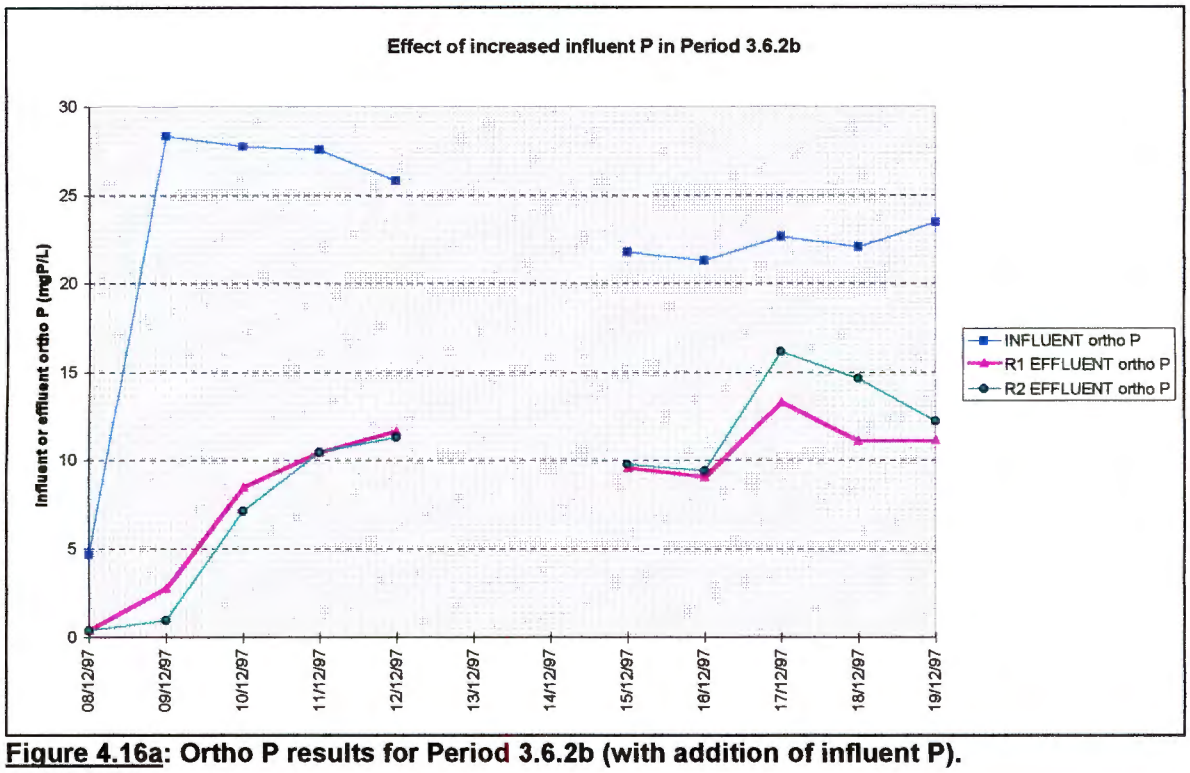


Figure 4.16a: Ortho P results for Period 3.6.2b (with addition of influent P).

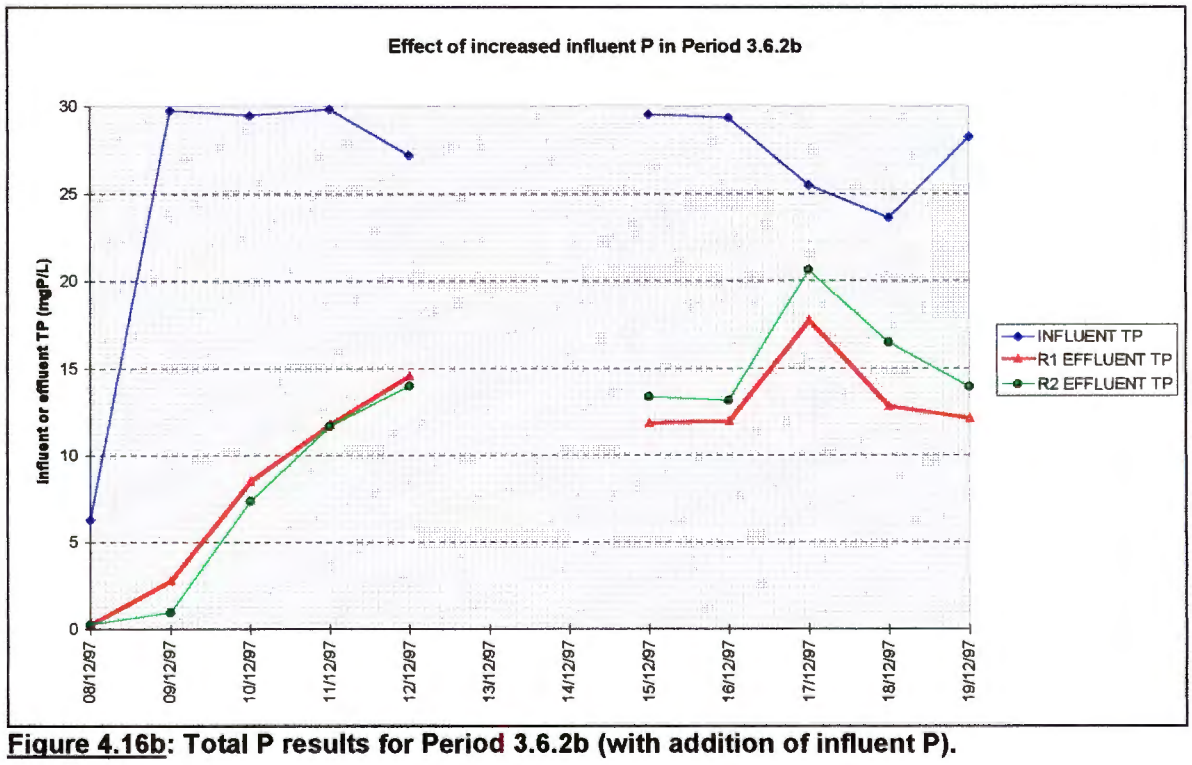


Figure 4.16b: Total P results for Period 3.6.2b (with addition of influent P).

4.3.12 Increase in influent P after period of P limitation (Period 3.6.2b)

The effect of an increase in influent phosphate following a prolonged period of P limitation is shown in Figs. 4.16a and 4.16b (ortho P and total P results respectively). From these figures it can be seen that, initially (first week after increased influent P), the Test unit (R1, iron dosed), gave a slightly higher effluent P result than the Control (R2). This implies that iron dosing showed no benefit at this point, due to the fact that the biological P removal mechanism was now less well established in the Test unit, compared to the Control. This provides evidence (c.f. sections 4.3.11.1 and 4.3.11.2 above) that the extent "inhibition" (depression) of bio-P removal as a result of chemical dosing during the preceding period of P limitation, although relatively small, becomes significant. Most likely, the chemical precipitation reactions are "favoured" in that they are faster than the biological uptake/ release reactions, and thus the fraction of the influent P load available for biological storage is diminished when metal precipitant is dosed under P-limiting conditions. This leads to a reduction of the numbers of poly P accumulating organisms (PAOs) in the system, and hence a depression of the bio-P activity. However, the bio-P activity recovers quickly when the influent P load increases, as shown in Figs. 4.16a and 4.16b: in the second week (after the increase in influent P concentration), the system P removal in the Test unit became greater than in the Control. It was assumed that this indicated the onset of a familiar pattern observed under conditions without P limitation (Periods 3.3.1 to 3.3.6 - see section 4.3.1 above), in which iron dosing always produced a *net* greater system P removal in the Test unit, relative to the Control.

The results in Figs. 4.16 (a, b) have important implications for the operation of full-scale plants with simultaneous chemical precipitation. Using a large pilot plant (inflow ca. 82 m^3/d), operated under real conditions to achieve low effluent P concentrations, Aspegren (1995) made similar observations to those described in sections 4.3.11 and 4.3.12 above, namely that a relatively high iron dose in the influent has the effect of increasing the chemical (metal phosphate) fraction of the sludge, but *decreasing the bio-P fraction*[16]. If it assumed that precipitation with metal precipitant renders part of the system P unavailable to the bio-P mechanism, it seems logical that a sudden increase in P concentration following low (limiting) P conditions will lead to lower numbers of bio-P bacteria and weakened overall P removal (or no net gain in P removal *potential*) in the system which is metal dosed. Since the objective of real, full-scale applications is usually to achieve effluent ortho P concentrations of < 0.5 mgP/ℓ, these systems must basically be operated under P-limiting conditions (Aspegren, 1995). Under P limiting conditions, some additional metal hydroxide accumulation in the system may be expected, but it is most likely that chemical P precipitation will be kinetically favoured over the biological enhanced P removal (BEPR) mechanism. If precipitation with metal ions has replaced the BEPR operation for prolonged periods where the secondary effluent was < 0.5 mgP/ℓ (approximately), it may not be possible to shift from the chemical mechanism to the BEPR mechanism without experiencing an increase in effluent P concentrations during the time when the bio-P population increases in number (Aspegren, 1995). That is, the "lost" (diminished) BEPR potential cannot be instantaneously re-established when P limitation is lifted, and the "spare" chemical removal capacity in the form of metal hydroxide accumulation (the so-called "persistence effect" described by Rabinowitz and Marais, 1980) is not sufficient to make up the difference. It follows that the operation of simultaneous precipitation-BEPR processes may be difficult to control in order to achieve consistently low effluent P concentrations (Aspegren, 1995). This appears to support the overall full-scale experience reported by Lötter (1991), and may also partly explain the failure of either alum dosing or iron (ferrous-ferric chloride) to achieve full compliance with the 1 mgP/ℓ ortho P standard at Darvill WWW (see section 3.4 of Chapter 3, and section 6.4 of Chapter 6).

Partial loss (depression) of the BEPR mechanism in the presence of simultaneous metal salt dosing under real operating (low effluent P) conditions implies that the biological P removal potential is not being fully utilised in combined chemical-biological P removal activated sludge systems. For maximal benefit from investment in bio-P removal technology, it implies that chemical dosing should be applied in either the primary (pre-precipitation) or tertiary (post-

[16] Aspegren (1995) measured bio-p activity by means of an anaerobic batch P release test in the presence of acetate. In order to circumvent the possible problem that some of the biologically released P may be trapped in the sludge by precipitation from "surplus" metal ions (i.e. metal hydroxide or equivalent) (c.f. sections 4.3.11.1 and 4.3.11.2 discussion of fractionation results after a similar test applied in this study), Aspegren (1995) estimated bio-P release from measured release of potassium (K^+) ions and assuming a constant P:K ratio during release.

precipitation) stages, rather than the secondary stage (simultaneous precipitation with activated sludge). Simultaneous precipitation does have the initial benefit of increasing the system P removal over that achieved by biological means alone. If the system does not become phosphorus limited (e.g. metal doses are kept fairly low and effluent ortho P concentrations remain approx. >0.5 mgP/ℓ), then it is likely that a *net* benefit from chemical addition will continue to be observed indefinitely. Apart from the net benefit of greater system P removal, compared to a Control system without metal addition, the accumulation to a degree of metal hydroxide (depending partly on effluent P concentrations) will be a further benefit in terms of acting as a "buffer" with "spare" P precipitation capacity to absorb cyclic variations in influent P load. However, if the system becomes phosphorus-limited for extended periods, the numbers of bio-P bacteria (PAOs) will decline to a greater extent with simultaneous chemical precipitation than without. With weakened BEPR, the danger exists that the plant will fall into an operational regime where, with variations in influent P load, the effluent P concentrations increase (perhaps only a little, but exceeding the required standard), causing the operators to add more chemical precipitant, thereby further exacerbating the problem. The tertiary (post-precipitation) alternative is potentially the most expensive since additional clarifier/ filter infrastructure is required. The primary (pre-precipitation) alternative may be the better option. However, in order to achieve optimal performance, chemical dosing at the primary stage will need to be flow-proportional (or preferably load-proportional) since the benefit of metal hydroxide accumulation with the recirculation of sludge (as in the activated sludge process) may not be practical for the primary sedimentation tanks and the "buffer" effect from accumulated metal hydroxide in the system will not be present. Moreover, if the economic benefit of BEPR activated sludge systems is to be realised, the danger of over-dosing at the primary stage (pre-precipitation) also needs to be avoided since limiting P concentrations to the activated sludge plant (and possibly even carryover of soluble metal in the settled sewage, or primary effluent) can still result in "inhibition" (depression) of the bio-P mechanism, as demonstrated by Aspegren (1995).

University of Cape Town

4.4 CONCLUSIONS

1. In the absence of phosphate limitation, pilot plant operational results over a period equivalent to approximately 12 sludge ages, as well as chemical fractionation results, suggest that interference in the biological P removal mechanism as a result of ferric chloride dosing is detectable but not severe. In these experimental periods, excess phosphate was added to the influent of the pilot plants and effluent phosphate concentrations always exceeded approximately 10 mgP/ℓ. The following conclusions were drawn from these periods:

   - A net improvement in P removal was virtually always found in the Test unit (ferric dosed), compared to the Control. At times the additional system P removal approached the 1:1 molar amount expected from the formation of $FePO_4$. On average, the additional system P removal was approximately 0.75 mol $P_{removed}$ per mol Fe $_{dosed}$.

   - The ratio of additional system P removal (in the presence of metal addition) to metal dosed is a measure of the overall "precipitation efficiency" since it includes the effect of potential inhibition of the biological P removal mechanism. However, the molar ratio of additional $P_{removed}$: Fe $_{dosed}$ cannot be regarded as a reliable measure of the stoichiometry of precipitation *per se*. In this study, an estimate of the stoichiometry of precipitation was obtained from phosphorus fractionation data in which the metal phosphate precipitate is expected to be solubilised from the mixed liquor solids as ortho P in the by (cold) perchloric acid (PCA) fraction. These data suggested that the stoichiometry of the precipitate was closer to 0.62 mol P/ mol Fe.

   - The ortho P content of the PCA fraction, when expressed as the ideal precipitate ($FePO_4$), did not always account for the all the $FePO_4$ predicted by the IAWQ model No. 2 (refer to Chapter 7). In several cases, the PCA ortho P fraction only accounted for about two-thirds of the iron phosphate predicted by the IAWQ model. Bearing in mind that the IAWQ model assumes that the biological and chemical mechanisms operate independently of each other (i.e. that no inhibition of the biological mechanism occurs), it appears that a significant component of the chemical P removal occurs in the form of a precipitate which is not extracted as (reactive) ortho P in the cold PCA fraction. It is hypothesised that this observation arises from phosphate removed though the PO_4^{3-}/ OH^- ion exchange mechanism with ferric hydroxide, as proposed by Rabinowitz and Marais (1980). It is likely that this ferric hydroxide/ ferric hydroxy-phosphate precipitate is largely amorphous or colloidal in nature, and that a close association forms between this precipitate and one or more macromolecules of the biomass (e.g. extracellular polysaccharides or proteins). It is proposed that this association prevents this chemical phosphate fraction (at least in part) from being extractable as reactive ortho P in the fractionation method applied here.

   - When comparing the system P removal as an indication of overall "precipitation efficiency" per unit iron dosed (on a molar ratio basis), it appears that precipitation is more efficient at a sludge age of 20 days than at 10 days. At a sludge age of 20 days, the precipitation appeared to have a efficiency close to the theoretical stoichiometry for precipitation of $FePO_4$ when dosing to the aerobic zone, whereas at 10 days, the efficiency was approximately half-stoichiometric for dosing to the same point. This appears to confirm the ferric hydroxide co-precipitation hypothesis of Rabinowitz and Marais (1980) since the PO_4^{3-}/ OH^- ion exchange reaction may be slow in relation to the direct precipitation of iron phosphate, but with the longer solids retention time (longer sludge age), the ion exchange process may reach completion.

   - Ferric chloride dosing to the anaerobic zone appears to be produce a "precipitation efficiency" which is about 20% less than that for dosing to the aerobic zone (i.e. an efficiency of approximately 0.8 mol P/ mol Fe at a 20 d sludge age, and 0.4 mol P/ mol Fe at a 10 d sludge age). It was suggested that complexation of iron by soluble organic molecules arising from the influent would be more likely in the anaerobic zone and could account for the lower precipitation efficiency toward phosphate.

   - In terms of the biological P removal mechanism, average P release in the anaerobic zone of the Test unit (ferric dosed) was depressed by between 3 and 21% (11% on average), compared to the Control, even when using a high dose of ferric chloride to the anaerobic

zone directly. Protracted iron dosing appeared to increase the degree of inhibition of P release.

- Fractionation studies showed that it appears to be invalid to measure the relative contribution of the biological P removal mechanism on the basis of the size of the acid-extractable complex P (or poly P) fraction alone, particularly when dosing large amounts of ferric salt. Fractionation studies showed that ferric ions appear to decrease the size of the complex P fraction which is extractable into PCA, and increase the size of the fraction which is extractable into sodium hydroxide (NaOH) at room temperature. Both the PCA and NaOH fractions are biologically active, as evidenced by their contributions to P release under anaerobic conditions in the presence of excess acetate. This suggests that both represent significant portions of the poly P in the biomass. However, the relative distribution of poly P between these fractions may be of little significance since it appears to be an artefact of the fractionation procedure and depends heavily on the concentration of iron in the mixed liquor solids during extraction with PCA (c.f. Chapter 2, section 2.4.7).
- Partial inhibition of the biological P removal mechanism was found from fractionation studies, even in the absence of P limitation. However, the sum of the acid-extractable and alkaline-extractable complex P (or poly P) fractions in the biomass from the Test unit (with ferric dosing) was never depressed by more than an estimated 17%, relative to the Control and in some cases was greater in the Test unit than the Control[17]. When added to the increased fraction attributed to chemical origin (acid-extractable ortho P), the mixed liquor of the Test unit always contained more total phosphate than that of the Control. This is in agreement with the observation of greater system total P removal in the Test unit with simultaneous ferric chloride addition.
- Anaerobic P release batch tests (with excess acetate) suggested that the biological mechanism in the Test unit was depressed approximately 7 to 15%; on the same basis, in one test, the biological mechanism may not depressed and may even have been slightly stronger in the Test unit, compared to the Control.

2. In the presence of phosphate limitation over a period of equivalent to fifteen sludges, the Control unit achieved virtually complete P removal by biological means alone. The Test unit which was dosed with ferric chloride at a constant dose of 10 mg/ℓ as Fe to the first aerobic reactor, also achieved virtually complete P removal. Fractionation data showed that the extent of depression of the biological mechanism in the Test unit (relative to the Control) was greater (about 30 to 35%) under P limiting conditions, compared to non-P-limiting conditions[18]. However, the P:Fe stoichiometry estimated from fractionation data was also approximately 33% lower under P limiting conditions, compared to non-P-limiting conditions. It was concluded that both the biological and chemical P removal mechanisms are "disadvantaged" to approximately the same degree under P-limiting conditions. However, the chemical precipitation mechanism does limit the extent to which the biological P removal *potential* can be utilised by removing part of the soluble phosphate fed to the system. This was evident from a small but significant shift in the relative proportions of the biological and chemical sludge P fractions, as well as the smaller magnitude of the biological fractions in general under P-limiting conditions. The disadvantage of a depressed bio-P removal mechanism became obvious when P limitation was removed by adding phosphate to the influent: P removal was initially slightly *weaker* in the Test system than in the Control system, in spite of a constant iron dose to the Test unit. After approximately one sludge age, P removal in the Test system recovered and began to exceed that of the Control. This was interpreted as indicating that "inhibition" or depression of the bio-P mechanism under P limiting conditions in the presence of simultaneous precipitation is probably due to a decrease in the numbers of poly-P accumulating organisms (PAOs) in the system. These numbers increase (or "recover") over a

[17] When expressed on a mgP/gVSS basis, the fractionation results may be influenced to a limited extent by the slightly higher VSS production in the Test system (see point 9 of this section). However, close inspection of the fractionation data (Table 4.9a) shows that, even when the results are expressed on a volume (mgP/ℓ) basis, 3 to 20% inhibition of the biological fractions was found in the Test unit with alum dosing, relative to the Control.

[18] As noted in the previous footnote, differences in VSS could influence interpretation of the fractionation results when expressed on a mgP/gVSS basis. However, even when expressed on volume (mg/ℓ) basis for these periods (Table 4.15), the percentage inhibition of the biological fractions in the Test unit vs. the Control was still significant (22 to 29%).

period of several days when P limitation is removed and the biological P removal potential is more fully utilised.

3. The greater degree of inhibition of the biological P removal mechanism under low P conditions has important implications for the operation of simultaneous precipitation-BEPR activated sludge systems. In order to consistently achieve low effluent P concentrations (e.g. <0.5 mgP/ℓ), such systems must basically be P-limited. However, depression of the bio-P mechanism due to the addition of chemical precipitant, implies the BEPR potential is not being optimally utilised, which in turn diminishes the economic value of investment in BEPR technology. Furthermore, the combined chemical-biological system may be more susceptible to transient increases in effluent P concentration under real conditions of varying influent P load since it will not be possible for the system to develop stronger bio-P removal rapidly (i.e. within < 1 day) because the processes are growth-dependent. The temptation on the part of the operator will be to increase the chemical dose to compensate for the failure of the system to rapidly exhibit its BEPR potential. The increased chemical dose may produce lower effluent P concentrations but will further depress the bio-P removal mechanism, thus setting up a counter-productive sequence of events.

4. The "loss" of BEPR potential in the presence of chemical dosing, suggests that primary or tertiary dosing (i.e. pre or post-precipitation processes respectively) should be favoured over secondary (simultaneous) precipitation in designs where BEPR alone is not considered capable of meeting the required effluent P standard. Tertiary dosing systems have the disadvantage of requiring additional capital infrastructure in the form for solids-liquid separation. Primary dosing systems have the advantage that primary settling tanks could serve this purpose. However, careful control of dosing will nevertheless be required to prevent over-dosing since an equivalent effect of P-limitation of the downstream activated sludge BEPR processes could result almost as easily with primary dosing as with simultaneous (secondary) dosing.

5. Conversely, the longer solids retention time and advantage of sludge recirculation in the activated sludge process may make it possible to achieve more efficient P precipitation (higher P:Fe stoichiometry) with simultaneous (secondary) than with the primary precipitation systems, which usually lack sludge recirculation. Accumulation of metal hydroxide in the mixed liquor, particularly under P-limiting conditions, may help to buffer (reduce) the increase in effluent P concentrations under conditions of varying load. In the experimental system used here with sustained high influent P concentrations following after a long period of P limitation, this "reserve" chemical adsorption/ precipitation capacity was not sufficient to compensate completely for the loss of bio-P removal capacity. However, for a given system, smaller variations in influent P load may be effectively absorbed by the combined chemical-biological system. There is limited evidence to suggest that the biological and chemical removal mechanisms interact to some extent in that a minor P fraction may "migrate" from the PAO cells to chemical adsorption sites (e.g. on ferric hydroxide colloid) during P release under anaerobic conditions; presumably, desorption occurs at low soluble P concentrations during aerobic P uptake by the cells. A degree of exchange of phosphate ions between the chemical and biological mechanisms in this manner may partly explain how the bio-P mechanism is able to compete almost as effectively with the chemical precipitation mechanism under P limiting conditions as under non-P-limiting conditions. Adsorption/ desorption (or transient "entrapment") of phosphate in ferric hydroxide colloid at or near the active sites for biological P release and uptake may also explain why mass balance considerations of P release in the anaerobic reactor of the Test vs. Control unit apparently over-estimated the degree of depression of the bio-P mechanism, when compared to fractionation studies. Certainly, the physical location of colloidal ferric hydroxide (or ferric hydroxy-phosphate) in close proximity to cell membranes or possibly even bound to microfibrils of biological origin has been observed by electron microscopy (He *et al.*, 1996). Similarly, the storage of polyphosphate in the periplasmic space between inner and outer cell membranes has been found for *Acinetobacter* (Halvorsan *et al.*, 1987), and good evidence has been reported for the location polyphosphatases (enzymes involved in the breakdown of polyphosphate) either close to or outside the cell membrane and complexed to the cell wall with metal cations (Hill *et al.*, 1989).

6. Concerning the effect of pH and alkalinity, ferric dosing did not appear to be very sensitive to pH changes in the range of approximately pH 7.0 to 7.7 at the point of dosing, nor to changes in effluent bicarbonate alkalinity in the range approximately 70 to 250 mg/ℓ as $CaCO_3$. Under realistic (i.e. low effluent P) conditions, a drop in aerobic reactor pH at the point of iron dosing from median pH 7.4 to 7.0 did not significantly change the stoichiometry of precipitation estimated from fractionation results. It would appear that a residual effluent alkalinity of approx. (75 to) 100 mg/ℓ $CaCO_3$ (Table 4.14, R1) is adequate for sustaining stable operation of a BEPR activated sludge system in the presence of simultaneous iron (ferric chloride) dosing.

7. Bicarbonate alkalinity consumption due to chemical dosing (based on the difference in effluent bicarbonate alkalinity between the Test and the Control units) was approximately 0.7 mg as $CaCO_3$ / mg as $FeCl_3$ dosed (or approx. 2.3 mol Alk./ mol Fe dosed), which is lower than the theoretical value of 0.93 mg as $CaCO_3$ / mg as $FeCl_3$ dosed on same basis for the precipitation of pure $Fe(OH)_3$ (Loewenthal *et al.*, 1986). This suggests that the iron precipitate which formed involved fewer than 3 mol OH/ mol Fe. Using the observed alkalinity changes and fractionation data an estimate of the average formula for precipitation without P limitation was:

$$Fe_{1.66}\ (X^{2+})\ PO_4\ (OH)_4$$

where X^{2+} is some unknown (possibly divalent) cation (e.g. Mg^{2+} or Ca^{2+}) (c.f. Arvin, 1985)[19]. This is the same as the average formula found in Chapter 3 for alum and compares with the following general formula used by Luedecke et al. (1989) and Briggs (1996):

$$Fe_rPO_4\ (OH)_{(3r-3)}$$

which will predict less alkalinity loss per mol Fe. Nevertheless, Luedecke *et al.* (1989) reported values for r in the range approximately 1 to 2 mol Fe/mol P for residual phosphate concentrations of approx. 1 to 5 mgP/ℓ which are consistent with the stoichiometry observed in this study for non P-limiting conditions.

Under P limiting conditions, the average P:Fe stoichiometry estimated from fractionation data was in the range 0.32 to 0.46 mol P/ mol Fe. The bicarbonate alkalinity consumption due to precipitation was approx. 3 mol Alk./ mol Fe for these periods. This implies that the average formula for ferric hydroxy phosphate formed under these conditions could lie in the following approximate range:

$$Fe_3\ (X^{2+})\ PO4\ (OH)_8 \text{ to } Fe_{2.2}\ (X^{2+})\ PO4\ (OH)_7\ .$$

Although differing from the point of view of alkalinity consumption, this range of general formulae for precipitate is in agreement with the results of Luedecke *et al.* (1989) who proposed a model precipitate formula of $Fe_{2.5}\ PO_4\ (OH)_{4.5}$ at low residual phosphate concentrations (ca. 0.1 to 0.4 mgP/ℓ at pH 7.2).

8. Settling (and turbidity) problems were sometimes experienced during periods of ferric chloride dosing to the pilot plant Test unit, but mainly where effluent P was *not* limiting. These problems appeared to be due to pin floc sludge formation resulting in a reduced (unstirred) zone settling velocity but apparently good DSVIs. The effect may be positive in terms of DSVI but may be negative in other respects (e.g. floc disruption, formation of a turbid effluent due to large numbers of free bacteria, and a low zone settling velocity). The nature of the effect of iron on floc structure and composition was not investigated. The fact that the observed effects were differed between experimental periods (e.g. with and without P limitation) suggests that population dynamics are important in this regard.

9. Sludge production was greater in the Test unit, with ferric chloride dosing. Minor increases were noted in VSS production (ca. 3 to 14%), particularly during periods with P-limitation. These changes suggest that iron (or iron hydroxide) affects the coagulation/ biodegradation mechanism of activated sludge toward organic material. Most probably, the iron forms complexes with a minor fraction of the colloidal (particulate) influent COD, rendering it unbiodegradable, but retaining it in enmeshed/ adsorbed form in the mixed liquor and, hence,

[19] Note: if H^+ is used to substitute for X^{2+}, then these protons removed from solution would represent a gain in alkalinity.

contributing additional VSS. Significant increases in TSS were observed, as expected, due to the additional ISS contributed by chemical precipitate. The observed increase in ISS could be approximately estimated (to within 10% of the TSS in the Test unit) on the basis of the precipitation stoichiometry observed from differences in system P removal between the Test and Control unit. The biggest constraint in this regard was the apparent failure to observe steady-state behaviour with respect to solids concentration. This is partly due to the inherent slowness with which the inert solids attain equilibrium in activated sludge systems, particularly at long sludges ages, and partly due to variation in the sewage composition used during this study.

REFERENCES

Arvin, E. (1985) Biological removal of phosphorus from wastewater. *CRC Critical Reviews in Environmental Control* 15, 25 - 64.

Aspegren, H. (1995) *Evaluation of a high loaded activated sludge process for biological phosphorus removal.* Ph.D. Thesis, Dept. of Water and Environmental Engineering, Lund University of Technology, Lund, Sweden.

Barker, PS and Dold, PL. (1995) COD and nitrogen mass balances in activated sludge systems. *Water Res.*, 29, 633.

Briggs, TA. (1996) *Dynamic modelling of chemical phosphorus removal in the activated sludge process.* M. Eng. Thesis, School of Graduate Studies, McMaster University, Hamilton, Ontario, Canada.

Brown, MJ and Lester, JN. (1979) Metal removal in activated sludge: the role of bacterial extracellular polymers. *Water Res.*, 13, 817-837.

De Haas, DW. (1989) Chemical fractionation of activated sludge with special reference to enhanced biological phosphate removal. MSc. Thesis, Dept. of Biochemistry, Rand Afrikaans University, Johannesburg., November 1989.

De Haas, DW and Greben, HA. (1991) Phosphorus fractionation of activated sludges from modified Bardenpho processes with and without chemical precipitant supplementation. *Water Sci. Technol.* 23 (Kyoto), 623-633.

Fleit, E. (1995) Intracellular pH regulation in biological excess phosphorus removal systems. *Water Res.*, 29 (7), 1787-1792.

Halvorsan, HO, Suresh, N, Roberts, MF, Coccia, M and Chikarmane, HM. (1987) Metabolically active surface polyphosphate pool in *Acinetobacter lwoffi*., *In: Phosphate Metabolism and Cellular Regulation in Microorganisms,* (Torriani-Gorini, A, Rothman, H, Silver, S, Wright, A and Yagil, E, eds.). American Soc. for Microbiology, Washington DC, 220-224.

He, QH, Leppard, G, Paige, CR and Snodgrass, WJ. (1996) Transmission electron microscopy of a phosphate effect on the colloid structure of iron hydroxide. *Water. Res.*, 30 (6), 1345-1352.

Henze, M, Harremoës, P, Jansen, J la Clour, and Arvin, E. (1992) Spildevandsrensning. Biologsik og kemisk (2nd edition). Polyteknisk Forlag, Lyngby, Denmark. (In Danish, cited by Aspegren, 1995, see above).

Hill, WE, Benefield, LD and Jing, SR. (1989) ^{31}P-NMR spectroscopy characterization of polyphosphates in activated sludge exhibiting enhanced phosphorus removal. *Water Res.*, 23 (9), 1177-1181.

Loewenthal, RE Wiechers, HNS and Marais, GvR. (1986) *Softening and stabilization of municipal waters*. Water Research Commission, Pretoria, June 1986.

Lötter, LH. (1991) Combined chemical and biological removal in activated sludge plants. *Water Sci. Technol.*, 23 (Kyoto), 611-621.

Luedecke, C, Hermanowicz, SH and Jenkins, D. (1989) Precipitation of ferric phosphate in activated sludge: a chemical model and its verification. *Water Sci. Technol.* 21 (Brighton), 325-327.

Mamais, D, Jenkins MC and Pitt, P. (1993) A rapid physical-chemical method for the determination of readily biodegradable COD in municipal wastewater. *Water Res.* 27 (1), 195-197.

University of Cape Town

Moosbrugger, RE, Wentzel, MC, Ekama, GA and Marais, GvR (1993) Simple Titration Procedures To Determine H2CO3* Alkalinity And Short-Chain Fatty Acids In Aqueous Solutions Containing Known Concentrations Of Ammonium, Phosphate And Sulphide Weak Acid/Bases. Report TT 57/92, Water Research Commission, Pretoria.

Munro, HN and Fleck, A (1966) The determination of nucleic acids. In: *Methods of Biochemical Analysis*. (Glick, D. ed.) Interscience, New York, 113-1785.

Ozinsky, AE and Ekama, GA. (1995) Secondary settling tank modelling and design. Part 2: Linking sludge settleability measures. *Water SA* 21 (4), 333-350.

Röske, I and Schönborn, C. (1994) Influence of the addition of precipitants on the biological phosphorus elimination in a pilot plant. *Water Sci. Technol.,* 30 (6), 323-332.

Rabinowitz, B and Marais GvR. (1980) Chemical and biological phosphorus removal in the activated sludge process. Research Report W32, Dept. of Civil Engineering, University of Cape Town, Rondebosch, Cape Town, South Africa.

Randall , EW, Wilkinson, A and Ekama, GA. (1991) An instrument for the direct determination of oxygen utilisation rate. *Water SA* 17 (1), 11-18.

Slatter, NP and Alborough, H (1990) Chemical oxygen demand using microwave digestion: A tentative new method. *Water SA* 18 (3), 145-148.

Standard Methods for the Examination of Water and Wastewater (16th edn.) (1985). American Public Health Association, Washington DC.

Streichan, M and Schön, G. (1991) Periplasmic and intracytoplasmic polyphosphate and easily washable phosphate in pure cultures of sewage bacteria. *Water Res.,* 25 (1), 9-13.

Wentzel, MC, Ekama, GA, Loewenthal, RE, Dold, PL and Marais, GvR. (1989) Enhanced polyphosphate organism cultures in activated sludge systems. Part II: Experimental behaviour. *Water SA* 15 (2), 71-88.

Wiechers, HNS (ed.). (1987) *Guidelines for chemical phosphate removal from municipal waste waters.* Collaborative publication compiled by staff of the Town Council of Boksburg, City Council of Pretoria, National Institute of Water Research and the Water Research Commission. Water Research Commission, Pretoria, January, 1987.

Wuhrmann, K. (1968) Objective, technology and results of nitrogen and phosphorus removal processes., *Adv. Water Quality Improvement,* University of Texas Press, p21. *cited by* : Jenkins, D. Ferguson, JF and Menar, AB. (1971) Chemical processes for phosphate removal. *Water Res.,* 5, 369-389.

University of Cape Town

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting biological enhanced phosphate removal.

Chapter 5

Ferrous-ferric chloride blend dosing to pilot plants

DW de Haas

CHAPTER FIVE

FERROUS - FERRIC CHLORIDE BLEND DOSING TO PILOT PLANTS

5.1 INTRODUCTION

A major supplier of industrial chemicals for water and waste water treatment in South Africa (*NCP Ultrafloc*) manufactures ferric chloride by dissolving iron (including scrap iron) in hydrochloric acid to give a solution of mainly ferrous chloride, followed by oxidation of the ferrous ions to ferric ions using chlorine (Leopold, 1996). The option exists of removing a fraction of the ferrous chloride solution for commercial sale *prior* to the oxidation step. Work carried out by the Johannesburg City Council (Lötter, 1991) had demonstrated the value of *ferrous* (iron [II]) sulphate for simultaneous phosphate precipitation in nutrient removal plants, although the mechanism for the superior performance compared to *ferric* (iron [III]) chloride could not be explained. Subsequently, many of the Johannesburg biological nutrient removal activated sludge plants have been converted to *ferrous* chloride dosing (Leopold, 1996).

A review of the literature revealed that oxidation of ferrous ions to ferric ions may be expected under aerobic conditions in an activated sludge plant (Chapter 1). The theoretical oxygen demand for this reaction is small, namely 0.125 g O_2/ g Fe^{2+} [(1)]. From the requisite supplementary P removal, the required iron doses would also be small (e.g. 5 to 10 mg/ℓ as Fe). This implies that the aeration capacity for the iron oxidation would be negligible compared to that required for carbonaceous removal and nitrification in an activated sludge plant.

In view of the above, and the experiments with ferric chloride at pilot-scale (Chapter 4), it was decided to extend the study to cover a commercially available product comprising a blend of ferrous chloride and ferric chloride (manufactured by *NCP Ultrafloc*), in which approximately 90% of the total iron content is in the ferrous form, and the remainder in the ferric form (Reynolds, 1996). Preliminary work with the ferrous-ferric chloride blend (see Chapter 4, section 4.3.10) had indicated that significantly better settling could be expected in the pilot plants with this product compared to ferric chloride.

5.2 MATERIALS AND METHODS

5.2.1 Pilot plants

Two identical pilot plant units (R1 and R2) were set up and operated in the same manner as described in Chapter 3.

5.2.2 Feed supplementation for enhanced cultures

Experiments with the ferrous-ferric chloride blend commenced in early December 1995 and followed directly on from the last ferric chloride dosing period (i.e. from Period 3.3.6, which ended on 3/12/95 - see Table 1.2, Chapter 2 for overview of the experimental periods and refer to Chapter 4 for discussion of the ferric chloride dosing periods). A ten day transition period (one sludge age) was allowed before data collection for the blend was started on 13/12/95. There was therefore no need to re-develop enhanced cultures *de nova* as described in Chapter 3.

---

[1] Yeoman *et al.* (1988) quoted an oxygen demand of 0.15 g O_2/ g Fe^{2+} from Singer (1970), stating that the oxygen demand is high and can cause operational problems. Taking the case of Darvill WWW, with an average daily flow of 60 Ml/d, a typical maximum (dry weather) influent COD of 350 mgO_2/ℓ and TKN of 42 mgN/ℓ, at summer temperatures (ca. 22°C), the average total oxygen demand will not exceed approx. 21 400 kg O_2/d, excluding any oxygen "recovery" from denitrification (WRC, 1984). Assuming an additional 3 mgP/ℓ removal is required by dosing hypothetically pure ferrous chloride, and that a molar ratio of 2 mol Fe/ mol P suffices, then the daily iron dose will be approx. 650 kg Fe/d. The oxygen demand for oxidation of the ferrous ions to ferric form will then be approx. 98 kg O_2/d, which is about 0.5% of the total biological oxygen demand in the system. This is a negligible contribution.

Table 5.1 gives the composition of sewage supplements for the experimental periods relevant to this chapter. Each sewage batch (160 ℓ) was augmented with the following constituents:

- sodium acetate (e.g. 150 mg/ℓ as COD or 30.8 g anhydrous sodium acetate per 160 ℓ batch);
- orthophosphate (e.g. 40 mgP/ℓ as K_2HPO_4 or 80 mℓ of a concentrated stock solution containing 450 g/ℓ K_2HPO_4 per 160 ℓ batch);
- magnesium chloride (constant 84 mg Mg per g COD as acetate added e.g. for 12.6 mg Mg/ℓ required 90 mℓ of a concentrated stock solution containing 189.7 g/ℓ of $MgCl_2.6H_2O$ per 160 ℓ batch);
- sodium bicarbonate for alkalinity (usually 100 mg/ℓ as $CaCO_3$ or 26.9 g of $NaHCO_3$ per 160 ℓ batch).

From Table 5.1 it can be seen that for the first three ferrous-ferric chloride dosing periods, the influent composition was not changed from that used in the ferric chloride and alum dosing periods (Chapters 3 and 4). The acetate feed concentration was kept constant at 150 mg/ℓ as COD, as was magnesium, potassium, phosphate and alkalinity supplementation (Table 5.1). Hence the only variation in respect of the influent composition during the experimental ferrous-ferric dosing periods (Periods 3.4.1 to 3.4.3) was that of the settled sewage abstracted from the full-scale Works.

During Period 3.4.4, the effect of reducing the added influent P (and K) concentration was tested, while the acetate concentration added was left unchanged (at 150 mg/ℓ as COD). This had the effect of allowing the "semi-enhanced" cultures to function under conditions in which the effluent P concentrations became limiting (<2 mgP/ℓ as TP). In this way, the relative performance of the competing biological and chemical P removal mechanisms could be examined.

During Periods 3.5.1 and 3.5.2, an attempt was made to operate the pilot plants with an influent composition which closely resembled that of the full-scale activated plant at Darvill WWW. Hence the amount of added acetate was reduced to 20 mg/ℓ as COD [2], and no phosphate (nor potassium) addition. In order to eliminate the possibility of influent magnesium limiting biological P removal (Lindrea *et al.*, 1993), a constant magnesium supplement was supplied though all the experimental periods (Table 5.1). Similarly, the alkalinity supplement was held constant throughout all the experimental periods (Table 5.1). Supplemental influent alkalinity had been found to be an important factor in establishing stable P removal in the pilot plants (refer to Chapter 3, sections 3.3.2 and 3.3.3.3)

Table 5.1: Sewage supplement composition by experimental period.
(Refer to Table 5.3 for relevant ferrous-ferric chloride blend dose, acid dose and sludge age).

Period Date range	Na-acetate mg/ℓ as COD	K_2HPO_4 mgP/ℓ	$MgCl_2$ mg Mg/ℓ	K_2HPO_4 mg K/ℓ	$NaHCO_3$ mg/ℓ as $CaCO_3$
3.4.1 (Ferrous-ferric) 13/12/95 to 13/1/96	150	40	12.6	100	100
3.4.2 (Ferrous-ferric) 15/1/96 to 17/2/96	150	40	12.6	100	100
3.4.3 (Ferrous-ferric) 18/2/96 to 18/3/96	150	40	12.6	100	100
3.4.4 (Ferrous-ferric) 1/4/96 to 10/6/96	150	15	12.6	38	100
3.5.1 (Ferrous- ferric) 11/6/96 to 26/7/96	20	0	12.6	0	100
3.5.2 (Ferrous- ferric) 27/7/96 to 27/8/96	20	0	12.6	0	100

[2] Based on the expected dilution of a primary supernatant "side stream" (ca. 1.7 Mℓ/d, containing a maximum of 700 mg/ℓ COD as volatile fatty acid, into the average dry weather flow of the full-scale plant (ca. 60 Mℓ/d).

5.2.3 Ferrous-ferric chloride and acid dosing

Ferrous-ferric chloride is supplied commercially by *NCP Ultrafloc* as a blend containing 12 to 14 % m/m total Fe, of which a *minimum* of 60% is guaranteed to be in the form of ferrous ions. In practice, the product ranges 85 to 95% Fe [II] (Reynolds, 1996). Like ferric chloride, the product contains approx. 0.5 to 1.0 % free HCl.

For the experimental periods described in this chapter, two batches of ferrous-ferric chloride blend were used[3]. Upon analysis by atomic absorption spectrometry, the first was found to contain 13.3 % m/m total Fe, and had an S.G. of 1.30 kg/ℓ, while the second contained 12.4 % m/m total Fe and had an S.G. of 1.32 kg/ℓ. A suitable stock solution (80 to 85 mℓ per ℓ) of this product was prepared using deionised water containing approximately 0.04M hydrochloric acid (to ensure that the solution remained acidic and the oxidation of ferrous ions to ferric ions was retarded). This stock solution lasted for approximately one month, with one aliquot of 25 mℓ/d supplying 6.2 mmol Fe/d and approx. 0.5 mmol/d as HCl to the pilot plant Test unit (R1).

A dilute solution of chemical precipitant was prepared from the stock solution according to Table 5.2. The daily aliquot (25 mℓ) was dosed into the anaerobic (AN) or first aerobic (AE1) zone of the Test reactor (R1) at the rate of 500 mℓ/d, after further dilution with tap water. For consistency with earlier work (Chapters 3 and 4) a small amount of acid was added in the diluted solutions of ferrous-ferric solution dosed. For this reason, 10 mmol/d of HCl was added to the diluted solution of precipitant dosed to R1, and the same amount of acid was fed with tap water only to R2, also at a rate of 500 ml/d. An acid dose of 10 mmol/d as HCl is equivalent to 14 mg/ℓ as HCl, based on an influent flow rate of 36 ℓ/d. This was considered small in relation to an influent alkalinity supplement of 100 mg/ℓ as $CaCO_3$. However, it was subsequently found, that the supply of 0.02M HCl in the first dilution of ferrous blend (see above) was sufficient to prevent precipitation of iron hydroxide upon further dilution to 500 mℓ and was equivalent to an acid dose of ≤1 mmol/d (or ≤1.4 mg/ℓ as $CaCO_3$, which was negligible). Accordingly, the dosing of additional acid (10 mmol/d) to both Test and Control units was stopped in period 3.4.4 (see Table 5.3).

Table 5.3 gives the actual dosage rates applied for the respective experimental periods. Assuming a molar ratio of 0.5 mol $P_{removed}$/ mol Fe_{dosed} in the precipitation reaction, a dose of 6.2 mmol Fe/d or 12.4 mmol Fe/d translates into an expected additional P removal of 2.7 and 5.4 mgP/ℓ respectively at an influent flow rate of 36 ℓ/d. As with alum and ferric chloride dosing (Chapters 3 and 4), this appeared to be a reasonable target for "low" and "high" iron dosage rates on the basis of full-scale operating experience at Darvill WWW.

Table 5.2: Ferrous-ferric chloride blend dosing protocol for Test unit (R1).

Chemical (Source)	% m/m S.G. (kg/ℓ)	First dilution for working stock	Daily feed Volume diluted to 500 mℓ/d with tap water	Expected dose based on Q_i (ℓ/d):	
Ferrous-ferric chloride 90% $FeCl_2$ 10% $FeCl_3$ Mean MW = 130 g/mol *(NCP Ultrafloc)*	13.3 % m/m as Fe 1.30 kg/ℓ [172.9 g/ℓ as Fe]	80 mℓ/ℓ [13.8 g/ℓ as Fe]	**25 mℓ (6.2 mmol/d Fe)** [346 mg/d Fe]	36 ℓ/d :	9.6 mg/ℓ as Fe
			50 mℓ (12.4 mmol/d Fe) [693 mg/d Fe)	36 ℓ/d :	19.2 mg/ℓ as Fe

[3] The ferrous-ferric chloride blend could not be stored for extended periods (> 4 months) because it was found that a precipitate formed in the concentrated stock solution. The composition of this precipitate was not determined, but its reddish-brown colour suggested that it was an oxide. By comparison, the ferric chloride solution was more stable and did not give a precipitate, even after storage under identical conditions for over a year.

Table 5.3: Experimental periods of ferrous-ferric chloride and acid dosing to the Test unit (R1).

Period name Date range	No. of days	Fe dose to R1 (Test) reactor (mmol/d as Fe)	Zone dosed with Fe/acid	Acid (HCl) dose (mmol/d)	Sludge age Rs (d)
3.4.1 High Fe 13/12/95 to 13/1/96	32	12.4	AE1	Yes: 10	10
3.4.2 Low Fe 15/1/96 to 17/2/96	34	6.2	AE1	Yes: 10	10
3.4.3 Low Fe 18/2/96 to 18/3/96	30	6.2	AN	Yes: 10	10
3.4.4 Low Fe 1/4/96 to 10/6/96	70	6.2	AE1	Yes: 0.5	10
3.5.1 Low Fe 11/6/96 to 26/7/96	46	6.2	AE1	Yes: 0.5	10
3.5.2 Low Fe 27/7/96 to 27/8/96	32	6.2	AN	Yes: 0.5	10

5.2.4 Parameters measured

All parameters measured were in accordance with Standard Methods (1985) or methods described in Chapter 2 or Appendices 1 through 4. The exceptions to this were: OUR, which was measured according to Randall *et al.* (1991); bicarbonate alkalinity, which was measured by a modified Gran titration procedure (Moosbrugger *et al.*, 1993); DSVI, which was measured according to Ekama and Marais (1984); and COD, which was measured by the open reflux and manual titration method in Standard Methods (1985). as well as a microwave digestion method followed automated potentiometric titration (Slatter and Alborough, 1990).

In summary, the parameters routinely measured were:

- COD (influent, effluents): see above
- TKN (influent, effluents): Appendix 1
- Total P (influent, effluents, mixed liquors, filtered AN, AX, AE1 and AE2 zones): Chapter 2 (2.2)
- Soluble reactive P , or SRP (effluents): Chapter 2 (2.3)
- Soluble ammonia (effluents): Appendix 1
- Soluble nitrate (effluents, filtered AN, AX, AE1, AE2 zones): Appendix 2a
- MLSS, VSS (mixed liquors): Standard Methods (1985)
- DSVI and zone settling velocity (mixed liquors): Ekama and Marais (1984)
- pH (in AN, AX, AE1, AE2 zones): Standard Methods (1985)
- OUR (AE2 zone): Randall *et al.* (1991)
- Total Mg (influent, effluents): Appendix 4
- Bicarbonate alkalinity : Moosbrugger et. al. (1993)

5.2.5 Chemical fractionation of sludge samples

Fractionation and P release batch tests was carried out according to the procedure described in Chapter 2 and summarised in Table 2.11 of that chapter.

Table 5.4: Pilot plant results for ferrous-ferric chloride dosing periods 3.4.1 to 3.5.2.

Results are averages with sample standard deviations in parentheses. N.D. = Not determined. See Appendix 8 for definition of symbols.

Period Unit	Sti mgO/ℓ	Ste mgO/ℓ	Nti mgN/ℓ	Nte mgN/ℓ	Nae mgN/ℓ	No3e mgN/ℓ	Pti mgP/ℓ	Pte mgP/ℓ	Δ Pt mgP/ℓ	P/VSS mgP /gVSS	TSS mg/ℓ	VSS mg/ℓ	% VSS	DSVI mℓ/g	fPt,a mgP/ℓ	fPt,d mgP/ℓ	fPt,b1 mgP/ℓ	fPt,b2 mgP/ℓ
3.4.1 R1	237 (53)	14 (6)	15.4 (4.8)	2.29 (0.55)	1.51 (1.47)	3.32 (0.86)	43.57 (2.74)	18.00 (3.54)	25.57 (4.45)	254.8 (134.1)	3475 (747)	1361 (329)	39.2 (4.5)	33 (13)	69.80 (11.23)	34.83 (6.17)	24.10 (3.51)	18.01 (2.70)
3.4.1 R2	237 (53)	16 (8)	15.4 (4.8)	2.14 (0.38)	1.12 (1.13)	2.78 (0.79)	43.57 (2.74)	25.80 (3.58)	17.77 (4.39)	248.83 (132.4)	2167 (598)	1135 (349)	52.1 (5.5)	76 (23)	78.77 (17.75)	45.83 (8.80)	33.55 (4.85)	26.83 (4.52)
3.4.2 R1	284 (59)	15 (5)	18.0 (5.0)	2.17 (0.58)	0.75 (0.57)	4.66 (2.19)	44.22 (2.99)	23.37 (3.59)	20.81 (4.26)	342.25 (99.03)	2070 (260)	999 (163)	48.5 (6.2)	48 (9)	82.30 (10.37)	42.44 (5.42)	30.52 (3.70)	22.64 (3.54)
3.4.2 R2	284 (59)	15 (4)	18.0 (5.0)	2.17 (0.60)	1.29 (3.14)	3.96 (1.98)	44.22 (2.99)	27.22 (5.30)	17.00 (4.73)	297.28 (49.33)	1735 (138)	892 (75)	51.5 (3.6)	83 (18)	88.46 (12.45)	45.50 (6.55)	33.98 (6.03)	25.82 (5.10)
3.4.3 R1	264 (69)	16 (2)	15.6 (3.5)	2.95 (1.80)	0.52 (0.11)	5.09 (0.85)	42.90 (2.98)	22.41 (3.32)	20.48 (3.89)	332.76 (34.72)	1855 (117)	901 (54)	48.6 (2.2)	55 (8)	80.46 (10.17)	41.93 (5.36)	29.82 (4.14)	22.63 (4.09)
3.4.3 R2	264 (69)	17 (2)	15.6 (3.5)	2.83 (1.75)	0.55 (0.16)	3.87 (1.00)	42.90 (2.98)	31.19 (3.09)	11.68 (3.70)	254.32 (87.36)	1363 (91)	781 (43)	57.4 (2.8)	138 (13)	82.01 (10.41)	47.93 (5.56)	39.24 (4.14)	31.33 (4.28)
3.4.4 R1	323 (71)	26 (31)	26.6 (5.9)	2.28 (0.71)	0.36 (0.67)	6.46 (1.66)	16.58 (3.00)	0.93 (0.68)	15.58 (2.85)	179.32 (33.20)	1642 (214)	939 (139)	57.2 (3.2)	92 (29)	49.67 (10.99)	16.68 (3.56)	4.96 (2.83)	0.77 (0.65)
3.4.4 R2	323 (71)	19 (4)	26.6 (5.9)	2.27 (0.57)	0.21 (0.25)	6.55 (1.75)	16.58 (3.00)	2.07 (1.66)	14.44 (2.86)	163.66 (20.90)	1503 (184)	945 (108)	63.0 (3.3)	118 (24)	63.22 (23.05)	20.34 (4.36)	8.40 (3.87)	4.17 (4.32)
3.5.1 R1	278 (66)	19 (3)	34.1 (5.2)	2.33 (0.65)	0.21 (0.16)	10.51 (4.03)	9.91 (2.41)	3.87 (2.06)	6.04 (2.40)	74.06 (19.51)	1627 (229)	1078 (157)	66.2 (2.9)	88 (5)	13.76 (9.45)	6.59 (1.99)	5.19 (1.63)	4.76 (2.27)
3.5.1 R2	278 (66)	19 (3)	34.1 (5.2)	2.28 (0.54)	0.26 (0.28)	9.89 (3.55)	9.91 (2.41)	6.06 (2.57)	3.85 (2.56)	62.90 (25.82)	1282 (197)	965 (103)	75.7 (4.1)	161 (20)	15.34 (9.73)	8.60 (2.10)	7.66 (1.70)	6.66 (2.05)
3.5.2 R1	341 (59)	20 (2)	35.7 (5.6)	3.74 (1.71)	0.25 (0.08)	8.86 (3.09)	10.77 (1.96)	2.68 (1.46)	8.15 (1.79)	68.97 (7.54)	1581 (106)	1061 (70)	67.1 (1.5)	76 (4)	12.77 (4.10)	6.39 (1.94)	3.84 (1.60)	2.88 (1.52)
3.5.2 R2	341 (59)	23 (2)	35.7 (5.6)	3.42 (1.51)	0.23 (0.07)	8.64 (3.03)	10.77 (1.96)	3.65 (2.21)	6.99 (2.24)	61.79 (10.38)	1287 (127)	985 (84)	76.7 (2.5)	125 (15)	17.20 (4.76)	9.06 (2.56)	6.06 (2.48)	4.29 (2.47)

f = filtered; a = anaerobic; d = anoxic; b1 = 1st aerobic; b2 = 2nd aerobic reactors of 3-stage Phoredox system (see Fig. 3.1, Chapter 3).

Table 5.5: Mass balances for ferrous-ferric chloride dosing periods 3.4.1 to 3.5.2.
Results are averages with sample standard deviations in parentheses.

Period Unit	Flow Q, l/d	VSS mg/ℓ	No3a mgN/ℓ	No3d mgN/ℓ	No3b2 mgN/ℓ	Nte mgN/ℓ	No3e mgN/ℓ	Nti mgN/ℓ	% N Bal.	Ot mgO/ℓ.h	Sti mgO/ℓ	Ste mgO/ℓ	% COD Bal.	Δ Pt mgP/ℓ	P/VSS mgP/gVSS	% P Bal.
3.4.1 R1	36.0	1361 (329)	0.08 (0.05)	1.97 (0.61)	3.29 (0.92)	2.29 (0.55)	3.32 (0.86)	15.4 19.3	109	7.88 (1.97)	237 (53)	14 (6)	117	25.57 (4.45)	254.8 (134.1)	121
3.4.1 R2	35.8	1135 (349)	0.07 (0.02)	1.39 (0.67)	2.68 (0.93)	2.14 (0.38)	2.78 (0.79)	15.4 19.3	98	8.53 (2.46)	237 (53)	16 (8)	110	17.77 (4.39)	248.83 (132.4)	142
3.4.2 R1	35.6	999 (163)	0.06 (0.08)	2.68 (1.08)	4.96 (1.82)	2.17 (0.58)	4.66 (2.19)	18.0 22.5	99	9.27 (1.95)	284 (59)	15 (5)	85	20.81 (4.26)	342.25 (99.03)	149
3.4.2 R2	35.4	892 (75)	0.08 (0.17)	2.40 (1.08)	4.42 (1.78)	2.17 (0.60)	3.96 (1.98)	18.0 22.5	88	10.64 (2.46)	284 (59)	15 (4)	88	17.00 (4.73)	297.28 (49.33)	138
3.4.3 R1	36.7	901 (54)	0.07 (0.02)	2.96 (0.52)	5.18 (0.94)	2.95 (1.80)	5.09 (0.85)	15.6 19.5	112	9.02 (1.00)	264 (69)	16 (2)	82	20.48 (3.89)	332.76 (34.72)	117
3.4.3 R2	35.6	781 (43)	0.10 (0.06)	2.46 (0.90)	3.64 (1.07)	2.83 (1.75)	3.87 (1.00)	15.6 19.5	82	10.65 (1.05)	264 (69)	17 (2)	92	11.68 (3.70)	254.32 (87.36)	153
3.4.4 R1	36.2	939 (139)	0.08 (0.02)	3.15 (1.13)	6.32 (1.68)	2.28 (0.71)	6.46 (1.66)	26.6 (5.9)	100	13.35 (2.69)	323 (71)	26 (31)	87	15.56 (2.82)	179.32 (33.20)	96
3.4.4 R2	36.3	945 (108)	0.07 (0.02)	3.72 (1.15)	6.45 (1.56)	2.27 (0.57)	6.55 (1.75)	26.6 (5.9)	92	11.64 (2.45)	323 (71)	19 (4)	79	14.31 (2.96)	163.66 (20.90)	94
3.5.1 R1	36.0	1063 (152)	0.57 (0.92)	6.85 (3.00)	10.74 (4.04)	2.33 (0.65)	10.51 (3.93)	34.1 (5.2)	89	11.91 (1.60)	278 (67)	19 (3)	95	6.04 (2.40)	82.08 (19.51)	116
3.5.1 R2	36.0	965 (98)	0.64 (0.87)	6.79 (2.60)	10.56 (4.09)	2.28 (0.54)	9.89 (3.49)	34.1 (5.2)	82	11.98 (1.64)	278 (67)	20 (3)	89	3.85 (2.56)	73.79 (25.82)	138
3.5.2 R1	36.4	1061 (70)	0.08 (0.05)	3.93 (2.25)	8.26 (3.63)	3.74 (1.71)	8.86 (3.09)	35.7 (5.6)	99	13.73 (1.27)	341 (59)	21 (2)	81	8.15 (1.79)	68.97 (7.54)	84
3.5.2 R2	36.3	985 (84)	0.08 (0.03)	4.07 (2.30)	8.06 (3.14)	3.42 (1.51)	8.64 (3.03)	35.7 (5.6)	95	13.05 (0.97)	341 (59)	23 (2)	77	6.99 (2.24)	61.79 (10.38)	92
								Mean S.D.	95 10			Mean S.D.	90 12		Mean S.D.	120 24

Figures in red indicate estimates where spurious actual values were recorded, probably due to analytical difficulties (refer to section 3.3.3.1 of Chapter 3).

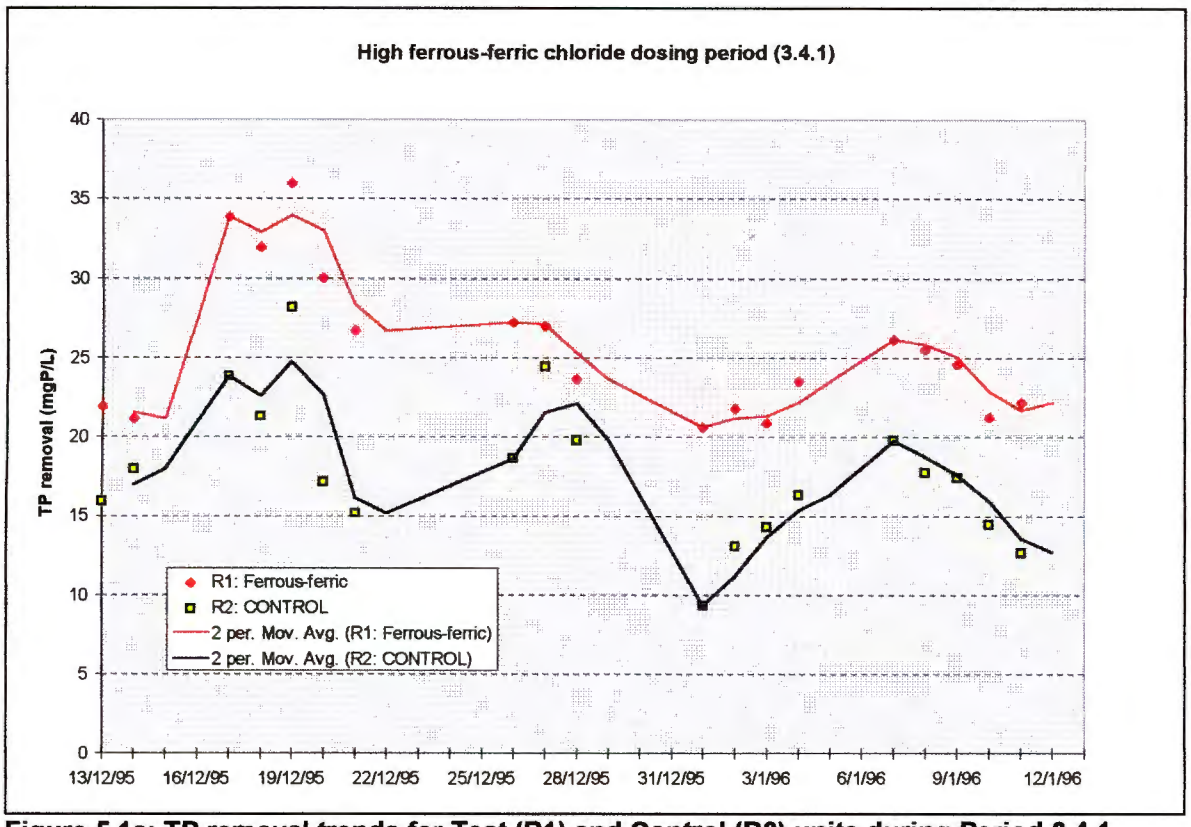


Figure 5.1a: TP removal trends for Test (R1) and Control (R2) units during Period 3.4.1.

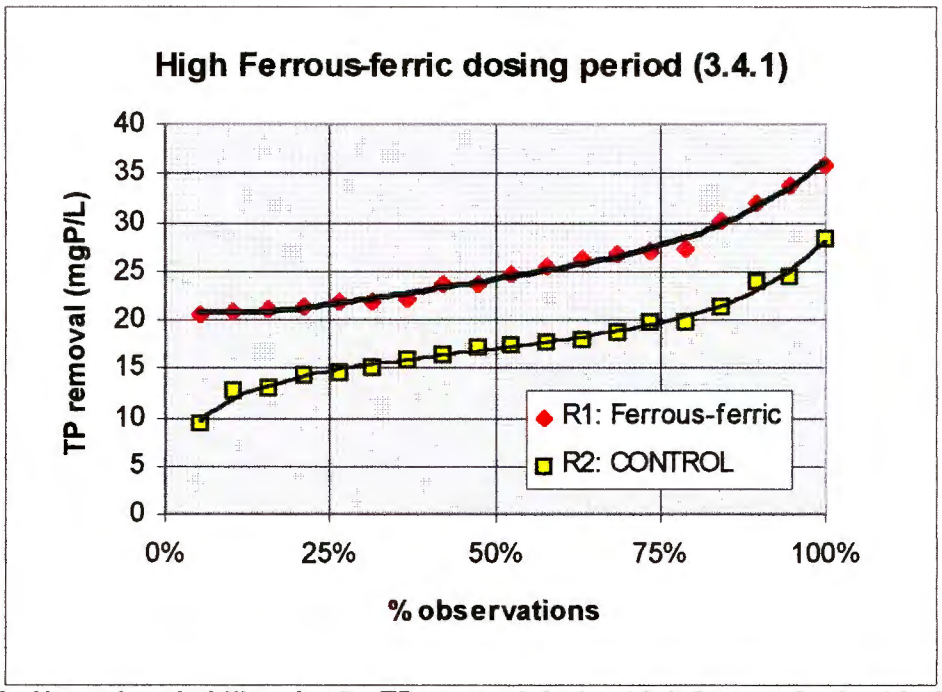


Figure 5.1b: Normal probability plot for TP removal during high ferrous-ferric chloride dosing period (3.4.1).

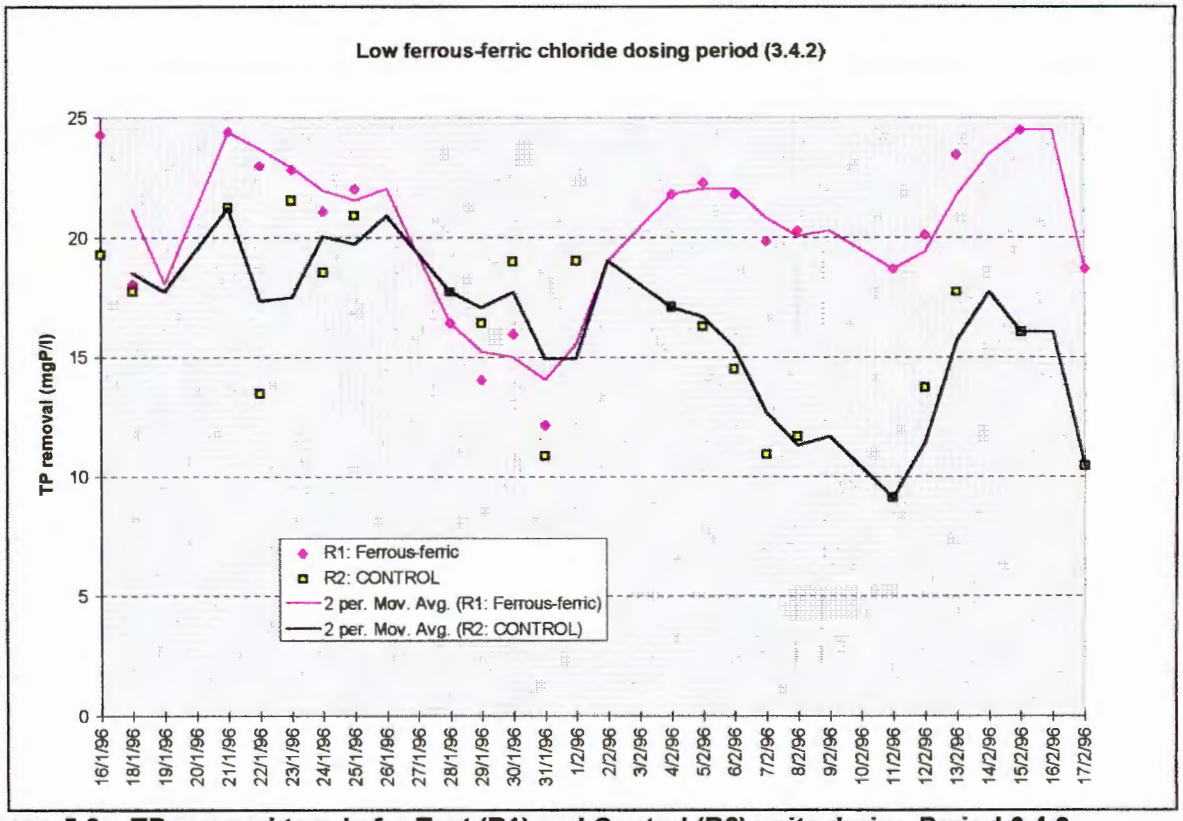


Figure 5.2a: TP removal trends for Test (R1) and Control (R2) units during Period 3.4.2.

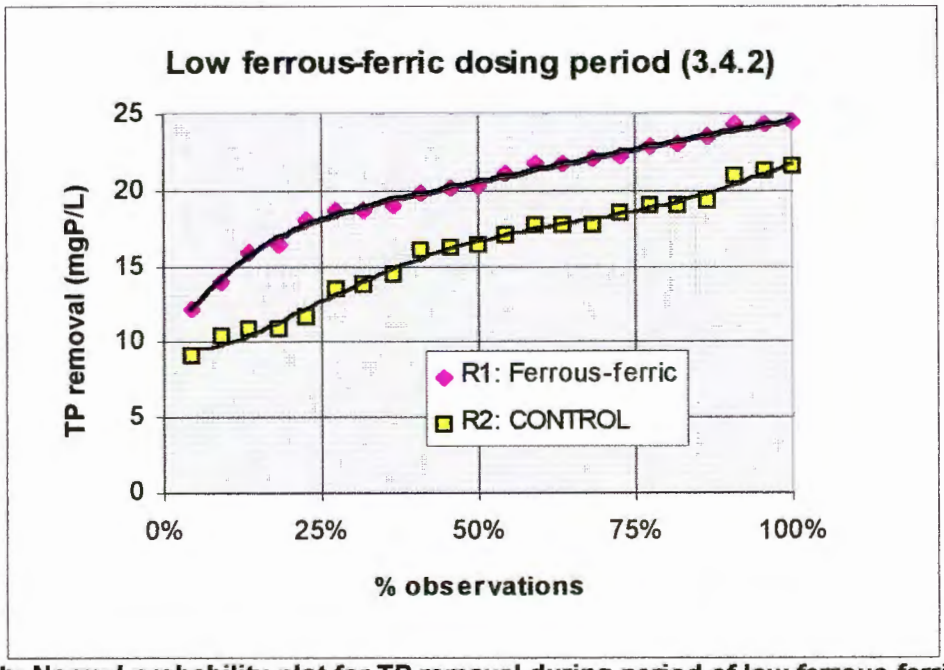


Figure 5.2b: Normal probability plot for TP removal during period of low ferrous-ferric chloride dosing to aerobic zone (3.4.2).

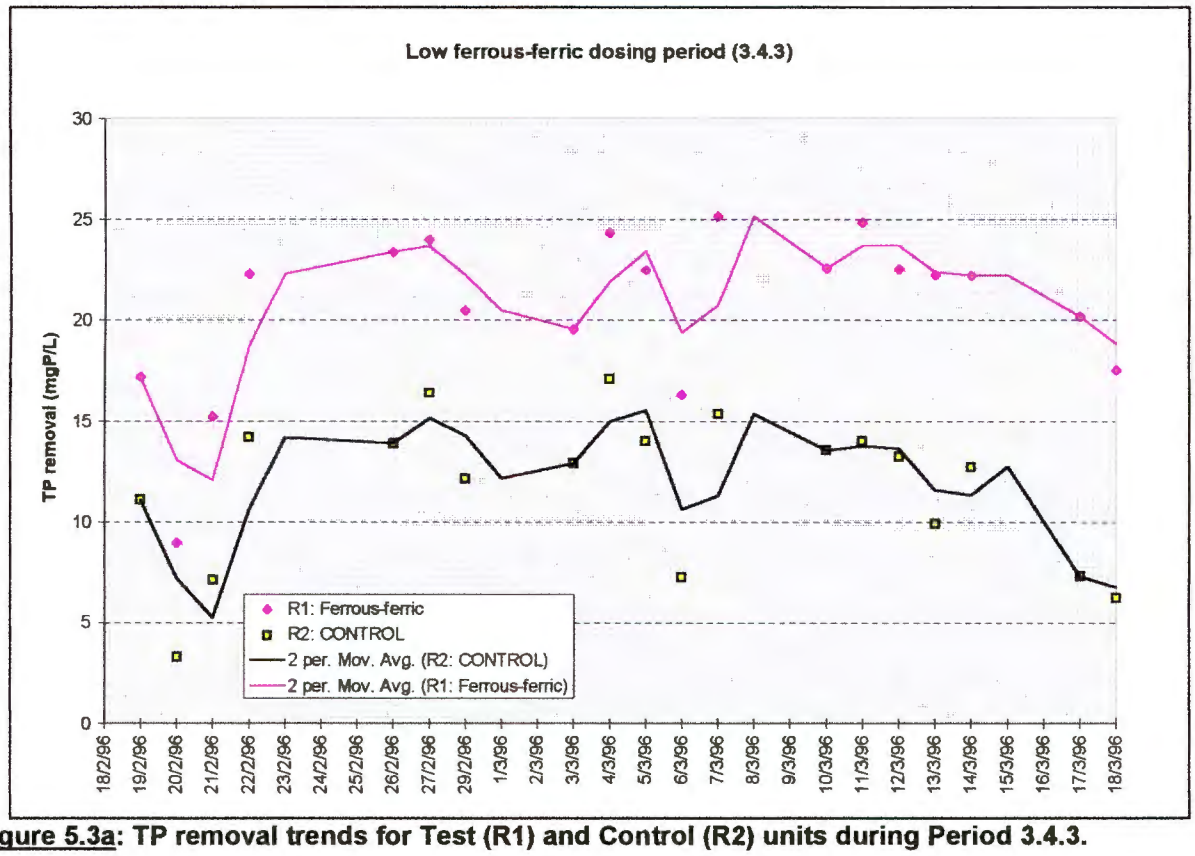


Figure 5.3a: TP removal trends for Test (R1) and Control (R2) units during Period 3.4.3.

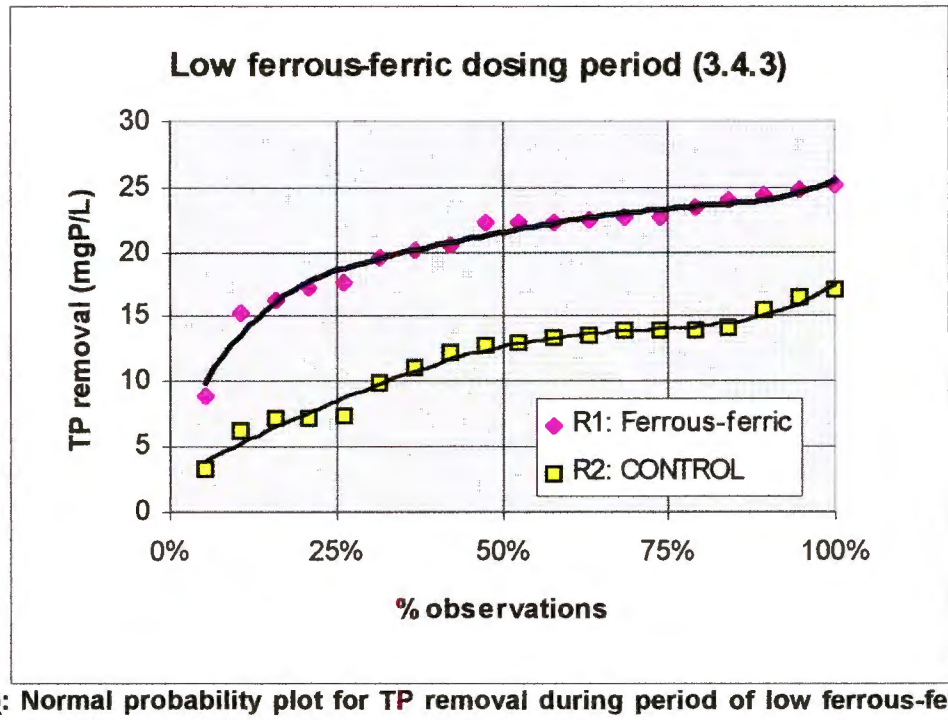


Figure 5.3b: Normal probability plot for TP removal during period of low ferrous-ferric chloride dosing to anaerobic zone (3.4.3).

Table 5.6: Summary: P removal due to ferrous-ferric chloride measured in pilot plants.
ΔPt implies TP removal (Influent - Effluent) : **(1)** = R1 (Ferrous-Ferric); **(2)** = R2 (Control).

Period	Fe dose, R1 mmol/d ; (zone)	Δ Pt(1) - ΔPt(2) mgP/ℓ	M[Δ Pt(1) - ΔPt(2)] mgP/d	mmol P/mmol Fe
3.4.1	12.4 ; AE1	7.80	284.35	0.74
3.4.2	6.2; AE1	3.81	118.81	0.62
3.4.3	6.2; AN	8.80 *	335.81*	1.75 *
3.4.4	6.2; AE1	1.25	43.82	0.23
3.5.1	6.2; AE1	2.19	78.84	0.41
3.5.2	6.2; AN	1.09	40.37	0.21

* Depressed bio-P removal in Control (R2) unit during Period 3.4.3 (see section 5.3.1.1 below)

5.3 RESULTS AND DISCUSSION

5.3.1 Overall results for ferrous-ferric chloride dosing periods

A summary of the results for the ferrous-ferric chloride dosing periods is given in Tables 5.4 to 5.6.

5.3.1.1 Enhanced cultures

Comparing the results for effluents of the units (R1 and R2), it can be seen from Table 5.4 that the ferrous-ferric chloride blend almost always produced a net improvement in P removal (lower P_{te} or higher ΔPt). This can be seen more clearly in the time series and normal probability plots given in Figures 5.1 (a & b), 5.2 (a & b) and 5.3 (a & b). Analysis of the variance in the data (e.g. Student's t-test) was not attempted since the two sample sets (R1 and R2) were not independent due to the experimental units having the same influent source.

From a comparison of Figs. 5.2b and 5.3b, it may be seen that the change in dosing point from the aerobic (Period 3.4.2) to anaerobic zone (Period 3.4.3) did not produce a large change in average P removal in the Test unit (R1) receiving ferrous-ferric chloride. Fig. 5.2a shows that what changes did occur were mainly related to a temporary deterioration in P removal in R1 during the first two weeks of Period 3.4.2, followed by a recovery in the second two weeks of this period. The reasons for this temporary deterioration were not self-evident.

According to Rabinowitz and Marais (1980), reduced P "precipitation efficiency" (i.e. reduced system P removal due to the combined chemical and biological mechanisms), accompanied by turbid effluent, may occur with simultaneous iron dosing at a process pH <7.2. The median pH in the first and second aerobic reactors of the Test unit for the first two weeks of Period 3.4.2 was 7.39 and 7.61 respectively (7.35 and 7.66 in the Control). For the second two weeks of Period 3.4.2, comparable median pH values were 7.36 and 7.54 respectively for the first and second aerobic reactors of Test unit (7.30 and 7.58 in the Control). On the basis of the work of Rabinowitz and Marais (1980) and results discussed in Chapter 4 (section 4.3.11), these data suggest that pH was unlikely to have been a significant factor influencing P removal in the Test unit during Period 3.4.2. Similarly, from visual examination, turbidity of the effluents from the two units were compared during Period 3.4.2. The effluent from the Test unit was recorded as very clear (Control slightly turbid) during the week in which deterioration in P removal in the Test unit was most noticeable. This tends to confirm the pH data, implying that some other explanation for the temporary deterioration in P removal in the Test unit during Period 3.4.2 should be sought.

From an examination of the operating records, one likely explanation for the temporary deterioration in P removal during Period 3.4.2 is that the stock solution of ferrous-ferric chloride (first dilution - see Table 5.2) was found to have turned from a straw yellow to rust brown colour over about two weeks. This solution did not have acid added to lower the pH (refer to 5.2.3 above), and it is possible that the ferrous ions had been oxidised to ferric ions to form a colloidal ferric oxide (e.g. Fe_2O_3) while standing on the shelf, prior to being dosed to the pilot plants. A small amount of sediment had also formed in the bottle. It is possible that this precipitate removed some of the iron from solution, thus reducing the iron dosage to the Test unit. Also, if a colloidal form of iron oxide had formed in the solution, this may have had a

limited phosphate precipitating capacity and would have reduced the formation of ferric hydroxide, which is also implicated in chemical P removal (Rabinowitz and Marais, 1980). On 27/1/96, a fresh stock solution of ferrous-ferric chloride was prepared from commercial concentrate, including 0.02M HCl as described under 5.2.3 above. This prevented the emergence of the rust colour colloid and sediment in the working solution. Approximately one week later, P removal in the Test unit had recovered and remained consistently better than in the Control during the second half of Period 3.4.2, as well as throughout Period 3.4.3.

Comparing Figs. 5.2b and 5.3b, parts of Period 3.4.2 and Period 3.4.3 showed significantly poorer P removal in the Control, compared to the first part of Period 3.4.2. By comparison of the median values in Figs. 5.2b and 5.3b, P removal in the Test unit was similar for the two periods, or slightly better in Period 3.4.3. When relating the differences in TP removal for the two units, a potentially false impression may be created, namely, that a significant improvement in total P removal was obtained by dosing ferrous-ferric chloride to the anaerobic zone as opposed to the aerobic zone. Hence, possible reasons were sought for the relatively weak P removal in the Control during part of Period 3.4.2 and Period 3.4.3.

Observations during the latter part of Period 3.4.2 and most of Period 3.4.3 suggested that settling problems developed in the Control unit, with fine sludge floc and turbid effluent noted on some days, as well as a significantly increased DSVI (refer to Fig. 5.4 - average 138 ml/g for Period 3.4.3, compared with 83 ml/g for Period 3.4.2). The DSVI in the Test unit also showed an increase during the corresponding period, but not to the same degree as the Control (Fig. 5.4). It may be speculated that the impaired settling in the Control unit could have given rise to P release in the clarifier, which would have accounted for the weakened P removal in the Control unit. However, this possibility is not supported by the data in Table 5.4 which shows that the filtered second aerobic zone total P concentration was very similar, on average, to the effluent total P concentration for the Control during Period 3.4.3.

DSVI data over a longer term is presented in Fig. 5.13 and discussed under section 5.3.9 below. It should be noted from Fig. 5.13 that the trend of increasing DSVI from the latter part of Period 3.4.2 into Period 3.4.3, showed a temporary reversal toward the end of that period; this was followed by a further increase at the start of Period 3.4.4 and a subsequent rapid decrease during April 1996. It is unlikely that the termination of the relatively small supplemental acid dose (equivalent to 14 mg/ℓ as $CaCO_3$ - see Table 5.3) on 1 April 1996 (start of Period 3.4.4), could have been the sole cause of these changes. Additional factors could also have influenced DSVI and biological P removal during these periods. One such factor may have been sewage composition.

As will be discussed in more detail in Chapter 6, the sewage composition at Darvill WWW tends to be very variable in summer when rainfall in the catchment can lead to severe ingress of stormwater and/ or groundwater to the sewerage system. There may be a link between the influent quality and the observed DSVI. From Fig. 5.5 it can be seen that late December 1995 and January 1996 were characterised by high rainfall in the catchment of Darvill WWW. It is normal operational practice at this Works to divert surplus wet weather flows (ca. >3 x ADWF) to a storm dam. When the storm dam is full (as it was through most of January 1996 until the second week of February 1996), the excess sewage overflows from the storm dam to the Umsunduzi River. When flow conditions and capacity permit, the storm dam contents are pumped back into the Works for treatment. For the period under review, this began in the first 10 days of February 1996 (i.e. during Period 3.4.2 when P removal in the Control unit was weakened - see Fig. 5.2a), but was interrupted again by heavy rain in the second and third week of February 1996. The pumping of sewage back from the dam was resumed over the first ten days of February, but was accomplished mainly in March 1996 as the summer rains came to an end (Fig. 5.5). It is possible that increased sulphide concentrations in the influent to the Works resulted from pumping back septic sewage from the storm dam during February-March 1996. Since the sewage feed for the pilot plants was derived from settled sewage of the full-scale Works (pumped in batches every two to three days), the increased influent sulphide concentrations may have partially inhibited the biological P removal mechanism (Comeau *et al.*, 1986) (Figs. 5.2a & 5.3a), and septic sewage is also known to influence sludge settleability (Jenkins *et al.*, 1984) (Fig. 5.4). In the Control unit, these effects may have been directly exerted (e.g. weakened P removal during sub-period 2/2/96 to 11/2/96 in Fig. 5.2a; and 5/3/96 to 18/3/96 in Fig. 5.3a). On the other hand, the addition of ferrous iron to the Test unit may have ameliorated the inhibitory effect of the sulphide by formation of insoluble iron sulphide precipitate (FeS or similar compound). This would have been particularly likely during Period 3.4.3 when ferrous ions were dosed directly to the anaerobic zone of the Test unit. An additional link between a strong biological P removal mechanism and good DSVI may exist through the increased density of sludge flocs produced by the

large mass of stored polyphosphate in the cells of the "poly P organisms" (Wentzel et al., 1988). This point will be is discussed further in section 5.3.9 below.

In summary, there appears to be circumstantial evidence to suggest that variable influent composition (and increased septicity in particular) affected P removal and settleability for experimental periods with enhanced cultures, particularly in the Control unit. Hence, although a benefit in terms of total P removal could almost always be demonstrated for ferrous-ferric chloride dosing, caution needs to be exercised in drawing conclusions from different experimental periods on the relative merits of dosing the anaerobic zone versus the aerobic zone, for example.

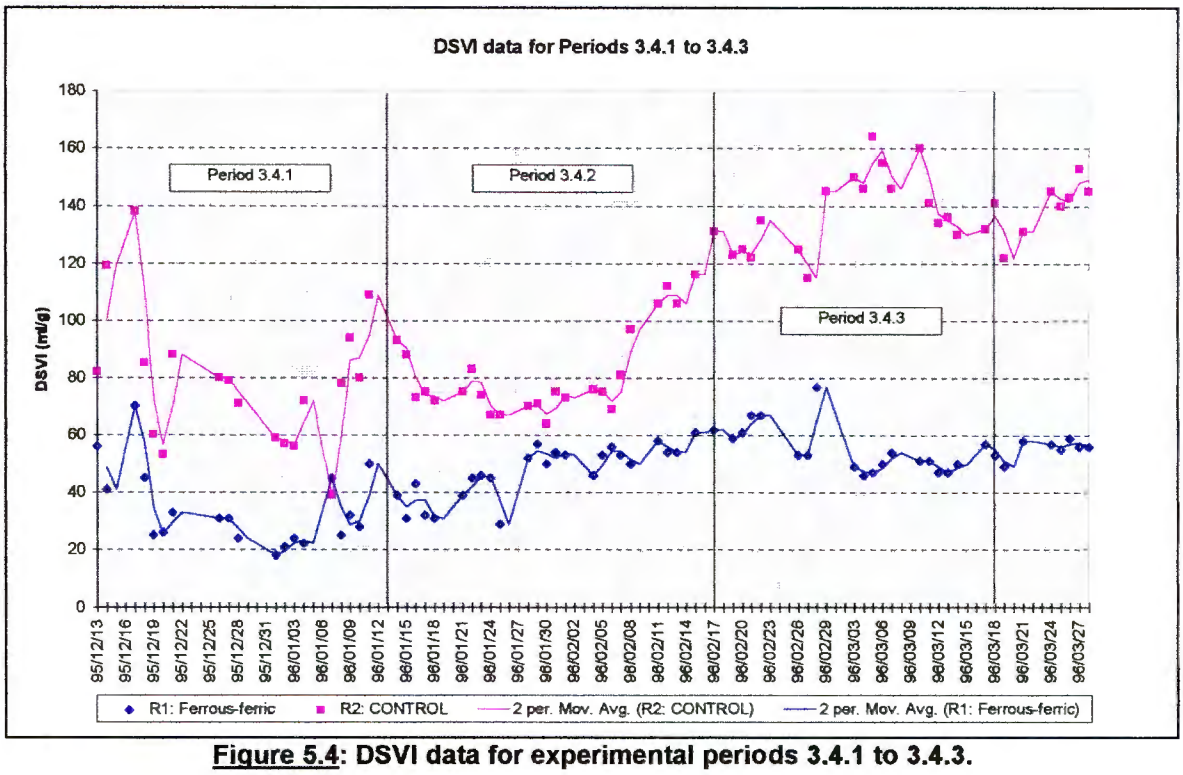


Figure 5.4: DSVI data for experimental periods 3.4.1 to 3.4.3.

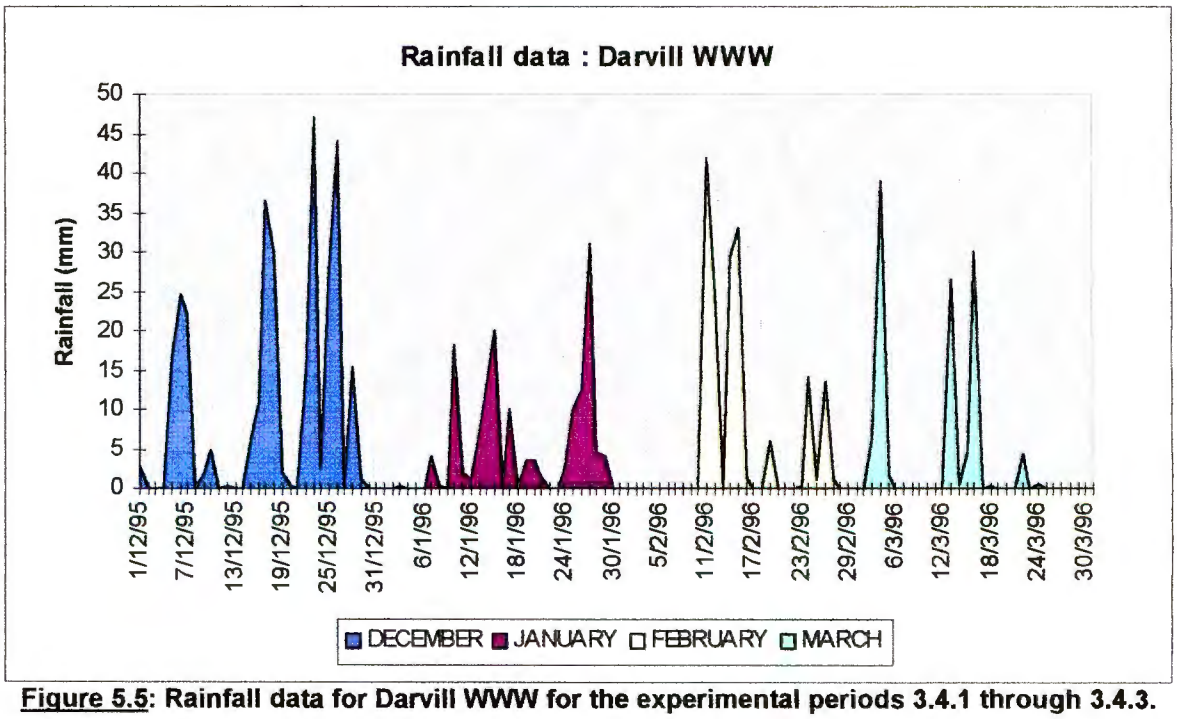


Figure 5.5: Rainfall data for Darvill WWW for the experimental periods 3.4.1 through 3.4.3.

5.3.1.2 P-limited enhanced cultures

The results in Table 5.4 for Period 3.4.4 show that the effluent phosphate total P concentrations dropped to 1.01 mgP/ℓ on average in the Test unit and 2.27 mgP/ℓ in the Control. The effluent ortho P concentrations were very similar (average 1.12[4] and 2.07 mgP/ℓ respectively - see Appendix 5). These data show that under low effluent P conditions, the dosing of ferrous-ferric chloride still produced a net improvement in phosphate removal, compared to the Control. However, the smaller difference in observed effluent TP concentrations between the Test and Control units under such operational conditions, suggests that P removal efficiency by the chemical mechanism becomes less efficient as the residual (dissolved) phosphate concentration decreases. The same observation was made by Rabinowitz *et al.* (1980) for ferric chloride.

In this study (Period 3.4.4), it proved difficult to maintain the effluent TP concentrations consistently below 1 mgP/ℓ in the Test unit (or <0.5 mgP/ℓ at times), without allowing the Control unit effluent TP concentration to do the same (Fig. 5.6a). The main reason for this was insufficient control over the influent COD concentration and composition, which, in turn was caused by the intermittently low influent COD to Darvill WWW in general and during the wet season in particular (de Haas and Borain, 1995; also refer to Chapters 3 and 6). In spite of this, the fact that the Test unit (R1) continued to remove phosphate to lower concentrations than the Control unit (R2) over a period of 71 days (seven sludge ages), suggests that the dosing of ferrous-ferric chloride was not severely inhibitory to the biological P removal mechanism. This is further illustrated by means of the probability plot for this experimental period (Figure 5.6b). From the data falling in the lower quartile in Fig. 5.6b, the benefit of ferrous-ferric dosing was more apparent (in terms of P removal) under conditions when overall P removal was low. In this respect, it may be very valuable in improving compliance on full-scale plants under conditions in which the biological P removal mechanism may be weakened by factors such as low influent COD.

5.3.1.3 "Normal sewage"

During Periods 3.5.1 and 3.5.2 the pilot plants were fed with settled sewage supplemented with a only a small amount of acetate (20 mg/ℓ as COD) and with no added phosphate. From Table 5.4 it can be seen that this had the expected effect of weakening the biological P removal mechanism, such that the Control unit removed only 3 to 7 mgP/ℓ on average, depending mainly on the influent COD. From Table 5.4 and Fig. 5.7 (a&b), it can be seen that during Period 3.5.1, effluent total P concentrations from the Test unit averaged 3.9 mgP/ℓ (6.1 mgP/ℓ in the Control), while the corresponding ortho P concentrations averaged 3.2 and 5.3 mgP/ℓ respectively (Appendix 5). During Period 3.5.2 (Fig. 5.8 a&b), effluent total P concentrations from the Test unit averaged 2.7 mgP/ℓ (3.7 mgP/ℓ in the Control), while the corresponding ortho P concentrations averaged 1.3 and 2.3 mgP/ℓ respectively (Table 5.4 and Appendix 5). These data suggest that P limiting conditions were emerged at times during Periods 3.5.1 and 3.5.2 (particularly in the latter), and that, under these conditions, the ferrous-ferric blend was still capable of improving total P removal, though at reduced efficiency.

Dosing to the aerobic zone (Period 3.5.1) produced a net average improvement in system P removal of 2.2 mgP/ℓ, while dosing to the anaerobic zone produced an improvement of only 1.0 mgP/ℓ. Figures 5.7 (a&b) and 5.8 (a&b) illustrate these points more clearly. No simple explanation for the improved system P removal with dosing to the aerobic zone was self-evident. However, it may be speculated that ferrous ions may have been "lost" in part due to the formation of ferrous sulphide from soluble sulphide potentially present in the influent and anaerobic zone. In the aerobic zone, one would expect oxidation of the sulphide to sulphate ions (see 5.3.1.1 above). Similarly, the loss of ferrous (or ferric) ions due to coagulation with soluble (colloidal) influent organic matter may have accounted for poorer P precipitation, compared to the aerobic zone where most of colloidal organic matter will have been adsorbed to the biomass or metabolised. Figs. 5.7 (a&b) and 5.8 (a&b) also indicate a trend (as for period 3.4.4) in which TP removal in the lower range (first and second quartile) is significantly better with ferrous-ferric dosing (R1) than without (R2). Again, this is most likely to be manifest at full-scale by producing improved compliance with the Special Phosphate Standard under conditions when biological P removal alone may be weak.

---

[4] The minor extent to which the average ortho P value exceeded the average total P value is probably due to constraints posed by the detection limit of the vanadate-molybdate method used for total P determination, as opposed to the more sensitive ascorbic acid method use for ortho P. Refer to Chapter 2.

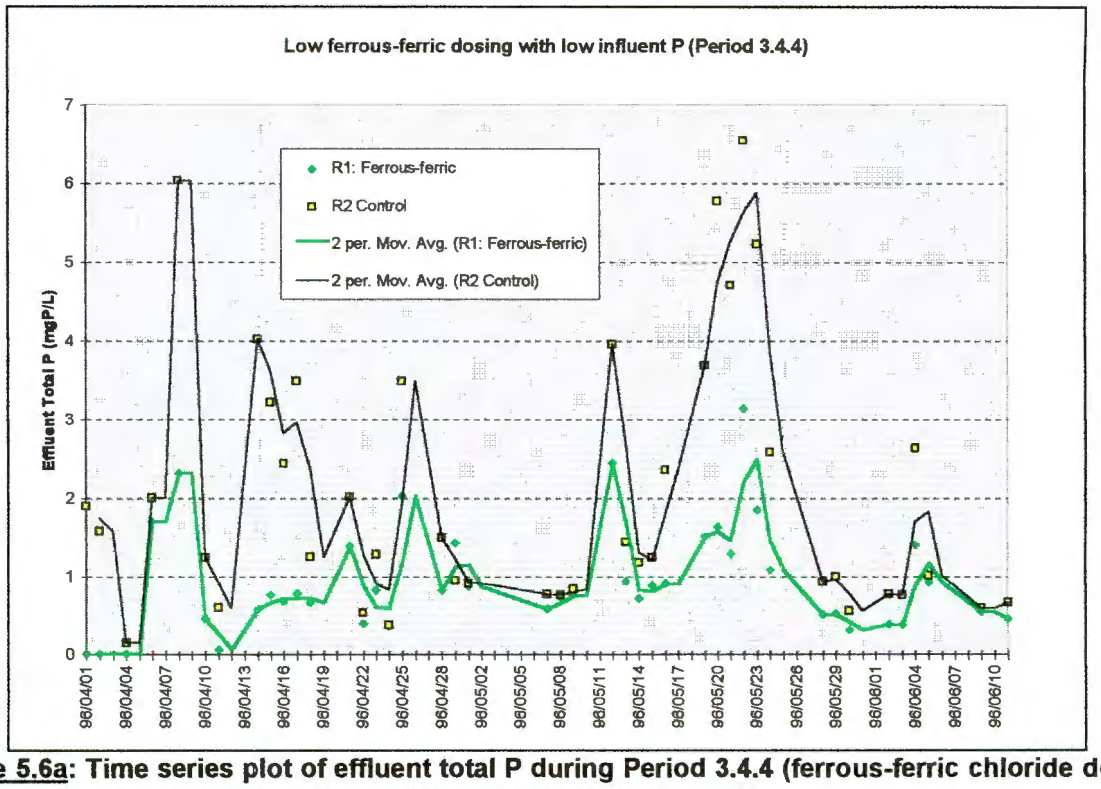


Figure 5.6a: Time series plot of effluent total P during Period 3.4.4 (ferrous-ferric chloride dosing to semi-enhanced cultures under conditions of limited influent P).

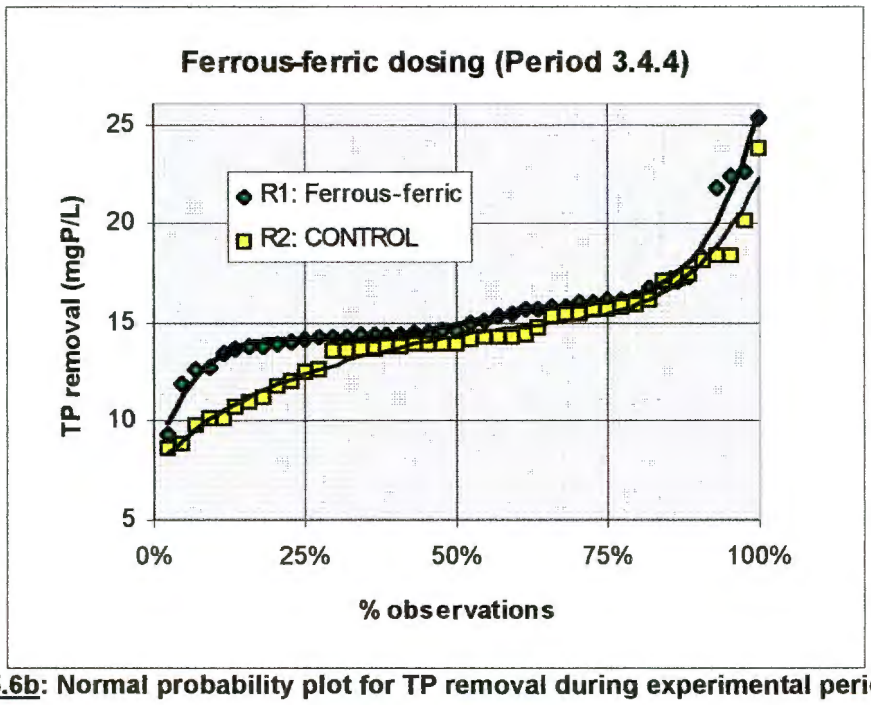


Figure 5.6b: Normal probability plot for TP removal during experimental period 3.4.4.

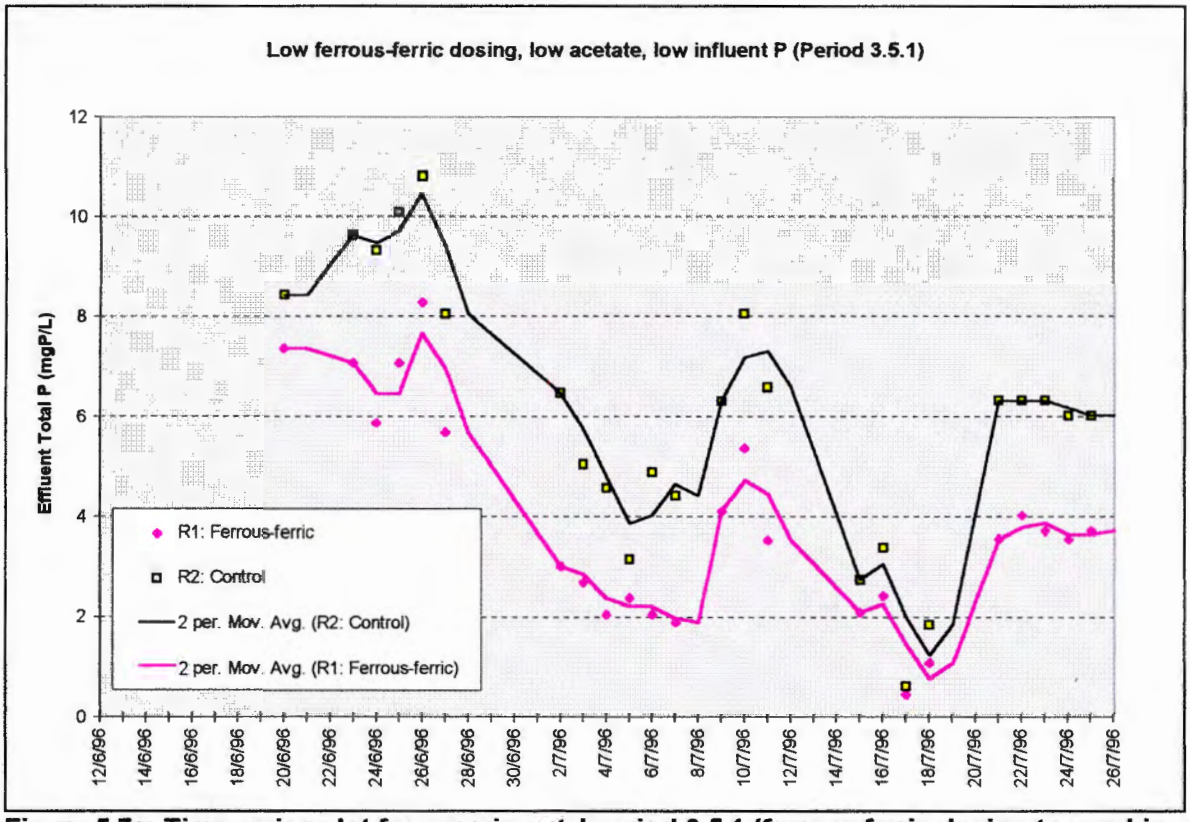


Figure 5.7a: Time series plot for experimental period 3.5.1 (ferrous-ferric dosing to aerobic zone) during which a low acetate and no phosphate supplement was added to the influent sewage.

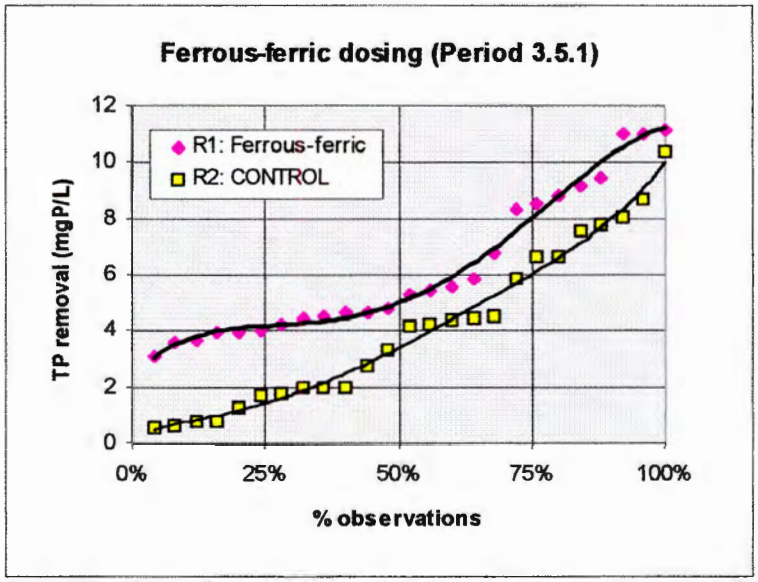


Figure 5.7b: Normal probability plot for experimental period 3.5.1.

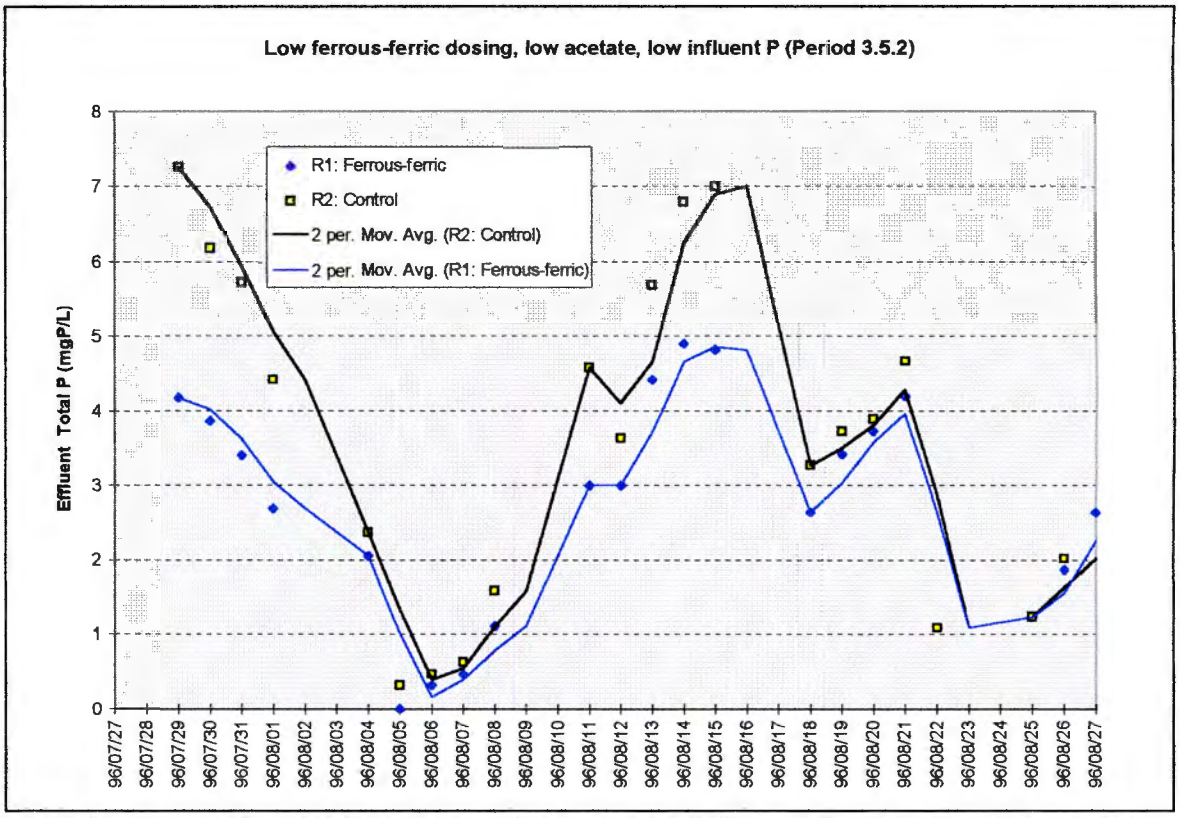


Figure 5.8a: Time series plot for experimental period 3.5.2 (ferrous-ferric dosing to anaerobic zone) during which a low acetate and no phosphate supplement was added to the influent sewage.

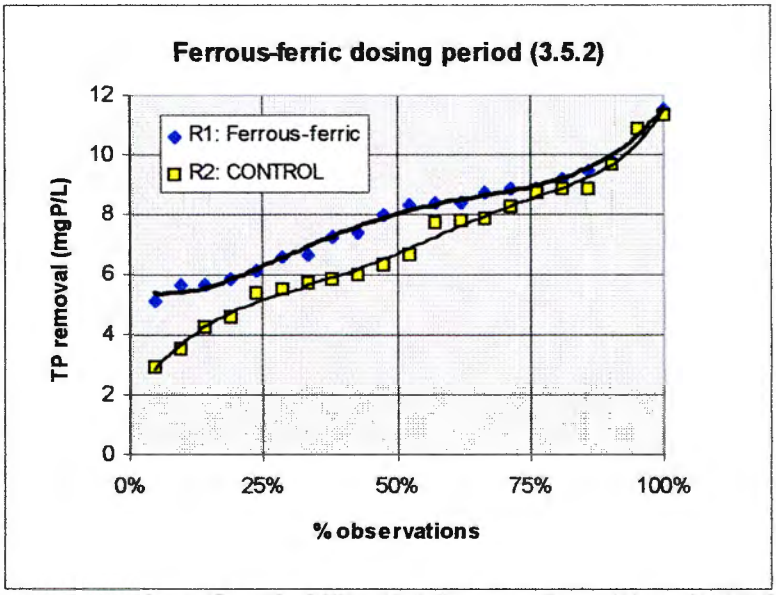


Figure 5.8b: Normal probability plot for experimental period 3.5.2.

5.3.2 Molar ratios of P removed/ Fe dosed and point of dosing

Calculation of the average molar ratio of $P_{removed}$/ Fe_{dosed} in Table 5.6 (above) is based on the assumption that the difference in P removal between R1 and R2 is *only ascribable to chemical addition*. As pointed out in previous chapters, the problem with this assumption is that effects of both chemical and biological origin are lumped; if the biological mechanism is weaker in R1 than R2, it will reflect as a lower P (removal)/ Fe molar ratio and could be confused with a weaker chemical precipitation mechanism which may not be directly linked to biological causes (or vice versa).

As an example, Table 5.6 shows a markedly higher molar ratio of $P_{removed}$/ Fe_{dosed} observed for the dosing of ferrous-ferric chloride to the anaerobic zone (Period 3.4.3) compared to that for the aerobic zone (Period 3.4.2). This differs from the results for Periods 3.5.1 and 3.5.2 at lower influent P concentrations (see discussion under 5.3.1.3 above). In section 5.3.1.1 above, it was pointed out that Table 5.4 and the normal probability plots (Figs. 5.2b and 5.3b) show that whereas there was almost no change in the mean TP removal in the Test unit (R1) for Period 3.4.3, compared to 3.4.2, the Control unit showed a significant decrease in TP removal in Period 3.4.3. A possible explanation for this has already been advanced (see section 5.3.1.1). It follows that the molar ratio data in Table 6 cannot be interpreted in isolation.

In broad terms, Table 5.6 does suggest that , a lower molar ratio of $P_{removed}$/ Fe_{dosed} was obtained during periods in which the influent P concentration was limited. This has already been mentioned (sections 5.3.1.2 and 5.3.1.3 above), and suggests that the chemical removal mechanism is less efficient at lower (dissolved) P concentrations; moreover, the biological removal mechanism may be unable to "compete" as effectively with the chemical mechanism for available phosphate under such conditions. These two possibilities will be further examined in the light of the fractionation data presented in section 5.3.5.

5.3.3 Mass Balances

5.3.3.1 Overall mass balances for COD, N and P

The carbon and nitrogen mass balances (Table 5.5) were good or satisfactory for most periods. For Periods 3.4.1 through 3.4.3, it appeared that under-recovery of the influent TKN (by approximately 20%) occurred during analysis. This problem was encountered over the preceding periods (3.3.4 through 3.3.6) as well, and was discussed in Chapter 4 (section 4.3.2.1). The analytical problem appears to have been resolved in subsequent periods (Periods 3.4.4 through 3.5.2).

Phosphorus mass balances showed certain inconsistencies (Table 5.5), particularly in respect of recoveries exceeding 100% by a substantial margin in some periods. It is unlikely that the analysis for total P in the influent would be inconsistent to the degree required to explain the results in Table 5.5, particularly in so far as the digestion method for total P (unlike TKN) is relatively simple and gave good recoveries in the fractionation procedure. If analytical error is partly responsible for the inconsistent mass balances, it is more likely that the error stems from difficulty in accurately determining the P content of the solids (either P/MLSS or P/VSS) content of the reactors from one grab sample per day. Unlike the nitrogen mass balance where the nitrogen fraction of the solids wasted only accounts for a small part (ca. 30%) of the total N removal, phosphorus removal via solids wasting accounts for all the system P removal. Variation in influent COD (partly due to rainfall) (Table 5.7) strongly affects the P mass balance via the solids (VSS) fraction. Both the VSS and its associated P component take a long time (ca. two to three sludge ages) to reach steady state, while the kinetics of P removal (influent - effluent) are rapid (i.e. responds from one sewage batch to the next). Hence, where the influent COD decreases, the VSS decrease lags by several weeks and the COD and P mass balances will likely be >100%; conversely, when the influent COD increases, mass balances of <100% will probably result. It follows that, true steady state operation of the pilot plants was therefore not achieved throughout the experimental periods examined in this chapter. The results need to be interpreted with this in mind.

Table 5.7: Influent COD variance compared to P mass balance, based on experimental period.

PERIOD	Influent COD Mean	Influent COD Std. Deviation (s)	Influent COD Coefficient of Variation (s/Mean)	P Mass Balance (%) R1	P Mass Balance (%) R2
3.4.1	237	53	0.22	**118**	**139**
3.4.2	284	59	0.21	**149**	**138**
3.4.3	264	69	0.26	**117**	**153**
3.4.4	323	71	0.22	**96**	**95**
3.5.1	280	66	0.24	**131**	**166**
3.5.2	341	59	0.17	**84**	**92**

5.3.2.2 P mass balance around the anaerobic reactor

Using the measured data given in Table 5.4 (for P_{ti}, P_{te} and $fP_{t,a}$) and Table 5.5 (Q_i) and accepting $Q_i = Q_s$ (i.e. return sludge recycle ratio = 1:1 as set in the pilot plants), from mass balance considerations around the anaerobic reactor it can be shown that:

$$M(P_{rel}) = [(Q_i + Q_s).fP_{t,a}] - [Q_i.P_{ti} + Q_s.P_{te}] \quad \text{..... Eqn. 5.1}$$

where $M(P_{rel})$ is the mass of phosphate released to the (filtered) supernatant in the anaerobic zone.

Using Eqn. 5.1 and the data as outlined above, P release in the anaerobic zone of the Test unit (R1), when expressed as a percentage of that in the Control unit was found to be as follows:

- Period 3.4.1 : 89% (19 mgFe/ℓ, AE1 zone)
- Period 3.4.2 : 90% (10 mgFe/ℓ, AE1 zone)
- Period 3.4.3 : 110% (10 mgFe/ℓ, AN zone)
- Period 3.4.4 : 76% (10 mgFe/ℓ, AE1 zone, partially P limited)
- Period 3.5.1 : 93% (10 mgFe/ℓ, AE1 zone, low P, but not P limited)
- Period 3.5.2 : 61% (10 mgFe/ℓ, AN zone, partially P limited)

These data show that P release in the anaerobic zone of the Test unit was inhibited to a minor degree (11% or less) during periods of dosing ferrous-ferric chloride to the enhanced cultures without P limitation (Periods 3.4.1 through 3.4.3). In fact, during Period 3.4.3 (low ferrous-ferric dose to the anaerobic zone), P release in the Test unit appeared to be greater than that of the Control unit, which could imply that ferrous-ferric dosing had enhanced the biological mechanism. However, such a conclusion is not valid. As was discussed under 5.3.1.1 above, whereas P removal in the Control unit during this period was significantly *weaker* than in the two preceding periods, P removal in the Test unit was approximately constant. A similar conclusion was drawn in Chapter 7 (from data in Table 7.9 of that chapter) in which it was found that the observed poly P fractions in the Control unit (R2) during Period 3.4.3 were significantly less than the steady state poly P concentration predicted by the IAWQ model.

Under low effluent ortho P conditions (often <1 mgP/ℓ in Period 3.4.4, and often <2 mgP/ℓ in Period 3.5.2), P release in the anaerobic zone was significantly depressed in the Test unit compared to the Control (24 to 39%). Conversely, during Period 3.5.1 (when effluent ortho P concentration in the Test unit was usually >2 mgP/ℓ), the degree of inhibition of P release in the anaerobic zone of the Test unit was small (7%).

It may be concluded that inhibition of the biological P removal mechanism as a result of ferrous-ferric chloride dosing only appears to be significant when effluent P concentrations become limiting (<2 mgP/ℓ); even under such conditions, a net improvement in system P removal is achievable with simultaneous dosing over a 30 day period. Longer term testing with ferric chloride under P limiting conditions (Chapter 4, section 4.3.11) suggested that, the biological mechanism would be able to continue functioning indefinitely despite the apparent "inhibition" (or depression) arising from competition with the chemical mechanism for available phosphate. Since oxidation of ferrous ions to ferric ions is

expected in the system (see section 5.1), there is reason to believe that the same would hold true for ferrous-ferric chloride dosing over extended periods under low (limiting) P conditions.

5.3.4 Alkalinity and pH considerations

The acidity of ferrous-ferric chloride (0.5 to 1% free acid as HCl, according to the suppliers *NCP Ultrafloc*) may be a source of concern when using this chemical for applications with low influent waste water. In view of the apparent importance of added alkalinity in the stable operation of the pilot plants (Chapter 3), effluent bicarbonate (H_2CO_3*) alkalinity was measured in the effluent during the ferrous-ferric dosing periods. Table 5.8 gives a summary of the pH effluent alkalinity statistics.

From Table 5.8, it can be seen that the effluent bicarbonate alkalinity in R1 (ferrous-ferric dosed) was consistently lower than in R2 (Control), but the difference was always in the range 8 to 22 mg/ℓ as $CaCO_3$. This difference was smaller than that obtained for ferric dosing (Chapter 4, section 4.3.4) which may be significant for a Works such as Darvill where the relatively low influent alkalinity requires lime dosing on a routine basis (see Chapter 6).

The oxidation of ferrous ions to ferric ions involves a *gain* in alkalinity (theoretically +0.89 mg as $CaCO_3$/ mg Fe, according to Loewenthal *et al.,* 1986). The precipitation of ferric hydroxide involves a *loss* of alkalinity which theoretically is (-)0.92 mg as $CaCO_3$/ mg $FeCl_3$ (Loewenthal *et al.,* 1986), or (-)2.67 mg as $CaCO_3$/ mg Fe. Assuming that 90% of the total Fe in the blend is ferrous when dosed (Reynolds, 1996), and that all the ferrous ions are oxidised to ferric form, followed by precipitation as the hydroxide, the *net alkalinity loss* would be (-)1.87 mg as $CaCO_3$/ mg Fe. From Tables 5.2, 5.3 and 5.8 it can be calculated that the mean alkalinity loss (R1 compared to R2) was 1.7 mg $CaCO_3$/ mg Fe for Periods 3.4.2 to 3.5.2 when the Fe dose was low (6.2 mmol/d) and 1.0 mg $CaCO_3$/ mg Fe for Period 3.4.1 when the Fe dose was high (12.4 mmol/d), although the data set was smaller for the latter. These data suggest that the alkalinity consumption was in broad agreement with the theoretical amount for iron hydroxide formation at the lower iron doses. This aspect will be re-considered in section 5.4 below when conclusions are drawn for this chapter.

With the benefit of supplemented influent alkalinity to the pilot plants (Table 1), the data in Table 5.8 show that the pH in the anaerobic zone generally remained above 7.0, and there was little statistical difference between the behaviour of R1 compared to R2 in this respect, even in Periods 3.4.3 and 3.5.2 when the anaerobic zone (of R1) was dosed with the ferrous-ferric blend. There was a slight tendency for the pH of the aerobic zones to be lower in R1 than R2 (Table 5.8), which may be expected since the ferrous-ferric dosing still produced a net alkalinity demand (see above). However, this difference never exceeded 0.11 pH units on a median basis and therefore appeared to be insignificant. During Periods 3.4.1 through 3.4.4, the pH in the aerobic zones was >7.2 with few exceptions (Table 5.8). However, during Periods 3.5.1 and 3.5.2 (due to reduced total alkalinity in the system due to lower P concentrations), the pH of the first aerobic zone (point of dosing) fell more frequently into the range 7.1 to 7.2 and this may have contributed to a decrease in P precipitation "efficiency" (Rabinowitz and Marais, 1980).

5.3.5 Fractionation studies

5.3.5.1 Enhanced cultures

Fractionation studies for Periods 3.4.1 through 3.4.3 showed that ferrous-ferric chloride, like ferric chloride and alum, increased the ortho P ("chemical precipitate") fraction of the sludge (Fig. 5.9). During Periods 3.4.1 (high Fe dose to aerobic zone), the increase in the sludge ortho P fraction was six-fold and during Period 3.4.3 (low Fe dose to anaerobic zone) it was between five and six-fold, compared to the Control. During Period 3.4.2 (low Fe dose to the aerobic zone) the increase in sludge ortho P fraction was 2 to 3-fold. However, these results must be viewed against the background of complete steady-state conditions not being fully achieved (see P mass balance discussion under 5.3.3). It can be observed

Table 5.8: Alkalinity and pH data for periods of ferric chloride dosing (3.3.1 to 3.3.5)

Period	Unit: / Zone:	R1 AN	R2 AN	R1 AE1	R2 AE1	R1 AE2	R2 AE2	R1 H_2CO_3* Alk. mg/ℓ as $CaCO_3$ Effluent	R2 H_2CO_3* Alk. mg/ℓ as $CaCO_3$ Effluent
3.4.1	MEDIAN	7.16	7.00	7.35	7.34	7.55	7.62	258#	277#
	MIN.	6.93	6.93	7.11	7.15	7.33	7.46	230	232
	25%-ILE	7.11	6.97	7.28	7.25	7.49	7.57	-	-
	75%-ILE	7.22	7.07	7.38	7.41	7.59	7.67	-	-
	MAX.	7.30	7.21	7.65	7.46	7.99	7.78	290	315
3.4.2	MEDIAN	7.09	7.09	7.37	7.34	7.59	7.61	274#	287#
	MIN.	6.86	6.85	7.13	7.25	7.20	7.48	245	248
	25%-ILE	7.02	7.02	7.30	7.29	7.54	7.58	-	-
	75%-ILE	7.18	7.14	7.43	7.39	7.63	7.70	-	-
	MAX.	7.37	7.30	7.65	7.73	7.80	8.09	316	314
3.4.3	MEDIAN	7.05	7.01	7.44	7.33	7.68	7.62	271#	279#
	MIN.	7.01	6.94	7.21	7.23	7.40	7.46	250	257
	25%-ILE	7.02	6.98	7.39	7.31	7.62	7.59	-	-
	75%-ILE	7.07	7.03	7.48	7.37	7.73	7.68	-	-
	MAX.	7.16	7.18	7.82	7.73	8.16	8.15	284	290
3.4.4	MEDIAN	7.26	7.23	7.52	7.54	7.71	7.79	229#	251#
	MIN.	7.00	6.92	7.15	7.17	7.33	7.38	208	229
	25%-ILE	7.21	7.16	7.42	7.47	7.60	7.68	-	-
	75%-ILE	7.35	7.29	7.57	7.61	7.78	7.85	-	-
	MAX.	7.48	7.43	7.71	7.77	7.93	8.00	261	281
3.5.1	MEDIAN	7.50	7.53	7.21	7.26	7.32	7.37	109#	125#
	MIN.	7.27	7.29	7.09	7.11	7.21	7.27	82	102
	25%-ILE	7.45	7.44	7.14	7.18	7.27	7.34	-	-
	75%-ILE	7.56	7.59	7.33	7.34	7.47	7.52	-	-
	MAX.	7.67	7.72	7.55	7.59	7.81	7.90	148	153
3.5.2	MEDIAN	7.31	7.36	7.22	7.30	7.37	7.48	120#	142#
	MIN.	7.17	7.15	7.11	7.16	7.23	7.26	96	121
	25%-ILE	7.23	7.24	7.19	7.27	7.31	7.41	-	-
	75%-ILE	7.37	7.40	7.31	7.34	7.43	7.48	-	-
	MAX.	7.44	7.52	7.38	7.39	7.54	7.58	142	163

# denotes mean in place of median

from Fig. 5.9 that ferrous-ferric chloride had a similar effect to ferric chloride in decreasing the relative size of the PCA-extractable complex P fraction while increasing the NaOH complex P fraction. At the low ferrous-ferric dose (Periods 3.4.2 and 3.4.3) this effect was a lot less marked than at the high dose (Period 3.4.1) (Fig. 5.9). This observation links with the experiment described in Chapter 2 (section 2.4.7) in which ferric ions were added during the fractionation procedure in the PCA step. This produced an "artificial" shift in complex P extraction away from the PCA step in favour of the NaOH step. It was hypothesised that this shift was an artefact arising from solubilisation of iron from the sludge matrix during the PCA step, followed by complexation/ coagulation with complex P compounds in such a way as to render these compounds insoluble in cold PCA but soluble in NaOH. Since the shift in solubility of complex P from the PCA to the NaOH step was very marked for the high ferrous-ferric dose to the Test unit (Fig. 5.9), it follows that more iron was bound in the sludge matrix under these conditions, thus exerting a very strong effect on the complex P solubility during extraction.

If the explanation of the fractionation patterns in Fig. 5.9 described above is followed, then the similar extents of P release shown by the Test and Control units in anaerobic batch tests (with excess acetate) can also be explained. This point will be discussed in more detail in the context of the anaerobic batch test results (see 5.3.6 below).

The key data in Fig. 5.9 are consolidated in Table 5.9.

In summary, from the fractionation studies, it may be said that the ferrous-ferric chloride always conferred an advantage on the Test system by increasing the sludge total P content. It did this by increasing the "chemically" bound ortho P fraction, with little alteration (at low doses) to the acid-extractable complex P fraction. At the same time, it increased the alkaline-extractable complex P fraction such that the sum of the acid and alkaline-extractable complex P fractions was never depressed by more than 13%), relative to the Control, even at high ferrous-ferric dose (Table 5.9). In two of the fractionation experiments (at the commencement and end of Period 3.4.3 when the anaerobic zone was dosed with ferrous-ferric chloride), the Test unit showed more complex P (biological) fractions than the Control unit. Although this may suggests that the biological mechanism was stimulated by the metal dosing at this time, it is more likely that the biological mechanism in the Control was inhibited by influent characteristics to a greater extent than in the Test unit (see section 5.3.1.1). A similar conclusion was reached from mass balance considerations around the anaerobic reactor (5.3.3.2 above).

University of Cape Town

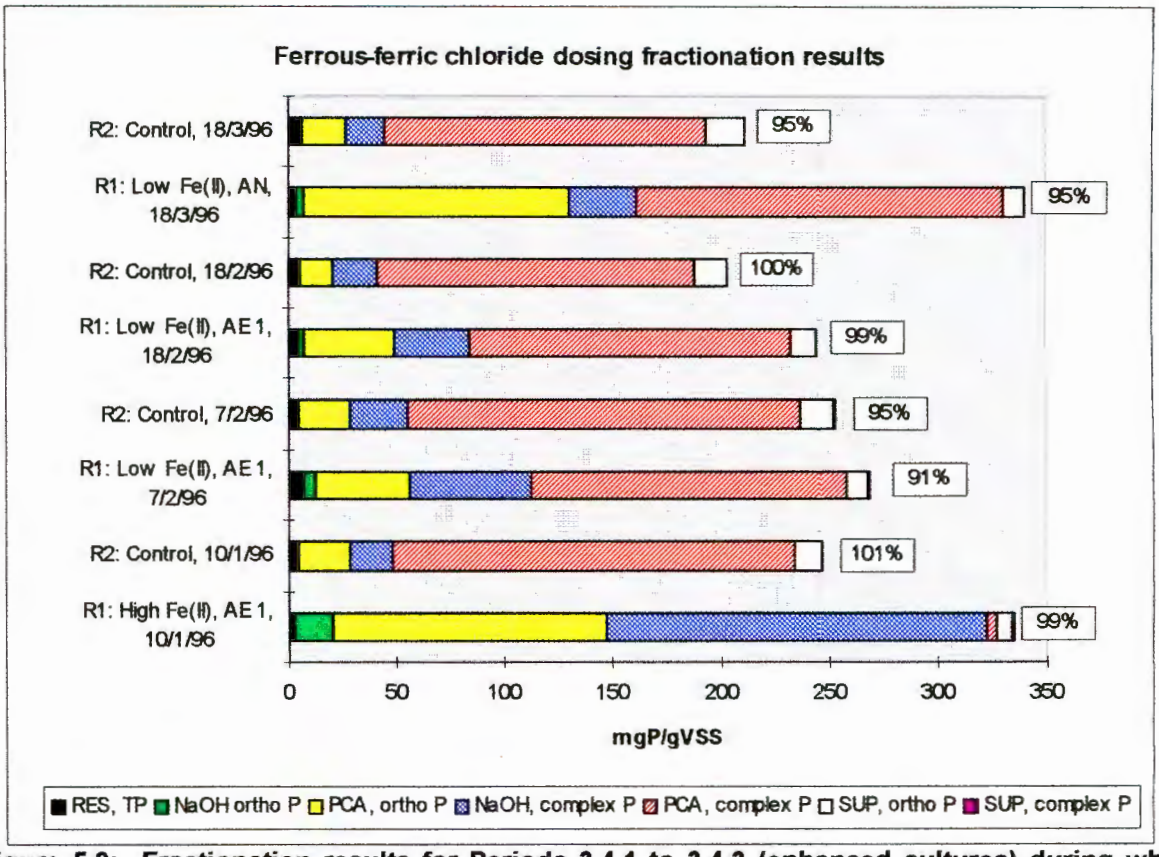


Figure 5.9: Fractionation results for Periods 3.4.1 to 3.4.3 (enhanced cultures) during which ferrous-ferric chloride was dosed to R1. Refer to Table 5.3 for ferrous-ferric chloride dose data. Percentage figures quoted are for % TP recovery in the fractionation procedure compared to the measured P/VSS content.

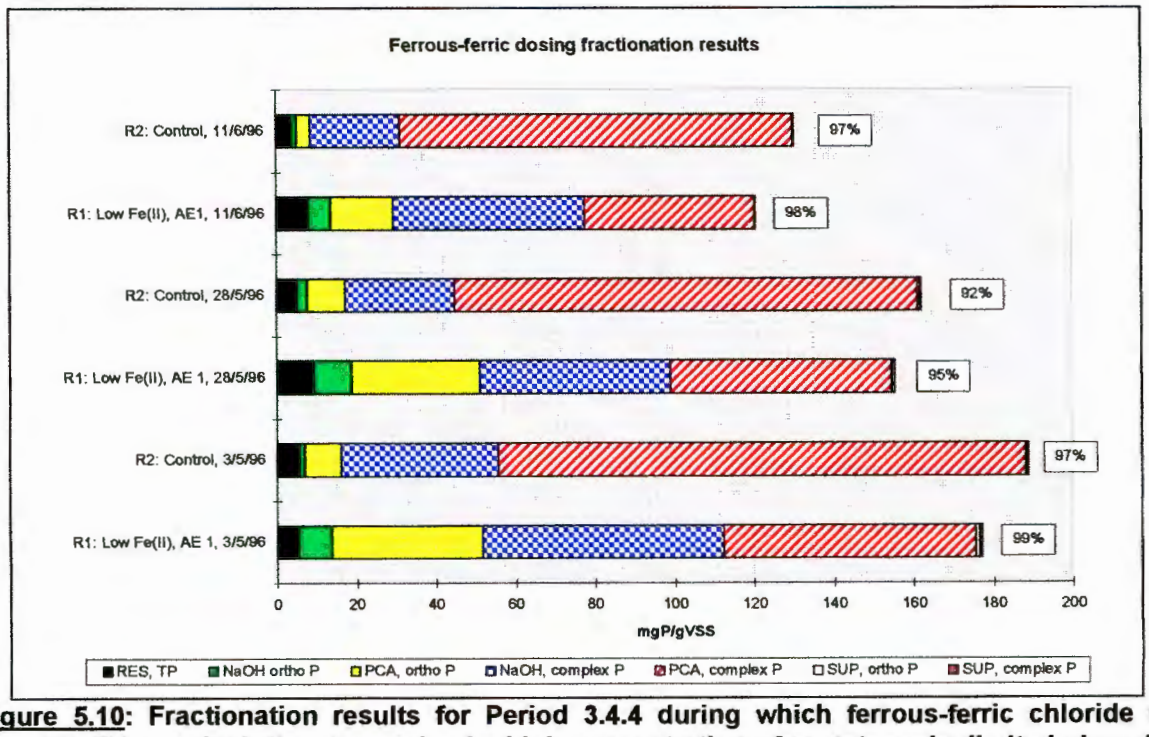


Figure 5.10: Fractionation results for Period 3.4.4 during which ferrous-ferric chloride was dosed to R1 and the influent contained a high concentration of acetate and a limited phosphate supplement. Refer to Tables 1 and 3 for further data. Percentage figures quoted are for % TP recovery in the fractionation procedure compared to the measured P/VSS content.

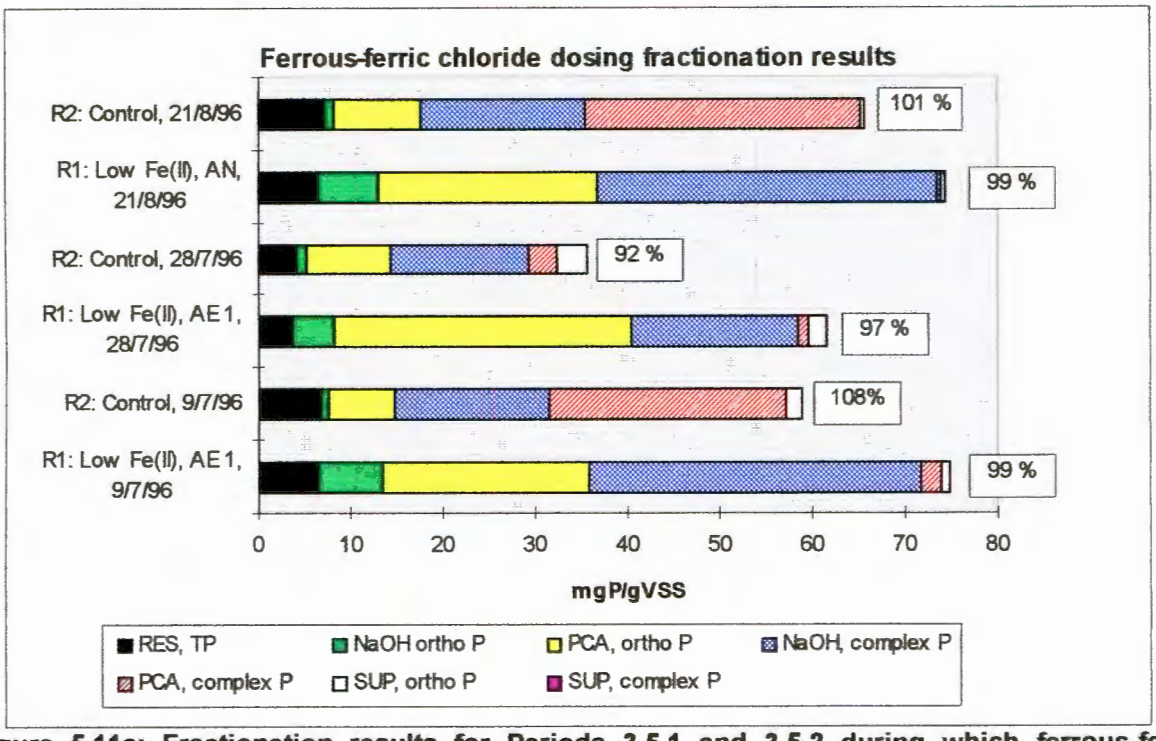


Figure 5.11a: Fractionation results for Periods 3.5.1 and 3.5.2 during which ferrous-ferric chloride was dosed to R1 and the influent contained low concentration of acetate and no phosphate supplement. Refer to Tables 5.1 and 5.3 for further data. Percentage figures quoted are for % TP recovery in the fractionation procedure compared to the measured P/VSS content.

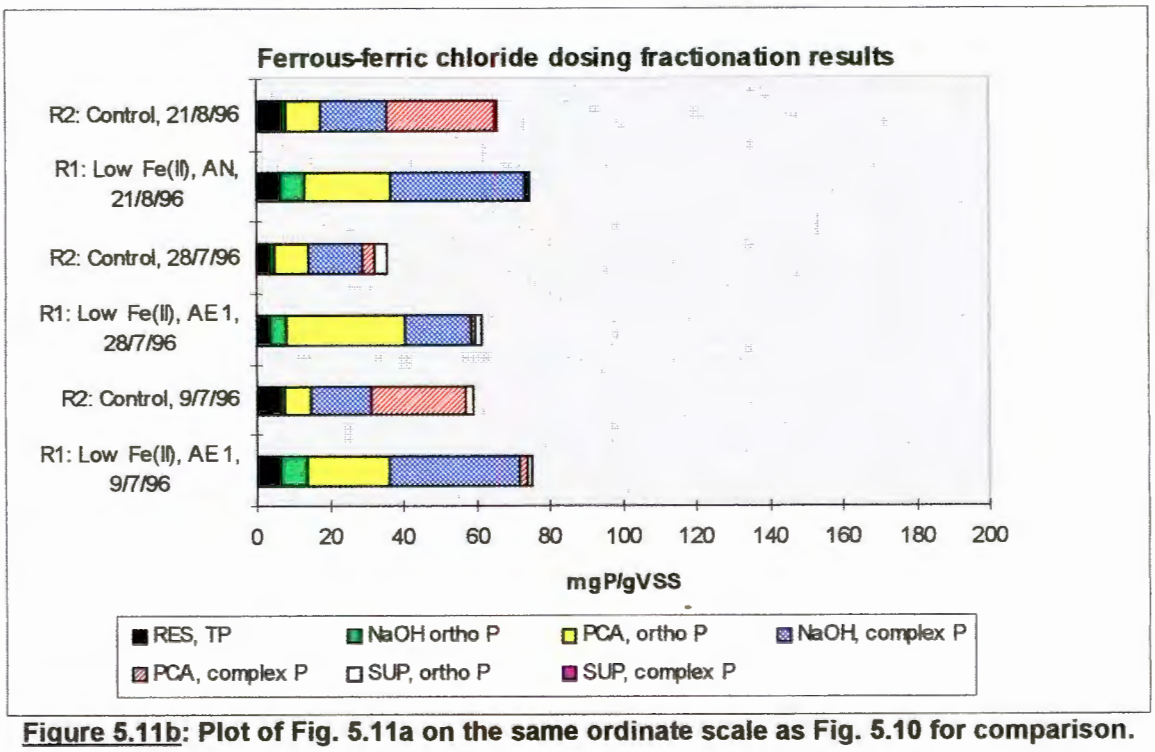


Figure 5.11b: Plot of Fig. 5.11a on the same ordinate scale as Fig. 5.10 for comparison.

Table 5.9: Summary fractionation data for Fig. 5.9 with ferrous-ferric chloride dosing.

Date, Unit	Period	Ferric dose Low = 6.2 High = 12.4 mmol/d	PCA Complex P mgP/gVSS	NaOH Complex P mgP/gVSS	Sum of PCA and NaOH Complex P fractions mgP/gVSS (#)	Sum of PCA and NaOH ortho P fractions mgP/gVSS (#)	VSS during fractionation g VSS/ℓ	Sum of PCA and NaOH Complex P fractions mgP/ℓ ##	Sum of PCA and NaOH ortho P fractions mgP/ℓ
		see Table 5.3	"Biological"	"Biological"	Total "Biological"	Total "Chemical"		Total "Biological"	Total "Chemical"
10/1/96, R1	3.4.1	High, AE1	4.452	175.99	**180.44 (56%)**	**143.578 (44%)**	**0.833**	**150.31 -5%**	**119.60**
10/1/96, R2		-	186.292	19.86	206.15 (89%)	24.834 (11%)	0.766	157.91 -	19.03
7/2/96, R1	3.4.2	Low, AE1	146.658	55.61	**202.27 (80%)**	**49.63 (20%)**	**0.907**	**183.46 -2%**	**45.01**
7/2/96, R2		-	180.863	27.40	208.27 (90%)	24.052 (10%)	0.866	187.20 -	20.83
18/2/96, R1	3.4.2/3	Low, AE1	148.83	34.96	**183.79 (81%)**	**44.22 (19%)**	**0.957**	**175.89 +18% ****	**42.32**
18/2/96, R2		-	146.61	20.69	167.30 ** (91%)	15.93 (9%)	0.888	148.56 -	14.15
18/3/96, R1	3.4.3	Low, AN	169.39	31.59	**200.98 (61%)**	**126.51 (39%)**	**0.906**	**182.09 +60% ****	**114.62**
18/3/96, R2		-	148.44	17.66	166.1 ** (89%)	21.48 (11%)	0.683	113.45 -	14.67

**: Partial inhibition of BEPR in the *Control* unit appeared to have occurred during Periods 3.4.2 & 3.4.3 (refer to section 5.3.1.1 in text).

#: (%) Percentages in parentheses refer to % sum of "Total Biological" and "Chemical".

##: Percentages, e.g. -5%, refer to percent inhibition of R1 "Total Biological" (mg/ℓ), relative to R2.

Table 5.10: Fractionation data relating to Figure 5.8 for Period 3.4.4.

Date, Unit	Period	Ferric dose Low = 6.2 High = 12.4 mmol/d	PCA Complex P mgP/gVSS	NaOH Complex P mgP/gVSS	Sum of PCA and NaOH Complex P fractions mgP/gVSS (#)	Sum of PCA and NaOH ortho P fractions mgP/gVSS (#)	VSS during fractionation g VSS/ℓ	Sum of PCA and NaOH Complex P fractions mgP/ℓ ##	Sum of PCA and NaOH ortho P fractions mgP/ℓ
		see Table 3	"Biological"	"Biological"	Total "Biological"	Total "Chemical"		Total "Biological"	Total "Chemical"
3/5/96, R1	3.4.4	Low, AE1	63.34	60.5	**123.84 (73%)**	**46.31 (27%)**	**0.661** (Low: error)	Error Low VSS	Error Low VSS
3/5/96, R2		-	132.18	39.52	171.7 (94%)	10.53 (6%)	1.076	184.75	11.33
28/5/96, R1	3.4.4	Low, AE1	55.49	47.99	**103.48 (71%)**	**41.56 (29%)**	**0.991**	**102.54 -28%**	**41.19**
28/5/96, R2		-	116.25	27.56	143.81 (92%)	11.98 (8%)	0.983	141.65 -	11.78
11/6/96, R1	3.4.4	Low, AN	42.75	48.07	**90.82 (81%)**	**21.34 (19%)**	**1.325**	**120.34 -19%**	**28.28**
11/6/96, R2		-	98.72	22.64	121.36 (96%)	4.62 (4%)	1.225	148.67 -	5.66

Table 5.11: Fractionation data relating to Figures 5.11 (a&b) for Periods 3.5.1 and 3.5.2 of ferrous-ferric chloride dosing.

Date, Unit	Period	Ferric dose Low = 6.2 High = 12.4 mmol/d	PCA Complex P mgP/gVSS	NaOH Complex P mgP/gVSS	Sum of PCA and NaOH Complex P fractions mgP/gVSS (#)	Sum of PCA and NaOH ortho P fractions mgP/gVSS (#)	VSS during fractionation g VSS/ℓ	Sum of PCA and NaOH ortho P fractions mgP/ℓ	Sum of PCA and NaOH ortho P fractions mgP/gVSS
		see Table 3	"Biological"	"Biological"	Total "Biological"	Total "Chemical"		Total "Biological"	Total "Chemical"
9/7/96, R1	3.5.1	Low, AE1	2.17	35.77	**37.94 (56%)**	**29.38 (44%)**	**1.209**	**45.87 -0%**	**35.52**
9/7/96, R2		-	25.59	16.68	42.27 (84%)	8.08 (16%)	1.086	45.91 Low BEPR	8.78
28/7/96, R1	3.5.1/2	Low, AE1	1.16	17.84	**19.00 (34%)**	**36.74 (66%)**	**0.874**	**16.61 +3%**	**32.11**
28/7/96, R2		-	3.00	15.00	18.00 (64%)	10.24 (36%)	0.894	16.09 Very low BEPR	9.15
21/8/96, R1	3.5.2	Low, AN	0.59	36.56	**37.15 (55%)**	**30.23 (45%)**	**1.109**	**41.20 -22%**	**33.53**
21/8/96, R2		-	29.65	17.95	47.6 (82%)	10.27 (18%)	1.110	52.84	11.40

#: (%) Percentages in parentheses refer to % sum of "Total Biological" and "Chemical". ##: Percentages, e.g. -5%, refer to percent inhibition of R1 "Total Biological" (mg/ℓ), relative to R2.

5.3.5.2 P-limited enhanced cultures

Figure 5.10 and Table 5.10 summarise the fractionation results for Period 3.4.4 during which the influent to the units continued to be supplemented with sodium acetate (150 mg/ℓ as COD), but the added phosphate was limited to 15 mgP/ℓ. The effect was to produce an effluent with low P concentrations (Table 5.4) and hence to stimulate "competition" between the biological and chemical mechanisms for residual dissolved phosphate.

From Fig. 5.10 and Table 5.10 it can be seen that (unlike the enhanced cultures which were always fed excess phosphate), the Test unit (R1) began to show signs of a weaker combined P removal mechanism in that the mixed liquor solids contained slightly less phosphate (on a P/VSS basis) than the Control unit (R2). Whilst this was true for the days on which the units were tested by fractionation, Table 5.4 shows that it was not true for Period 3.4.4 as a whole, where R1 gave a mean of 179 mgP/gVSS, whereas R2 gave a mean of 194 mgP/gVSS. Moreover, the standard deviation on these data was greater for R1 (33 mgP/gVSS) than for R2 (21 mgP/gVSS) (Table 5.4). It is therefore not surprising that the normal probability plots for P removal were very similar for the two units during this period (Fig. 5.6b), with R1 showing a slight advantage over R2, possibly because the chemical mechanism allowed low concentrations of residual dissolved phosphate to be "captured" by precipitation. Fig. 5.10 clearly shows the increased size of the "chemical precipitate" (PCA ortho P) fraction in the Test unit, relative to the Control.

Figure 5.10 shows a continuation of the trend for the enhanced cultures in respect of the shift from acid-extractable to alkaline-extractable complex P in the presence of ferrous-ferric chloride dosing. The two complex P fractions became approximately equally "sized" in this experimental period for the Test unit (R1). As discussed under 5.3.5.1, this shift is probably attributable to an artefact produced by the fractionation procedure itself and will be considered also in the context of anaerobic P release batch tests (5.3.6).

In summary, Table 5.10 shows that under low effluent P conditions, the biological component in the Test unit appeared to be depressed by approximately 25 to 30%, compared to the Control, but the difference appeared to be largely compensated for by an increase in the chemically-bound fraction. Further experimentation over a period longer than seven sludge ages would be required to ascertain whether a gradual decline in the biological mechanism could occur under continuously low effluent P concentrations.

5.3.5.3 "Normal sewage"

Figure 5.11(a or b) and Table 5.11 summarise the fractionation results for Periods 3.5.1 and 3.5.2 during which the influent was essentially normal Darvill settled sewage with a small amount sodium acetate added (20 mg/ℓ as COD). No phosphate was added to the influent. From Table 5.4 it may be recalled that the effect of this operational mode was to produce an effluent with low P concentrations, although not as low as in Period 3.4.4, probably because the biological P removal mechanism was weakened by the lower influent acetate (or readily biodegradable COD) concentration. This would suggest that "competition" between the chemical and biological mechanisms for residual phosphate would probably not have been as strong in these experimental periods as in Period 3.4.4.

From Fig. 5.11a (or 5.11b) it can be seen that the sum of the fractions (sludge total P) were much lower than for the enhanced cultures (Figs. 5.9 and 5.10), as may be expected from the reduced acetate concentration in the feed. The "shift" in complex P extraction from PCA to NaOH fractions was again observed, as discussed under 5.3.5.1 and 5.3.5.2 above.

Figures 5.11 (a & b) show that fractionation pattern of 28/7/96 (end of Period 3.5.1, moving into 3.5.2) yielded a smaller sum of the P fractions (i.e. smaller sludge total P), particularly in the Control (R2), with the PCA-complex P fraction uncharacteristically "depressed". The detailed daily results given in Appendix 5 reflect that the fractionation pattern on 28/7/96 followed a period of six days during which P removal (particularly in R2) was low (0.78 to 2.78 mgP/ℓ removal, median 2.01 mgP/ℓ removal over six days, compared to the mean of 3.85 mgP/ℓ removal for Period 3.5.1 as a whole). This may have been due to a "weak" sewage because early July 1996 was

characterised by unseasonably wet weather in Pietermaritzburg, with heavy snowfalls in nearby parts of the country. The mean COD measured over this six day period was 269 mg/ℓ, which was close to the mean of 280 mg/ℓ for the whole period. However, modelling of data for Period 3.5.1 using either the UCTPHO or IAWQ model (see Chapter 7, section 7.1.5), required input of a high unbiodegradable particulate influent COD fraction and low readily biodegradable influent COD fraction(s). The requirement for a high unbiodegradable particulate fraction appeared in the modelling for several other experimental periods which all coincided with the spring/ summer season when the catchment of Darvill WWW typically receives most rain. As stated, July 1996 (Period 3.5.1) saw unseasonable high rainfall in this catchment.

It is interesting to note from Figs. 5.11 (a & b) that the Test unit (R1) performed significantly better than R2 over the same six day period preceding the 28/7/96 fractionation, with a median removal of 4.48 mgP/ℓ compared to a mean removal of 6.04 mgP/ℓ for the whole of Period 3.5.1. Allowing for a median of 1.70 mgP/ℓ *biological* removal during the six day period (on the basis of results for the Control unit, R2), the median *chemical* removal in the Test unit (R1) was 4.48 - 1.70 = 2.78 mgP/ℓ over the six day period. This compares with the mean chemical removal of 6.04 - 3.85 = 2.19 mgP/ℓ for Period 3.5.1 as a whole. In other words, the chemical mechanism performed slightly better than average during the six day sub-period and partly compensated for the weaker biological P removal. The fractionation results for R1 in 28/7/96 (Fig. 5.11a) showed a large relative fraction of "chemically" bound phosphate (PCA extractable ortho P). These results suggest that during Period 3.5.1, the mixed liquor in R1 had the capability of drawing from some "reserve" P removal potential at a time when the biological P removal was low. This point illustrates the value of a combined chemical-biological P mechanism in potentially improving effluent compliance at times when the influent conditions are not conducive to good biological P removal. The "reserve" P removal potential will most likely be in the form of metal hydroxide accumulated in the mixed liquor (see Chapter 7, section 7.1.1 and 7.1.5). The metal hydroxide has an ion exchange capacity for phosphate (c.f. Chapter 1, section 1.2.1.3; and Chapter 7, section 7.1.1). For a constant metal dose, at low effluent phosphate concentrations, more metal hydroxide will accumulate as phosphate becomes limiting. This will improve the "reserve" potential of the mixed liquor to remove phosphate chemically under transient conditions when the biological removal potential is weak.

It is worth noting that the mixed liquor sample from the Control unit (R2) on 28/7/96 exhibited a fractionation pattern of weak biological excess P removal (BEPR), tending toward the "baseline" for a non-BEPR sludge. The mixed liquor total P content for this sample was 38 mgP/gVSS. Allowing 20 mgP/gVSS for nucleic acids and phospholipids (De Haas, 1989), and subtracting ca. 9 mgP/gVSS for chemically-bound sludge ortho P and 3 mgP/gVSS for the mixed liquor supernatant ortho P, this leaves approx. 6 mgP/gVSS for possible poly P storage. Anaerobic P release with excess acetate over 4h amounted to 5.2 mgP/gVSS for the 28/7/96 sample (Fig. 5.14a or b) , which is in reasonable agreement with the afore-mentioned estimate based on fractionation results.

The fractionation results for Periods 3.5.1 and 3.5.2 are summarised in Table 5.11.

If the results for 28/7/96 are neglected (for above-mentioned reasons), Table 5.11 indicates that the "biological" component of complex P fractions was depressed by 10 to 22%, which, as expected, was less than for Period 3.4.4 when lower effluent P concentrations were achieved. This tends to confirm the hypothesis that competition between the biological and chemical mechanisms for available phosphate increases as the effluent P concentration decreases below ca. 1 mgP/ℓ. However, the difference in biologically stored fractions was more than compensated for by an increase in the "chemical" ortho P fraction. This is in keeping with the results which showed greater P removal in the Test unit compared to the Control for these periods (Figs. 5.7b & 5.8b).

5.3.5.4 Estimation of chemical precipitation efficiency from fractionation data

Based on the assumption that the PCA and NaOH ortho P fractions represent chemical precipitate extracted from the mixed liquor, it is possible to estimate the molar ratio of Fe:P in chemical precipitate formed as a result of ferrous-ferric chloride dosing on the basis of the relative size of these fractions between the Test and Control units. The results are shown in Table 5.12a may be

compared with those found on the basis of the difference in system P removal between the two units (Table 5.6 results, also shown in Table 5.12a).

Comparing the estimated molar ratio (P/Fe) of precipitation from fractionation data with that from the difference in system P removal (Table 5.12a), it can be seen that there are discrepancies in the results for certain periods:

- In Period 3.4.1 the P/Fe molar ratio estimated from the fractionation results was much greater than that estimated from the system P removal. This discrepancy probably arose from a failure of the Test system to reach satisfactory steady-state after the change from ferric chloride (previous experimental period - Period 3.3.6) to the ferrous-ferric chloride blend. As will be seen (section 5.3.8), the solids data in Table 5.13 also suggest that steady-state was not completely achieved in Period 3.4.1.
- The fractionation data for Periods 3.4.2 and 3.4.3 (at the lower Fe dose) showed an increase with time in the precipitate P:Fe molar ratio from 0.47 to 0.68 (Table 5.12a); again, this may reflect slow equilibration of solids in the Test system toward steady-state.
- In Period 3.4.3, as discussed above (see section 5.3.1.1), biological P removal in the Control unit (R2) was weakened, possibly due to the nature of the source sewage from Darvill WWW during this period. As expected, this affected the molar ratio estimate of the precipitate based on system P removal (Table 5.6), but not that based on fractionation data.

For the remainder of the experimental periods, the data in Table 5.12a showed reasonable agreement between the precipitate P:Fe molar ratio found by the two methods. Both methods suggested that that the precipitation efficiency is lower under conditions where low effluent P concentrations occur (i.e. the system reaches potential P limitation). Under high effluent P conditions (ca. 20 mgP/ℓ), the P:Fe molar ratio appeared to be approximately 0.7 (taking results for 18/3/96 at the end of Period 3.4.3 as being closest to steady state, for reasons given above). For low effluent P concentrations (ca. 1 mgP/ℓ), the P:Fe molar ratio fell to between 0.2 and 0.4, based on the fractionation results (notably by the end of Period 3.4.4, and for Periods 3.5.1 and 3.5.2). Similar results were found from the system P removal data by taking the overall average results for these experimental periods (from Table 5.6). Individual sub-periods of Period 3.4.4 showed more variation in the data based on differences in system P removal, which probably reflects limitations in accuracy of the vanadate-molybdate total P method at low concentrations (< 1 mgP/ℓ), as used here[5].

It is possible to use the stoichiometry calculated from fractionation data to estimate the steady-state concentration of metal (hydroxy) phosphate precipitate in the Test unit, and to compare this with the "metal phosphate" (MeP) concentration predicted using the IAWQ ASM2 model (refer to section 7.2.2.2 of Chapter 7). In order to do this, it is necessary to assume an hypothetical formula for the precipitate. The formula applied here was that used by (Luedecke et al., 1989), namely:

$$Me_r\ PO_4\ (OH)_{3r-3}$$

where Me is a trivalent metal ion (Fe^{3+} in this case) and r is the Me:P stoichiometry.

Using the above approach, the results in Table 5.12b were obtained. This table shows that fairly good agreement was achieved between the metal (hydroxy) phosphate (MeP) predictions of the IAWQ model and those estimated from fractionation results , excepting Period 3.4.1 (for which there was some doubt over the steady-state results). In absolute terms, the difference between the fractionation and model MeP estimates seldom differed by more than 100 mg/ℓ (TSS), which would be minimal in respect of design or operation of a real system. However, as expected, the comparison is very sensitive to Fe:P stoichiometry. This aspect is examined in detail in Chapter 7 (sections 7.2.2.2 and 7.2.4.2).

[5] During the course of the investigation, it was found that the vanadate-molybdate reagent deteriorated with age if stored for more than one week (evidenced by a fine yellow precipitate in the bottom of the reagent bottle). This may have limited the accuracy of the method, particularly at low P concentrations (e.g. <1 mgP/ℓ), which occurred at times in the Test unit during Period 3.4.4. In subsequent experimental periods (Periods 3.6.1. and 3.6.2, Chapter 4, section 4.3.11, the more sensitive molybdate-ascorbic acid method was used.)

5.3.6 Batch tests in association with fractionation studies

Figures 5.12 (a & b), 5.13 (a & b) and 5.14 (a & b) summarise the results of sludge fractionation before and after anaerobic P release batch tests in the presence of excess acetate. From calculated differences, these data indicate from which fractions P release took place. In the case of fractions where P uptake occurred, this is plotted as *negative release*. In theory, the sum of all the P release from the respective fractions (including uptake, if present) should equal the net release of ortho P observed for the supernatant (SUP), which is plotted as a line in Figs. 5.12a to 5.14b. In practice, this is only possible within the bounds of experimental error, and is constrained by the difficulty of ensuring 100% recovery of the various fractions, especially where dilutions are necessary (refer to Figs. 5.9, 5.10 and 5.11a for typical total P recoveries).

Figure 5.12a shows that for the enhanced cultures, a high ferrous-ferric chloride dose resulted in almost all the P release occurring from the NaOH complex P fraction; the PCA complex P fraction was virtually absent (see also Fig. 5.9). This was similar to the fractionation and P release pattern observed for a high ferric chloride dose (Fig. 4.4a of Chapter 4). By contrast, in the Control, most of the P release came from the PCA complex P fraction (Fig 5.10b).

Like ferric chloride, a high ferrous-ferric dose also apparently resulted in surplus chemical adsorption or precipitation capacity for binding P during the batch release test. This may be deduced from the uptake in the PCA ortho P fraction (Fig. 5.12a; also found in Fig. 4.4a).

From Figs. 5.12a and 5.12b, it can seen that the bulk of the P release came from the PCA complex P fraction in both units for low ferrous-ferric dosing periods, but apparently mainly from the NaOH complex P unit at high ferrous-ferric dose. Ferrous-ferric dosing did appear to give a degree of "inhibition" in so far as the net P release for the Test unit was depressed to a variable extent (10 to 23%) relative to the Control in two out of four cases, but was equivalent or slightly enhanced in the other two cases. The extent of this depression can also be calculated from the change in the respective fractions before and after P release (Figs. 5.12a & b). On this basis, the biological mechanism was depressed in the Test unit by approx. 15 to 22% at most, assuming that apparent uptake in the ortho P fractions is not counted as release. A similar conclusion was drawn from data given in Table 5.9. If uptake in the ortho P fractions (Fig. 5.12a) is counted as part of the P release, the extent of inhibition was less than 16%, and in one case (high ferrous-ferric dose, Period 3.4.1) P release from the Test unit sample was approx. 15% greater than that from the Control unit. However, this difference may not be significant in view of the fact that the Test unit probably did not approach steady state sufficiently closely in Period 3.4.1, as noted in sections 5.3.5.4 and 5.3.8.

Figure 5.12a shows that a low ferrous dose produced a small and variable tendency for uptake to occur in the alkaline (NaOH) complex P fraction during batch tests, and particularly in the case where the anaerobic zone was dosed. This did not occur to the same extent in the Control (Fig. 5.12b). It is not clear whether these observations may be artefacts of the extraction procedure itself, but could indicate the formation of colloidal iron (hydroxy) phosphate complexes in association with the biomass, so as to be alkaline (rather than acid) soluble.

Examining the results for enhanced cultures under P limitation (Figs. 5.13a & b), it is clear that for a low ferrous dose to the Test unit, the NaOH complex P fraction consistently appeared more prominent in the P release tests. A small amount of release was also noted from the NaOH ortho P fraction, which was surprising. However, release from the PCA complex P fraction was still predominant, although by the end of the experimental period (3.4.4), release from the PCA and NaOH complex P fractions were almost equal (Fig. 5.13a). This emphasises that the NaOH complex P fraction is an important biological component, but its size in relation to the PCA complex P fraction is largely an artefact of the fractionation procedure itself (see Chapter 2, section 2.4.7). By contrast, in the Control (Fig. 11b), release only occurred from the PCA complex P fraction. Variable minor uptake was noted for the Control NaOH or PCA ortho P fractions, but again, these may have been experimental artefacts.

Taking Figs. 5.13a & 5.13b as a whole, if the uptake in the ortho P fractions is not regarded as part of the P release, then the net P release was depressed by 26 to 28% in the Test unit relative to the Control. If the uptake in the ortho P fractions is counted as part of the release, the degree to which P release was depressed in the Test unit was less (5 to 23%).

With the non-enhanced (P-limited) cultures from "normal sewage", P release in the Control continued to be accounted for from the PCA complex P fraction (Fig 5.14b). Minor P release from the NaOH complex P fraction was noted in the Control (Fig. 5.14b) and appeared to be more significant because the scale of P release was smaller for Periods 3.5.1 and 3.5.2. P release (or sometimes uptake) of similar extent had been observed for the NaOH complex fraction in previous periods (e.g. Fig. 5.12b). Again these may be artefacts of the fractionation procedure, depending on the background concentration of metal ions bound in the sludge mass of the Control.

By contrast, in the Test unit with its small PCA complex P fraction, release from the PCA complex P fraction was virtually absent (Fig. 5.14a). Almost all the release from this unit occurred from the NaOH complex P fraction. It is worth noting that the magnitude of P release from the NaOH complex P fraction in the Test unit was of the same order as that from the PCA complex P fraction of the Control unit (note different scales of Figs. 5.14a and 5.14b). According to current understanding of the BEPR mechanism, release of P under anaerobic conditions in the presence of excess acetate is biologically mediated. In the past, the relative "size" of the biological mechanism has sometimes been taken to be represented by the size of the PCA complex P fraction (*inter alia* Kerdachi and Roberts, 1985; Mino *et al.*, 1985; Lötter, 1991; De Haas and Greben, 1991). From Fig. 5.14a it can be concluded that the alkaline-extractable complex P fraction obtained by crude fractionation techniques such as that applied here, can be equally important in the biological mechanism; its form (or solubility in extraction techniques) will be dependent on the nature of the influent and reactions involving metal ions usually considered to be chemical P precipitants.

From the fractionation results before/ after P release batch tests, there does appear to be a link between uptake into the PCA ortho P fraction (presumed chemical precipitate) and either low residual soluble phosphate concentrations or relatively high iron doses (compare Figs. 5.12a, 5.13a and 5.14a). Particularly Fig. 5.12a also shows that significant apparent uptake into the NaOH complex P fraction sometimes occurred as a result of the batch P release test. It may be speculated that this could be a result of an alkaline-soluble complex with a phosphate-binding capacity forming between ferric ions and a biological polymer such as extracellular polysaccharide. The existence of complexes between ferric ions and biological exopolymer in activated sludge was proposed by Brown and Lester (1979) and is supported by the electron microscope work of He *et al.* (1996). Uptake of phosphate in sludge fractions such as the PCA ortho P or NaOH complex P fractions, probably stems from the availability in the sludge matrix of "spare" iron (e.g. in the hydroxide form) with the capacity to adsorb/ complex/ precipitate ortho P as it is released from a stored biological (poly P) form under anaerobic conditions. It seems inevitable that this observation is linked to the manner in which the chemical and biological mechanisms interact. The fact that the biological mechanism remained relatively strong in the presence of simultaneous iron dosing under low effluent P conditions implies that the two mechanisms are not mutually exclusive. Nevertheless, a degree of inhibition of the biological mechanism cannot be ignored, particularly under low effluent P (<1 mgP/ℓ) conditions. This inhibition may come from the presence of ferric hydroxide (or similar) precipitate with "spare" capacity for phosphate adsorption/ ion exchange arising from metal dosed but not precipitated as metal phosphate due to the limiting dissolved ortho P concentrations in the mixed liquor. Some of the phosphate released biologically may then become adsorbed (or precipitated after ion exchange) to the accumulating ferric hydroxide, thus becoming "trapped" in the chemical mechanism rather than available for biological re-uptake in the aerobic zone.

Summarising, it may be concluded from the P release tests that the degree of biological P removal inhibition in the Test unit ranged from 15 to 37%, assuming uptake into the ortho P fractions is not counted as part of the P release. This agrees broadly with the conclusion from Table 5.11 that the biological fractions were depressed by 10 to 22%. On the other hand, the uptake in the ortho P fractions may be assumed to count as part of the release, which would imply that P release was depressed to a lesser degree in the Test unit (7% in one case) and may even have been up to about 35% greater in the Test unit (relative to the Control) in two cases. Evidence was found that P released biologically may be bound chemically. Since the biological mechanism appeared to compete fairly successfully with the chemical mechanism under low (or limiting) P conditions, it seems likely that a degree of migration of P between chemical and biologically bound forms will occur during successive anaerobic-aerobic cycles of biological P release and uptake.

Table 5.12a: Estimation of molar ratio of additional P removed as chemical precipitate (PCA and NaOH ortho P fractions) to iron dosed as ferric chloride. Sludge age = 10 d.

UNIT/ FERRIC	DATE	PCA + NaOH ortho P fractions mgP/gVSS	Ave. VSS for Period g/L	VSS wasted g/d	PCA+ NaOH ortho P wasted mgP/d	Difference R1-R2 PCA + NaOH ortho P wasted mgP/d	Fe dosed mmol/d	mol P/ mol Fe PCA + NaOH ortho P This table	mol P /mol Fe from system P removal Table 5.6
R1: High Fe, AE1: 3.4.1	10/1/95	143.57	1.332	4.262	611.97	523.92	12.4	1.37	0.74
R2: 3.4.1	10/1/95	24.83	1.108	3.546	88.05			*	
R1: Low Fe, AE 1: 3.4.2	7/2/96	49.63	0.999	3.197	158.65	90.00	6.2	0.47	0.62
R2: 3.4.2	7/2/96	24.05	0.892	2.854	68.65				
R1: Low Fe, AE 1: 3.4.2	18/2/96	44.22	0.999	3.197	141.36	95.89	6.2	0.50	0.62
R2: 3.4.2	18/2/96	15.93	0.892	2.854	45.47				
R1: Low Fe, AN: 3.4.3	18/3/96	55.86	0.901	2.883	161.06	130.02	6.2	0.68	1.75
R2: 3.4.3	18/3/96	12.42	0.781	2.499	31.04				**
R1: Low Fe, AN: 3.4.4	3/5/96	46.31	0.939	3.005	139.15	107.31	6.2	0.56	0.23
R2: 3.4.4	3/5/96	10.53	0.945	3.024	31.84				(0.16) #a
R1: Low Fe, AN: 3.4.4	28/5/96	41.56	0.939	3.005	124.88	88.65	6.2	0.46	0.23
R2: 3.4.4	28/5/96	11.98	0.945	3.024	36.23				(0.30) #b
R1: Low Fe, AN: 3.4.4	11/6/96	21.34	0.939	3.005	64.12	50.15	6.2	0.26	0.23
R2: 3.4.4	11/6/96	4.62	0.945	3.024	13.97				(0.07) #c
R1: Low Fe, AE1: 3.5.1	9/7/96	29.38	1.078	3.450	101.35	76.40	6.2	0.40	0.41
R2: 3.5.1	9/7/96	8.08	0.965	3.088	24.95				
R1: Low Fe, AE 1: 3.5.2	21/8/96	30.23	1.061	3.395	102.64	70.27	6.2	0.37	0.21
R2: 3.5.2	21/8/96	10.27	0.985	3.152	32.37				

Table 5.12b: Comparison of metal phosphate (MeP) predictions from fractionation results (PCA ortho P fraction) in Table 5.12a and those from the IAWQ model (refer to section 7.2 of Chapter 7).

PERIOD, UNIT	DATE	PCA + NaOH ortho P mgP/gVSS	Ave. VSS for period g/L	PCA + NaOH ortho P mgP/L	Difference mgP/L	PCA + NaOH ortho P MeP, mg/L	Frac. Stoich. P/Fe mol P/ mol Fe	IAWQ Model Stoich. P/Fe mol P/ mol Fe	IAWQ Model Predicted MeP, mg/L	PCA + NaOH /Model %
3.4.1, R1	10/1/95	143.57	1.332	191.24	163.72	306	1.37 *	0.75	559	55%
3.4.1, R2	10/1/95	24.83	1.108	27.52						
3.4.2, R1	7/2/96	49.63	0.999	49.58	28.12	188	0.47	0.75	282	67%
3.4.2, R2	7/2/96	24.05	0.892	21.45						
3.4.2, R1	18/2/96	44.22	0.999	44.18	29.97	187	0.50	0.75	282	66%
3.4.2, R2	18/2/96	15.93	0.892	14.21						
3.4.3, R1	18/3/96	55.86	0.901	50.33	40.63	180	0.68 **	0.75	282	64%
3.4.3, R2	18/3/96	12.42	0.781	9.70						
3.4.4. R1	3/5/96	46.31	0.939	43.49	33.53	185	0.56	0.60	207	89%
3.4.4, R2	3/5/96	10.53	0.945	9.95						
3.4.4, R1	28/5/96	41.56	0.939	39.02	27.70	190	0.46	0.60	207	92%
3.4.4, R2	28/5/96	11.98	0.945	11.32						
3.4.4, R1	11/6/96	21.34	0.939	20.04	15.67	198	0.26	0.60	207	95%
3.4.4, R2	11/6/96	4.62	0.945	4.37						
3.5.1, R1	9/7/96	29.38	1.078	31.67	23.87	190	0.40	0.40	206	92%
3.5.1, R2	9/7/96	8.08	0.965	7.80						
3.5.2, R1	21/8/96	30.23	1.061	32.07	21.96	190	0.37	0.40	202	94%
3.5.2, R2	21/8/96	10.27	0.985	10.12						

#a: Sub-period 1/4/96 to 3/5/96 (20 results); #b: 3/5/96 to 28/5/96 (15 results); #c: 28/5/96 to 11/6/96 (9 results)
*: Systems mixed liquors solids probably not at steady state; **: Bio-P removal in Control (R2) apparently inhibited

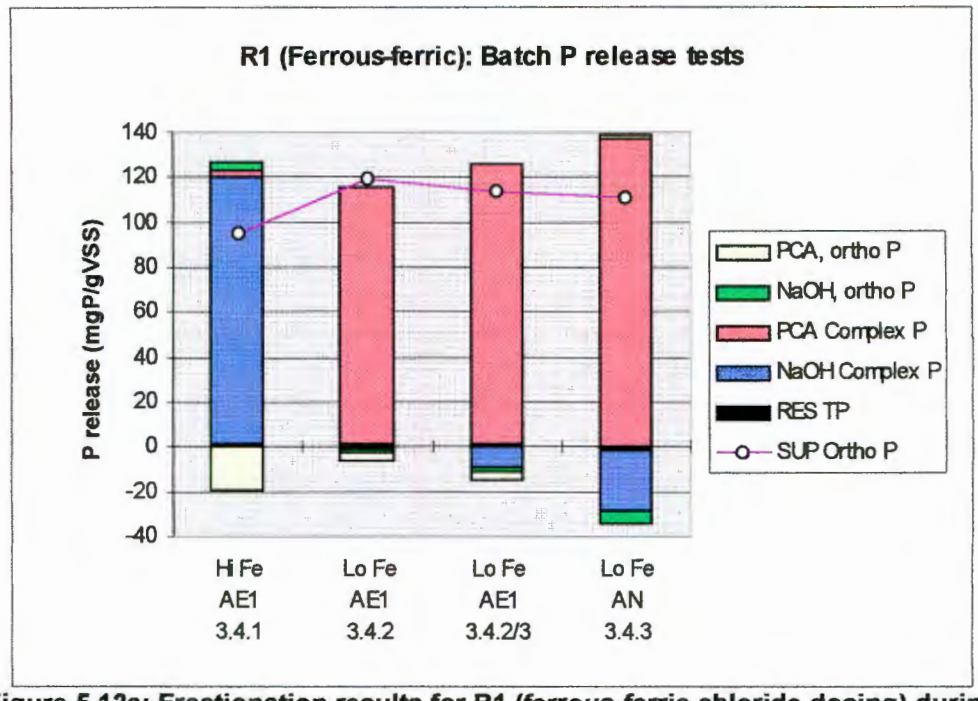


Figure 5.12a: Fractionation results for R1 (ferrous-ferric chloride dosing) during Periods 3.4.1 to 3.4.3 using P release batch tests in the presence of excess acetate.

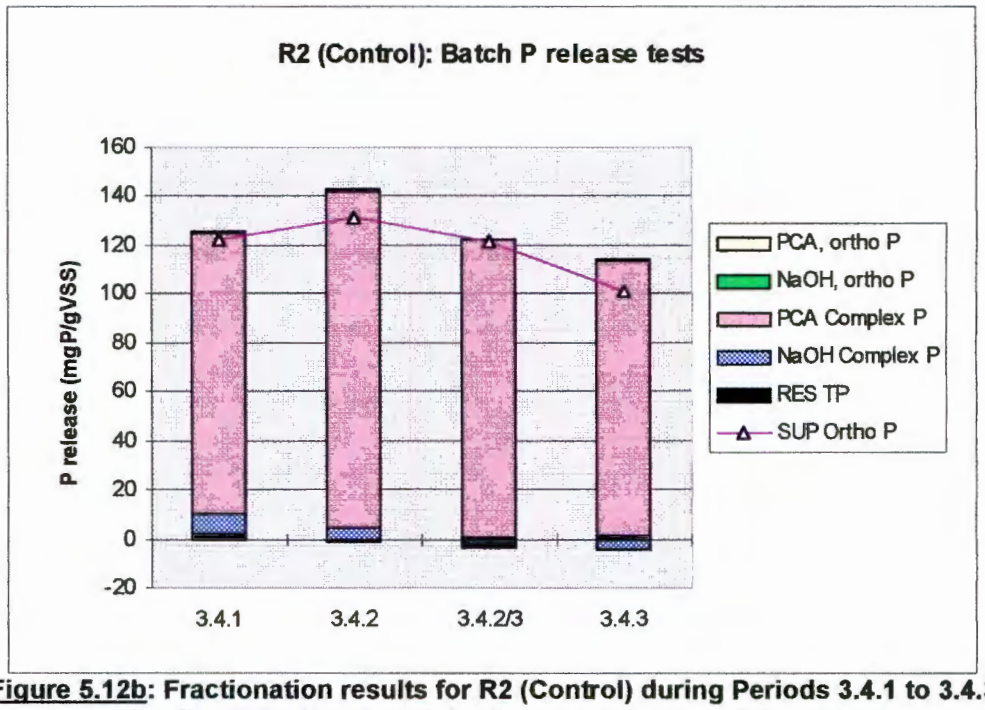


Figure 5.12b: Fractionation results for R2 (Control) during Periods 3.4.1 to 3.4.3 using P release batch tests in the presence of excess acetate.

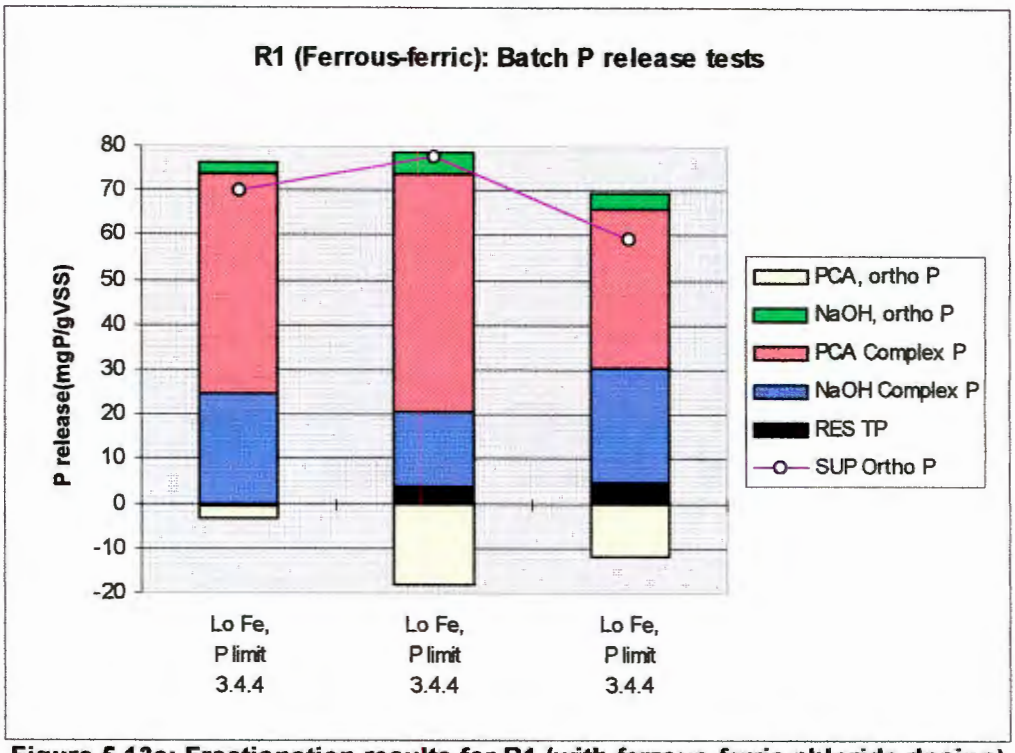


Figure 5.13a: Fractionation results for R1 (with ferrous-ferric chloride dosing) during Period 3.4.4 using P release batch tests in the presence of excess acetate.

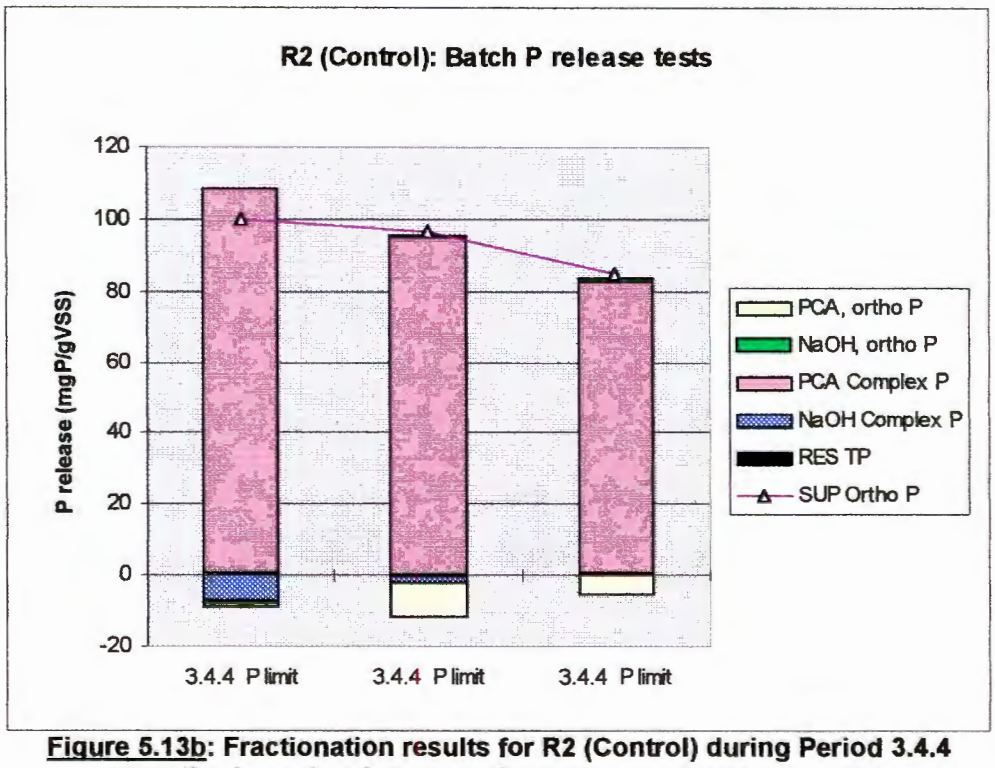


Figure 5.13b: Fractionation results for R2 (Control) during Period 3.4.4 using P release batch tests in the presence of excess acetate.

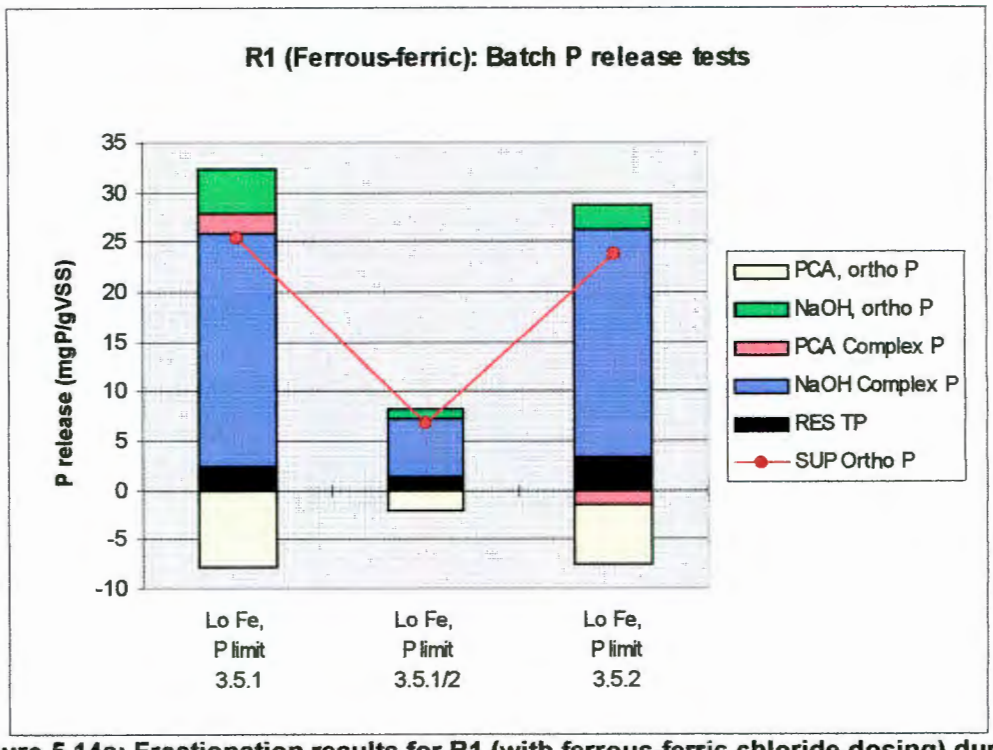


Figure 5.14a: Fractionation results for R1 (with ferrous-ferric chloride dosing) during Periods 3.5.1 and 3.5.2 using P release batch tests in the presence of excess acetate.

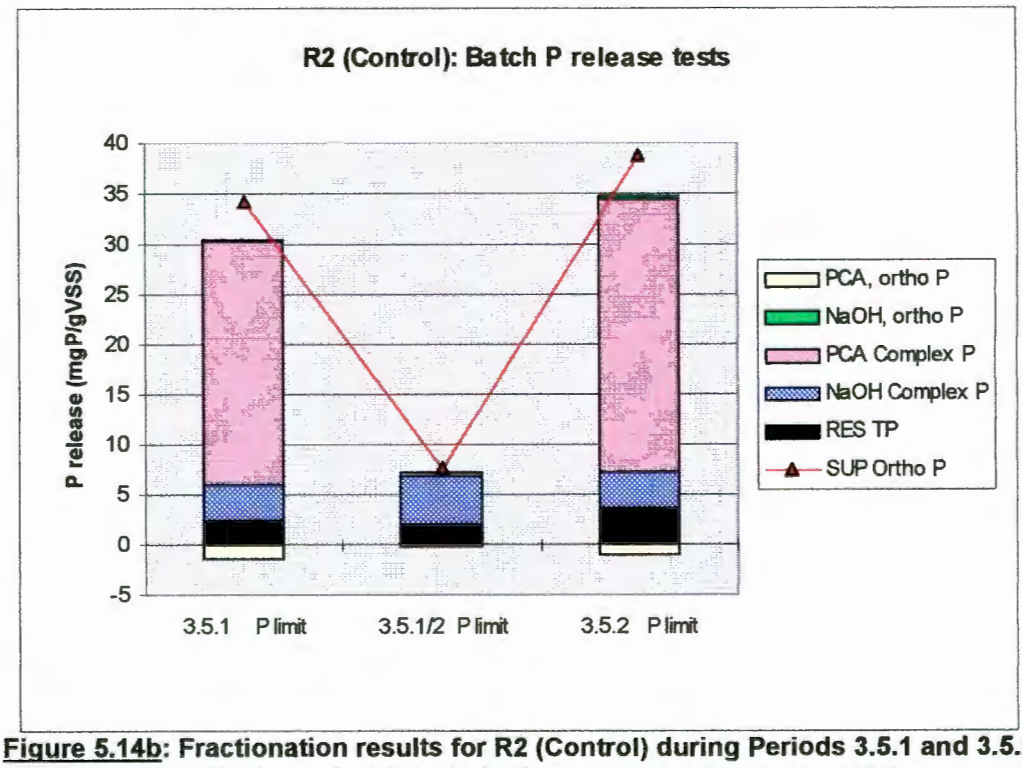


Figure 5.14b: Fractionation results for R2 (Control) during Periods 3.5.1 and 3.5.2 using P release batch tests in the presence of excess acetate.

5.3.7 Nitrification/ denitrification

Ferric chloride did not appear to inhibit nitrification-denitrification since the effluent ammonia and nitrate results of the Test and Control units were very similar (Table 5.4). Alkalinity consumption due to ferric dosing (based on measurements of bicarbonate alkalinity in the pilot plant effluents - refer to Tables 5.2, 5.3 and 5.8) was less than the theoretical amount for the precipitation of ferric hydroxide, and lower than that for comparable periods of ferric chloride dosing (see sections 4.3.4 and 5.3.4). This shows that the gain of alkalinity from oxidation of ferrous ions to ferric ions (Loewenthal *et al.*, 1986) is a benefit from using ferrous chloride in preference to ferric chloride for simultaneous precipitation.

5.3.8 Sludge production

In terms of sludge production, the Test unit (ferrous-ferric dosed) showed a significant increase in some cases, compared to the Control. However, these differences need to be seen against the experimental background.

During Period 3.4.1 (high Fe dose), a large additional mass of phosphate was removed by the Test unit (Table 5.4), which partly explains the large increase in TSS production (61%) for this Period, compared to the Control. However, for the same period, VSS production was 20% greater in the Test unit than the Control. At low Fe dose (Periods 3.4.2 and 3.4.3), the increase in sludge production in the Test unit was smaller, namely 19 to 36% for TSS, and 12 to 15% for VSS. These data suggest that iron (or iron hydroxide) forms complexes in the mixed liquor which involve increased adsorption/ enmeshment of colloidal organic material. Effectively, this would be equivalent to an increase in the inert (unbiodegradable) particulate COD fraction of the influent, which contributes directly to the VSS of the mixed liquor. However, the observed differences in VSS were probably exaggerated to a degree by the apparently weakened BEPR response in the *Control unit* during Periods 3.4.2 and 3.4.3 (refer to section 5.3.1.1 above). It is well known that BEPR results in increased VSS production, as a result of a lower death rate of poly P accumulating organisms (Wentzel et al., 1989). By contrast, during Period 3.4.4 (with good BEPR in the Control but P-limited in relation to the acetate dose), the increase in TSS production in the Test unit (10 mg/ℓ Fe dose) was significantly less (9%) and the difference in VSS production was negligible. During Periods 3.5.1 and 3.5.2 (low Fe dose, similar to real operating conditions at full-scale, without phosphate added to the influent), overall biological P removal was much weaker and chemical P removal appeared to play a bigger role in the Test unit, compared to the Control (section 5.3.5.3). For these periods, the Test unit showed increases of 23 to 27% for TSS, and 8 to 12% for VSS production. The TSS estimate is similar to that made by Schmidtke (1985) who reported a median 26% increase in sludge mass produced from a survey of 15 conventional activated sludge plants in Canada after chemical addition (ferric/ alum plus lime), relative to before chemical addition. Clearly, both the biological and chemical removal P mechanisms contribute to the changes in sludge production. An increase in TSS will be largely due to increased ISS[6] production, which is directly due to inorganic precipitation reactions. However, from the above-mentioned data, it seems that an increase in VSS of around 8 to 20% may also be expected for a ferrous-ferric chloride dose range of 10 to 19 mg/ℓ Fe (based on influent). This increase in VSS appears to be slightly greater than that noted for ferric chloride dosing, which could indicate minor differences in the interaction between the biomass (or colloidal organic material) and colloidal iron (hydroxide) colloid formed by the addition of ferrous ions, as opposed to ferric ions. For example, the oxidation of ferrous ions to ferric ions (which may take up to an hour, approximately[7]) may result in slower and slightly more efficient coagulation of colloidal organic material contributing to the VSS, as suggested above.

Since chemical precipitate contributes directly to the ISS, it is useful to examine the solids data from the Test and Control units in the context of additional P removal as a result of chemical precipitation.

---

[6] Inorganic suspended solids (ISS) - see discussion following.
[7] Refer to section 1.5 of Chapter 1.

From the data in Table 5.4, the ISS may be calculated:

$$ISS = TSS - VSS$$

The difference in ISS (ΔISS) between the two units can then be calculated. It is possible to compare the observed ΔISS with estimates of precipitate formation, based on the additional P removal in R1 ($\Delta Pt_{rem} = Pt_{rem,R1} - Pt_{rem,R2}$). In order to do this, the stoichiometry of the precipitate must either be assumed or estimated. An estimate of the stoichiometry may be obtained by taking the molar ratio of iron dosed to ΔPt_{rem} (Table 5.6), on the assumption that all the metal is removed through precipitation reactions[8] and becomes bound in the mixed liquor matrix and that the biological P removal mechanism is constant and uninhibited in the Test unit[9]. From a review of the literature (see Chapter 7, section 7.1), the ideal precipitation of phosphate with ferric ions would be stoichiometric in the form of $FePO_4$ (1 mol Fe/ mol P). If the observed precipitation is not stoichiometric (i.e. > 1 mol Fe_{dosed}/ mol $P_{removed}$) then it may be reasonably assumed that some mixture of iron phosphate and iron hydroxide precipitation is probably taking place. A convenient chemical formula for the hypothetical precipitate iron hydroxy-phosphate[10] may be written as:

$$Fe_r\ PO_4\ OH_{(3r-3)}$$

where r = stoichiometry of Fe:P (mol Fe/ mol P).

Furthermore, it should be noted that upon ashing (during VSS determination, at 550 °C), iron hydroxide will most likely be converted to iron oxide in the same manner as assumed for aluminium precipitates by Power et al. (1992). On a similar basis to the typical conversion of $Fe(OH)_3$ to Fe_2O_3, the above-mentioned hypothetical formula for iron hydroxy-phosphate converts to the following formula for hypothetical iron (phosphate) oxide:

$$Fe_r\ PO_4\ O_{(1.5r-1.5)}$$

where r = stoichiometry of Fe:P (mol Fe/ mol P).

Using the approach described above and the hypothetical formulae for precipitate before and after ashing, the data in Table 5.13 were calculated.

From Table 5.13 it can be seen that, with the exception of Periods 3.4.1 and 3.4.2, the estimates of ΔISS from precipitation stoichiometry show a degree of similarity to the observed ΔISS. For Period 3.4.3 to 3.5.2, the recovery of estimated and observed ΔISS was in the range 90 to 116%.

In the case of Period 3.4.1, the observed ΔISS values were smaller than the estimated values. This probably indicates that the experimental systems were not operating suitably close to steady-state throughout this period. Unlike the biological P removal processes, the TSS and VSS (and hence ISS) in the systems can be expected to take several sludge ages to reach steady-state. The first experimental period with the ferrous-ferric chloride dosing was Period 3.4.1, and a high dose (19 mg/ℓ as Fe) was administered. Period 3.4.1 lasted 32 days (three sludge ages) but followed directly from the last ferric chloride dosing period (Period 3.3.6), also at a high dose (20 mg/ℓ as Fe). A significant change in mean ISS for R1 and ΔISS for Period 3.4.1 (approx. +450 mg/ℓ) was noted when comparing Periods 3.3.6 and 3.4.1, possibly indicating that ferrous and ferric ions interact differently with the biomass (c.f. above comments on VSS production). Period 3.4.1 may also have been too short to approximate steady-state in the Test unit. If the final TSS and VSS data set for Period 3.4.1 is taken (refer to Appendix 5) and substituted for that in Table 5.13, the

[8] Rabinowitz and Marais (1980) found that this is virtually true, with <0.1 mg Fe/ℓ present in the effluent from laboratory-scale activated sludge systems dosed simultaneously with ferrous or ferric salts in the range 10 to 13 mg Fe/ℓ, based on influent.

[9] From Tables 5.9 to 5.11 and the discussion in section 5.3.1, this is not strictly true. However, as a result of a partial inhibition of bio-P removal, possible over-estimates of ISS production due an apparently higher Fe:P (lower P:Fe) stoichiometry (i.e. estimated from $\Delta Pt_{removed}$ data), will to some extent be compensated for by a loss of ISS from reduced biological accumulation.

[10] As applied to ferrous-ferric chloride dosing, this formula is assumes that all the ferrous ions are oxidised to ferric ions before the precipitation reactions take place (refer to section 1.2.1.1 of Chapter 1).

observed ISS value is 65% of the predicted ISS, which suggests that the Test system was closer to steady-state at the end of that period.

Similarly, in Period 3.4.2, halving of the iron dose resulted in close to a halving of the mean ISS for R1 and a large reduction in ΔISS compared to Period 3.4.1, which preceded. It is likely that Period 3.4.2 (34 days) was also too short to approximate steady-state in the Test unit.

In summary, the data in Table 5.13 suggest that the increase in ISS due to chemical dosing may be estimated with a degree of certainty using the above-mentioned hypothetical chemical formulae and either the observed stoichiometry of iron dosed : additional P removal. The ISS results are re-examined in Chapter 7 (sections 7.2.2.2 and 7.2.4.2) in the light of predictions using the precipitation model included in the IAWQ ASM2 Model.

Table 5.13: Comparison of observed ISS and that predicted from chemical P removal for ferric chloride dosing periods.

For all experimental periods, sludge age (R_s) = 10 d.
ISS = TSS - VSS (see Table 5.4 TSS and VSS data)
Fe~P~OH : hypothetical metal hydroxy-phosphate, $Fe_r PO_4 OH_{(3r-3)}$
Fe~P~O : hypothetical metal phosphate oxide, $Fe_r PO_4 O_{(1,5r-1,5)}$

Period (Duration) Ferric chloride dose	ISS Tables 5.4	ISS Tables 5.4	Δ ISS	ΔM Pt_{rem} Table 5.6	Stoichiometry Observed Table 5.6	*Stoichiometry Observed*	Estimate from *Stoichiometry Observed*	**Estimated ΔISS from *Stoichiometry Observed***	Estimate/ Observed
	mg/ℓ	mg/ℓ	mg/ℓ	mg P/d	mol P_{rem}: mol Fe_{dosed}	mol Fe_{dosed} : mol P_{rem}	*Fe~P~OH*	***Fe~P~O***	***Fe~P~O/*** Δ ISS
Unit:	R1	R2	**R1-R2**	R1-R2	P:Fe	*Fe:P*	mg/ℓ	mg/ℓ	%
3.4.1 (32 d) 19 mg/ℓ Fe, AE1	2114	1032	1082	284.4	0.74	*1.35*	540	513	47% #
3.4.2 (34 d) 10 mg/ℓ Fe, AE1	1071	843	228	210.7	0.62	*1.61*	460	424	186% #
3.4.3 (30 d) 10 mg/ℓ Fe, AN	954	582	372	335.8	1.75	*0.57*	356	395	106%
3.4.4 (70 d) 10 mg/ℓ Fe, AE1	703	558	145	39.8	0.23	*4.35*	204	168	116%
3.5.1 (46 d) 10 mg/ℓ Fe, AE1	549	317	232	78.8	0.41	*2.44*	242	211	91%
3.5.2 (32 d) 20 mg/ℓ Fe, AN	520	302	218	42.9	0.21	*4.76*	239	195	90%

AN = Anaerobic zone; AE1 = First aerobic zone
# : Reactor solids concentration probably not approximating steady-state condition

5.3.9 Sludge settleability

Sludge settleability during all periods of ferrous-ferric chloride dosing was improved in the Test unit, relative to the Control. This was noted, firstly, from visual inspection of the clarifiers. The Test unit clarifier normally contained less sludge (due to improved thickening) and the problems of fine floc carryover and effluent turbidity noted previously with ferric chloride (refer to Chapter 4) did not occur to a significant degree with ferrous-ferric chloride.

The DSVI data (Fig. 5.15) also indicates that settleability was generally improved in the Test unit (R1), compared to the Control. The only exception was a period in May 1996 (Period 3.4.4) when the DSVI in R1 underwent a sudden and transient increase, as opposed to the inverse in R2 (Fig. 5.15). During this period, imbalances in the microbial population may have occurred due to the high influent acetate concentration in relation to the low P concentration. Repeated problems were experienced with the units (particularly R1) with whitish clumps of organic matter clogging pipes in the system. Attempts (only partially successful) were made to remove this material from the unit

by means of sieving. Microscopic inspection revealed the problem appeared to be caused by excessive growth of the protozoan *Vorticella* which produces a distinctive "stalk". This organism tends to grow in clumps (or "rosettes"). In large numbers, the stalks tended to get entwined to form dense lumps which attached to the walls of the reactors and tubing in the pilot plant. Similar problems also tended to occur (in both units) from time to time with dense lumps of a "red worm", which when examined under the microscope, were revealed to be larvae of the Psychoda family of flies. Again, physical removal by cleaning the reactors or sieving the mixed liquor was the only means to prevent blockages and keep the systems operating.

Taking Fig. 5.15 as a whole, it is impossible to account for all the factors which might have influenced the DSVI. One of the factors (sewage septicity) has already been discussed in relation to the results for P removal during Period 3.4.3 (see 5.3.1.1 above). Some of the other variables which can be excluded when comparing the Test and Control units are:

- Temperature - generally well controlled in both pilot plants at 20 °C (±2) (see Appendix 5);
- Design and operation of both units was identical as far as possible, including flow and recycle rates;
- Influent was common to both units, although the manner in which the units responded to changes in influent sewage composition may have differed.

Figures 5.16a and 5.16b indicate that there is a fairly strong correlation between the mean daily mass of P removal and mean DSVI for the experimental periods covered in this chapter. This applies to both units. In the case of the Test unit (R1), the data for Period 3.4.4 was excluded from the regression in view of the above-mentioned operational problems. It is noteworthy that the slope and y-intercept of the regression line for the Test unit with iron dosing (Fig. 5.16a) are lower than that of the Control unit (Fig. 5.16b). From these data, it may be concluded that phosphate accumulation in the mixed liquor solids plays an important role in determining sludge settleability. Iron dosing itself should produce an improvement in settleability, by virtue of the density of the iron which becomes complexed with the biomass. However, this improvement will not be as marked where the effluent residual phosphate concentrations are already fairly low (due to an active biological P removal mechanism) and iron addition can only bring about a small further increment in phosphate accumulated by the mixed liquor solids.

Figures 5.15 and 5.16 (a & b) ...../

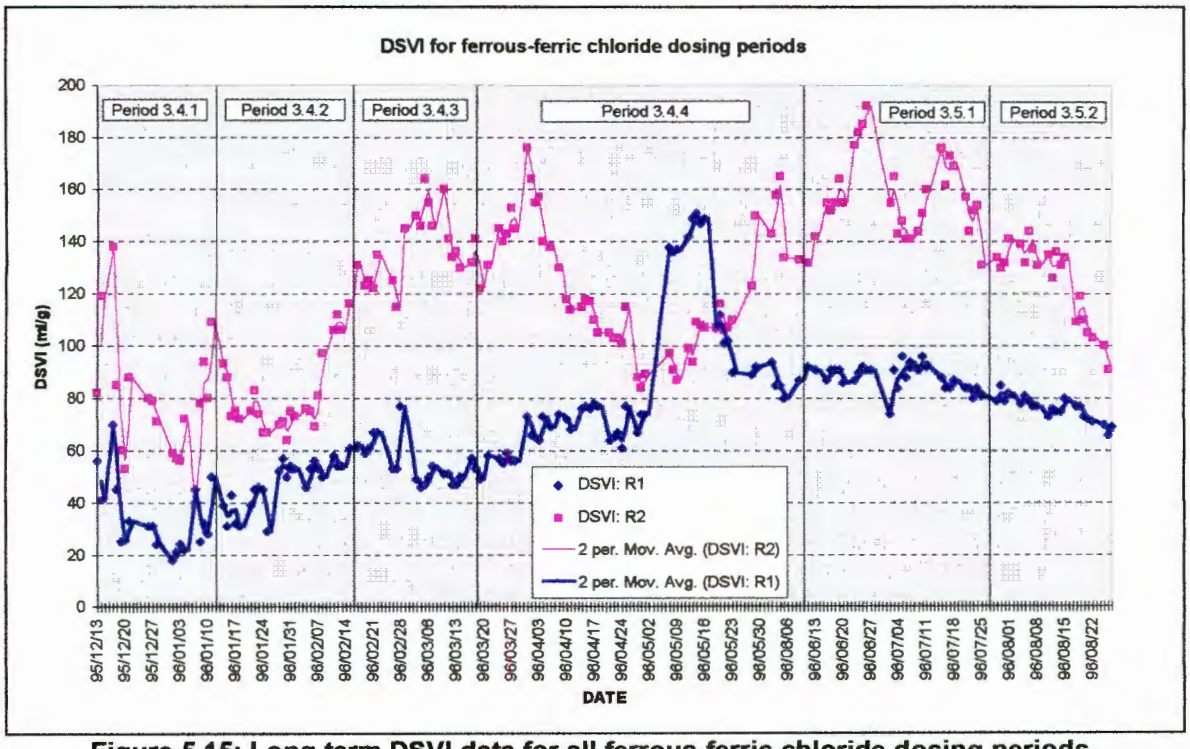


Figure 5.15: Long term DSVI data for all ferrous-ferric chloride dosing periods.

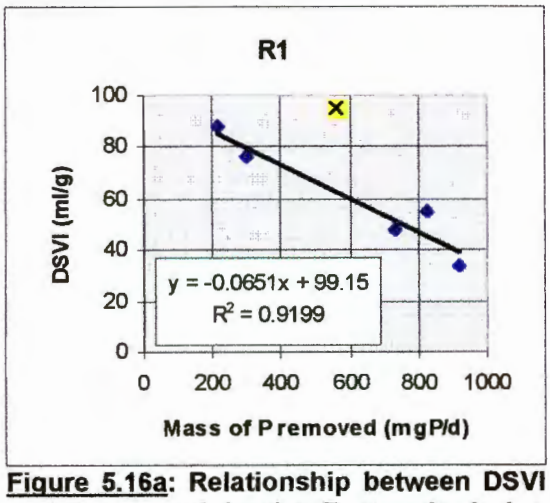


Figure 5.16a: Relationship between DSVI and P removal in the Test unit during periods of ferrous-ferric chloride dosing. Data for Period 3.4.4 (yellow symbol) excluded from regression.

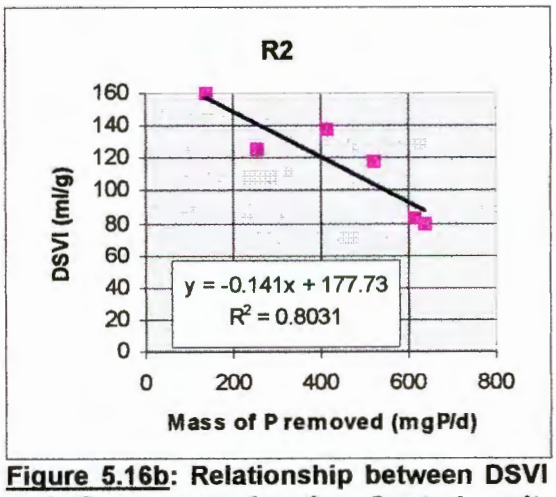


Figure 5.16b: Relationship between DSVI and P removal in the Control unit.

5.4 CONCLUSIONS

1. In the absence of phosphate limitation, pilot plant operational results over a period equivalent to approximately 10 sludge ages, as well as chemical fractionation results suggest that interference in the biological P removal mechanism as a result of ferrous-ferric chloride (blend) dosing is not severe. From these experimental periods, when effluent phosphate concentrations always exceeded 12 mgP/ℓ (and usually exceeded 20 mgP/ℓ), the following additional conclusions were drawn:

   - A net improvement in P removal was virtually always found in the Test unit (ferrous-ferric dosed), compared to the Control. On average, the additional P removal was approximately 0.68 mol $P_{removed}$ per mol Fe $_{dosed}$. A similar estimate (0.66 mol P/ mol Fe) was obtained from fractionation data after approximately six sludge ages with ferrous-ferric chloride dosing.

   - Ferrous-ferric dosing to the anaerobic zone produced additional P removal which amounted to approximately 1.75 mol $P_{removed}$ per mol Fe $_{dosed}$. This is in excess of the stoichiometric amount. However, careful analysis of the data for this period showed that the *apparent* additional removal may have been caused by the a relative deterioration of biological P removal in the Control unit, rather than an increase in the absolute P removal from the Test unit. No explanation for this observation was self-evident. It was proposed that influent composition played a role, and it was speculated that sulphide inhibition of the biological mechanism may have occurred to some extent. Circumstances surrounding the operation of the full-scale plant (from which the pilot plant influent was obtained) most likely increased the influent septicity and hence the sulphide concentration.

   - Compared to the Control, average P release in the anaerobic zone of the Test unit (ferrous-ferric dosed) was depressed by no more than 11% on average, even when using a high dose of ferrous-ferric chloride. Stimulation of P release appeared to result from dosing to the anaerobic zone, but this conclusion was not considered to be valid in view of the aforementioned weakened biological P removal in the Control during this experimental period.

   - In a similar manner to studies for ferric chloride dosing (Chapter 4), fractionation studies showed that it appears to be invalid to measure the relative contribution of the biological P removal mechanism on the basis of the size of the acid-extractable complex P (or poly P) fraction alone. Dosing with ferrous-ferric chloride appears to increase the size of the complex P fraction which is not extractable into cold perchloric acid, but which is extractable into sodium hydroxide at room temperature. This fraction is biologically active, as evidenced by its contribution to P release under anaerobic conditions in the presence of excess acetate, which suggests that it represents a significant portion of the poly P in the biomass.

   - The sum of the acid-extractable and alkaline-extractable complex P (or poly P) fractions in the biomass from the Test unit (with ferrous-ferric dosing) was never depressed by more than approximately 13%, relative to the Control and in some cases was greater in the Test unit than the Control[11]. When added to the increased fraction attributed to chemical origin (acid-extractable ortho P), the mixed liquor of the Test unit always contained more total phosphate than that of the Control. This is in agreement with the observation of greater system total P removal in the Test unit with simultaneous ferrous-ferric chloride addition.

   - Anaerobic P release batch tests (with excess acetate) indicated that the biological mechanism in the Test unit was depressed by at most 15 to 22%. In one test, the biological mechanism appeared to be significantly stronger in the Test unit, compared to the Control but this again was due to the depressed biological P removal in the Control during this period.

[11] This was due to an apparent inhibition of the BEPR mechanism in the *Control* unit during Periods 3.4.2 and 3.4.3 (see section 5.3.1.1 for discussion). Furthermore, differences in VSS production in the Test vs. Control units (see point 8 of this section) influence, to some extent, the interpretation of the fractionation results when expressed on a mgP/gVSS basis. Neglecting

2. Under partially limiting phosphate conditions (with low but variable effluent total P concentrations averaging close to 1 mgP/ℓ), the Test unit continued to achieve greater P removal in the presence of ferrous-ferric chloride dosing, compared to the Control. However, compared to non-P-limiting conditions, the biological mechanism was "inhibited" to a greater degree under (partially) P limiting conditions, as judged by 24 to 39% less P release in the anaerobic zone of the Test unit, smaller complex P fractions in fractionation studies, and less P release in anaerobic batch tests, relative to the Control.

3. Under partially limiting phosphate conditions, chemical precipitation also appeared to be somewhat less efficient (compared to conditions with high effluent phosphate concentrations). This was evidenced by a lower molar ratio of $P_{removed}$: Fe_{dosed}, as estimated both from a comparison of magnitude of the PCA ortho P fraction of the Test vs. Control units, as well as the difference in system P removal between the two units. Under these conditions, from fractionation data, the precipitation efficiency was approximately 0.3 to 0.4 mol $P_{removed}$/ mol Fe_{dosed} ; from the difference in system P removal, the stoichiometry dropped to 0.2 mol $P_{removed}$/ mol Fe_{dosed} at times. However, as reported in Chapter 4 for ferric chloride, under true P limiting conditions for both the Test and Control systems, net additional P removal as a result of iron dosing would be impossible, leading to low (or zero) P:Fe stoichiometry observed by this method.

4. Attempts to operate the pilot plants with an influent resembling that of the full-scale plant as closely as possible failed to produce very low effluent P concentrations on a consistent basis. This was mainly attributable to a smaller biological P removal potential resulting from reduced supplementary influent acetate concentrations. Fractionation and P release batch tests under these conditions indicated limited inhibition of the biological mechanism, similar to periods in which the influent contained more acetate but phosphate was never limiting. Nevertheless, during the periods of low acetate addition, phosphate may have become limiting at times in the Test unit, with effluent ortho P concentrations sometimes falling below 1 mgP/ℓ. Judging from average P release in the anaerobic zone, and fractionation data, the biological mechanism again did not compete as effectively with chemical mechanism under these conditions, compared to those in which phosphate was never limiting. Moreover, the chemical mechanism also showed reduced efficiency, with low P:Fe stoichiometry found by fractionation data (approx. 0.4 mol $P_{removed}$/ mol Fe_{dosed}) as well as by difference in system P removal (0.2 mol $P_{removed}$/ mol Fe_{dosed} , despite the fact that the lower quartile of effluent total P results was >1 mgP/ℓ in both units.

5. Future research should be directed toward the competition between the biological and chemical mechanisms highlighted in this study under phosphate-limiting conditions over extended periods (more than three sludge ages). The kinetics of the chemical phosphate precipitation with metal ions would be expected to be much faster than those of the biological release/ uptake reactions in activated sludge. On this basis, it may be expected that the chemical mechanism would "out compete" the biological mechanism under P limiting conditions. That is, the chemical precipitation "efficiency" (stoichiometry) should be essentially the same under both limiting and non-limiting P conditions, provided the soluble phosphate concentration at the point of metal dosing is not less than that required to satisfy the precipitation demand. However, this hypothesis is not consistent with fractionation data which suggested that the P:Fe stoichiometry of chemical precipitate is reduced to approximately the same extent as the inhibition of the biological complex P fractions. Furthermore, evidence was found in batch tests that phosphate released biologically may to some extent be chemically precipitated as an ortho P fraction which remains bound in the sludge matrix but is soluble in cold perchloric acid. A complex P fraction which is alkaline-soluble may be formed in a similar manner. This phenomenon was more pronounced for mixed liquor withdrawn from the Test unit (iron dosed), and is probably attributable to the accumulation in the sludge matrix of colloidal iron hydroxide, or possibly some related colloidal complex between ferric/ferrous ions and extracellular polysaccharide. Such colloid(s) may be expected to have the capacity to adsorb/ desorb or precipitate/ dissociate phosphate, depending on the soluble ortho P concentration in the reactor. Exchange (or "migration") of phosphate between such chemical fractions and the biologically stored/ released fractions suggests that the biological and

---

Periods 3.4.2 and 3.4.3, and expressing the accepting the fractionation results on a volume basis (mgP/ℓ), the degree of inhibition of the biological mechanism was 5 to 22% for periods without P limitation (Tables 5.9 and 5.11).

chemical mechanisms do not operate entirely independently, particularly under P-limiting conditions when "surplus" iron may be expected to accumulate in the sludge matrix as ferric hydroxide colloid (or similar form). However, as a *net observed effect* (i.e. disregarding the exchange of phosphate with ferric hydroxide), it would be true to say that the two mechanisms operate independently (Rabinowitz and Marais, 1980). The fact that the precipitation efficiency (P:Fe stoichiometry) was reduced at low residual P concentrations supports the conclusion by Rabinowitz and Marais (1980) that precipitation of iron-phosphate precipitation is in competition with a side reaction of ion exchange between ferric hydroxide colloid and phosphate. By inference from the effect sludge age on the stoichiometry of precipitation (without P limitation - see Chapter 4, section 4.3.3), the ion-exchange reaction may be expected to be substantially slower than the direct precipitation reaction. Under low residual P concentrations, the direct precipitation reactions may be kinetically disadvantaged, and the slower ion-exchange reactions dominant. This would explain the surprising ability of the biological mechanism to compete for available phosphate about as effectively as the chemical mechanism at low (or limiting) P concentrations.

6. Bicarbonate alkalinity consumption due to chemical dosing (based on the difference in effluent bicarbonate alkalinity between the Test and the Control units) was approximately 1 mg as $CaCO_3$ / mg as Fe dosed (or 0.35 mg as $CaCO_3$ / mg as $FeCl_3$ dosed). or approx. 2.2 mmol Alk./ mmol Fe dosed). This is lower than the theoretical alkalinity demand for ferric hydroxide precipitation alone but is in broad agreement with the net theoretical alkalinity demand, taking the alkalinity gain from oxidation of ferrous ions to ferric ions into account. On a molar basis, the observed additional alkalinity consumption was approx. 2.2 mmol Alk./ mmol Fe dosed. This suggests that the iron precipitate which formed involved fewer than 3 mol OH/ mol Fe. Since phosphate would obviously be involved in the precipitation, and since the additional P removed as ortho P (from fractionation data - refer to Table 5.12a) was of the order of 0.66 mol P/ mol Fe dosed, an estimate of the average formula for an ferric-hydroxy-phosphate complex formed could lie in the range:

$$Fe_{1.33}(X^{2+})PO_4(OH)_3 \quad \text{to} \quad Fe_{1.66}(X^{2+})PO_4(OH)_4$$

where X^{2+} is some unknown (possibly divalent) cation, such as calcium or magnesium.

This formula is similar to that estimated for alum and ferric chloride dosing by the same means in Chapters 3 and 4 respectively.

7. Settling (and turbidity) problems were seldom experienced during periods of ferrous-ferric chloride dosing to the pilot plant Test unit. Those which did occur may have been related to acid dosing to the Test system (which was subsequently stopped) or possibly to sewage septicity.

8. Sludge production showed a significant increase in the presence of ferrous-ferric chloride dosing. VSS showed an increase of approximately 10 to 20%, depending on iron dose. It was suggested that this was due to complexation of organic material by colloidal iron (hydroxide) precipitate in a manner analogous to the accumulation of unbiodegradable particulate COD. Increased TSS production was mainly due to an increase in ISS, as expected, from the accumulation of inorganic precipitates in the presence of iron dosing. The increase in ISS could be largely accounted for on the basis of the stoichiometry of phosphate precipitation found by difference in the system P removals of the Test vs. Control units. Exceptions in this regard appeared to be due to the observed mixed liquor solids data failing to approximate the steady-state condition.

9. Settling (DSVI) was strongly related to phosphate removal, as expected from the floc density imparted by accumulated phosphate mass. Ferrous-ferric iron addition almost always gave improved settling. Minor exceptions in this regard appeared to be related either to low phosphate concentrations in the presence of a relatively high influent acetate dose, and/or microbial populations imbalances as evidenced by excessive growth of protozoa.

10. Addition of acid to dilute working solutions of ferrous-ferric hydroxide was found to be important in order to prevent apparent oxidation to ferric forms and possible precipitation as an oxide prior to being dosed in the Test system.

REFERENCES

Brown, MJ and Lester, JN. (1979) Metal removal in activated sludge: the role of bacterial extracellular polymers. *Water Res.,* 13, 817-837.

Comeau , Y, Rabinowitz, B, Hall, KJ and Oldham, WK. (1987) Phosphate release and uptake in enhanced biological phosphorus removal from wastewater. *Journal WPCF* 59 (7), 707-715.

De Haas, DW. (1989) Chemical fractionation of activated sludge with special reference to enhanced biological phosphate removal. MSc. Thesis, Dept. of Biochemistry, Rand Afrikaans University, Johannesburg, November 1989.

De Haas, DW and Borain, GP. (1995) Pilot-scale investigation of biological phosphorus removal under conditions of low influent strength. Proceedings of New & Emerging Environmental Technologies and Products for Wastewater Treatment and Stormwater Collection Conference. 4-7 June 1995, Sheraton Centre Hotel and Towers, Toronto, Canada, p11:25 - 11:38.

De Haas, DW and Greben, HA. (1991) Phosphorus fractionation of activated sludges from modified Bardenpho processes with and without chemical precipitant supplementation. *Water Sci. Technol.* 23 (Kyoto), 623-633.

Fleit, E. (1995) Intracellular pH regulation in biological excess phosphorus removal systems. *Water Res.,* 29 (7), 1787-1792.

He, QH, Leppard, G, Paige, CR and Snodgrass, WJ. (1996) Transmission electron microscopy of a phosphate effect on the colloid structure of iron hydroxide. *Water. Res.,* 30 (6), 1345-1352.

Jenkins, D, Richard, MG and Daigger, GT. (1984) *Manual on the causes and control of activated sludge bulking and foaming.* Report prepared for Water Research Commission, PO Box 824, Pretoria, South Africa.

Kerdachi, DA and Roberts, MR. (1985) Further investigations into the modified STS procedure as used specifically to quantitatively assess 'metal phosphates' in activated sludge., *Proc. Int. Conf. Management Strategies for Phosphorus in the Environment,* Lisbon, Selper, UK, 66-71.

Leopold, P. (1996) Personal communication. *NCP Ultrafloc*, Johannesburg, South Africa.

Lindrea, KC, Pigdon, SP, Boyd, P and Lockwood, GA. (1994) Biomass characterization in a nitrification-denitrification biological enhanced phosphorus removal (NDBEPR) plant during start-up and subsequent periods pf good and poor phosphorus removal. *Water Sci. Technol.,* 29 (7), 91-100.

Loewenthal, RE Wiechers, HNS and Marais, GvR. (1986) *Softening and stabilization of municipal waters*. Water Research Commission, Pretoria.

Lötter, LH. (1991) Combined chemical and biological removal in activated sludge plants. *Water Sci. Technol.,* 23 (Kyoto), 611-621.

Luedecke, C, Hermanowicz, SH and Jenkins, D. (1989) Precipitation of ferric phosphate in activated sludge: a chemical model and its verification. *Water Sci. Technol.* 21 (Brighton), 325-327.

Mino, T, Kawakami, T and Matsuo, T. (1985) Location of phosphorus in activated sludge and function of intracellular polyphosphates in biological phosphorus removal process. *Water Sci. Technol.,* 17 (11/12), 93-106.

Moosbrugger, RE, Wentzel, MC, Ekama, GA and Marais, GvR. (1993) Simple titration procedures to determine h2co3* alkalinity and short-chain fatty acids in aqueous solutions containing known

University of Cape Town

concentrations of ammonium, phosphate and sulphide weak acid/bases. Report TT 57/92, Water Research Commission, Pretoria.

Power, SPB, Ekama, GA, Wentzel, MC and Marais, GvR. (1992) *Chemical phosphorus removal from municipal wastewater by the addition of waste alum sludge to the activated sludge system.* Research Report No. W66, University of Cape Town, Dept. of Civil Engineering, September 1992.

Rabinowitz, B and Marais, GvR. (1980) *Chemical and biological phosphorus removal in the activated sludge process.* Research Report No. W32, University of Cape Town, Dept. of Civil Engineering, March 1980.

Randall , EW, Wilkinson, A and Ekama, GA.. (1991) An instrument for the direct determination of oxygen utilisation rate. *Water SA* 17 (1), 11-18.

Reynolds, T. (1996) Personal communication. *NCP Ultrafloc*, Johannesburg, South Africa.

Munro, HN and Fleck, A (1966) The determination of nucleic acids. In: *Methods of Biochemical Analysis*. (Glick, D. ed.) Interscience, New York, 113-1785.

Schmidtke, NW.(1985) Estimating sludge quantities at wastewater treatment plants using metal salts to precipitate phosphorus. *Proc. Int. Conf. Management Strategies for Phosphorus in the Environment.,* Lisbon, Selper, UK, 379-385.

Slatter, NP and Alborough, H. (1990) Chemical oxygen demand using microwave digestion: A tentative new method. *Water SA* 18 (3), 145-148.

Standard Methods for the Examination of Water and Wastewater (16th edn.) (1985). American Public Health Association, Washington DC.

Wentzel, MC, Loewenthal, RE, Ekama, GA and Marais, GvR. (1988) Enhanced polyphosphate organism cultures in activated sludge systems - Part 1: Enhanced culture development. *Water SA,* 14 (2), 81-92.

Wentzel, MC, Ekama, GA, Lowenthal, RE, Dold, PL and Marais, GvR. (1989) Enhanced polyphosphate organism cultures in activated sludge systems. Part II: Experimental behaviour. *Water SA* 15 (2), 71-88.

WRC (1984) *Theory, design and operation of nutrient removal activated sludge processes.* Ekama, GA, Marais, GvR, Siebritz, IP, Pitman, AR, Keay, GFP, Buchan, L, Gerber, A and Smollen, M (eds.). Water Research Commission, Pretoria.

Yeoman, S, Stephenson, T, Lester, JN and Perry, R. (1988) The removal of phosphorus during wastewater treatment: a review. *Environmental Pollution,* 49 (1988), 183-233.

University of Cape Town

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting biological enhanced phosphate removal.

Chapter 6

Full-scale plant trial

DW de Haas

CHAPTER SIX

FULL-SCALE PLANT TRIAL

6.1 INTRODUCTION

Taking the results from Chapters 3, 4 and 5 as a whole, little difference in the biological enhanced P removal behaviour of the pilot-scale systems was found for the respective metal precipitants tested, namely: alum, ferric chloride and ferrous-ferric chloride. These chemicals showed similarity in the extent to which they depressed or "inhibited" the BEPR mechanism (see collated results in Table 8.1 of Chapter 8). The principal interaction between the chemical and biological P removal mechanisms appeared to be competition for available phosphate, as illustrated with ferric chloride under P-limiting conditions (Chapter 4, section 4.3.11). Experience at full-scale with simultaneous alum dosing (Chapter 3, section 3.4) had shown that sustained operation of the activated sludge plant under low and truly limiting effluent P concentrations was seldom achieved, leaving room for improvement. For some experimental periods, ferric chloride had shown higher overall stoichiometry of P removal in relation to iron dosed. However, concerns over the observed negative effect of ferric chloride on sludge flocculation and zone settling velocity at pilot scale resulted in ferrous-ferric chloride being selected for a plant trial. It was suggested that for an equivalent molar dose, ferrous-ferric chloride should produce P removal performance at least comparable to alum, but with potentially improved settleability. Furthermore, from a cost point of view, the ferrous-ferric chloride product was potentially cheaper on an metal equivalent basis.

In view of the above, the Operations Division (Inland Region) of Umgeni Water agreed to conduct a full-scale trial over a period of approximately three months at the activated sludge plant of Darvill Wastewater Works (Pietermaritzburg, South Africa).

Darvill Wastewater Works (WWW) was purchased by Umgeni Water in May 1992 from the Pietermaritzburg Municipality. The primary motivation for the purchase was to improve the quality of final effluent produced at this Works in view of its importance as the single largest point source discharge in the catchment of the Umgeni River upstream of Inanda Dam (Pillay, 1994). The latter was built in the late 1980s as the future supply of potable water for the greater Durban area. A system of aqueducts and tunnels links this dam to the major waterworks which purify water to potable standard for the Durban area. Should the quality of raw water from Inanda Dam deteriorate due to eutrophication, attainment of a high potable water quality at these water works could be compromised. For example, problems may be encountered with taste and odour or elevated concentrations of potentially carcinogenic trihalomethane compounds formed during chlorination. The correction of such treatment problems may require major capital extensions and will incur additional operating expenses at these waterworks. In view of this, compliance with the Special Phosphate Standard (see Chapter 1) at Darvill WWW is considered to be of strategic importance. Moreover, the possibility of a standard more stringent than the current 1 mgP/ℓ (dissolved ortho P) Special Phosphate Standard has been discussed at various forums but no decision in this respect has been announced by the Department of Water Affairs and Forestry (Howard, 1996).

The process at Darvill WWW involves conventional primary treatment and sedimentation, followed by an activated sludge process. The activated sludge plant was built in 1973-4 for full nitrification prior to the emergence of a good understanding of denitrification in activated sludge systems. Due to the soft (low alkalinity) water of the region, denitrification became virtually mandatory at this plant, like many others of its kind in Natal and the eastern, southern and south-western coastal regions of South Africa. Hence, the first one or two rows of surface aerators (in a series of six per activated sludge basin) were often turned off to encourage "simultaneous" denitrification by creating informal anoxic zones at the influent end of the basins. No partitioning walls exists between the aerobic and informal anoxic zones. With draught tubes fitted to the surface aerators, a large (but unquantified) recycle of nitrified mixed liquor from the aerobic area to the anoxic area is set up. Furthermore, the perpetual pumping action of the surface aerators in a vertical fashion may encourage the formation of additional informal anoxic zones at the bottom of the basins in the nominally aerobic area. Detailed discussion of nitrogen removal in such full-scale systems falls beyond the scope of this study. It suffices to say that an high degree of nitrogen removal has been obtained in this manner, and due to

the efforts of the Pietermaritzburg Municipality staff in the period 1985 to 1992, a substantial degree of biological phosphorus removal was also established in the Darvill activated sludge system despite the absence of formal anaerobic or anoxic zones.

As common experience throughout the world has shown, one of the main variables which induces enhanced biological P removal is the fermentation of primary sludge and addition of the resulting fermented ("VFA rich") supernatant directly to an anaerobic zone of the activated sludge plant. Furthermore, nitrate recycling to the anaerobic zone must be minimised. In order to make full use of the biological P removal potential, at the time of the Works' take-over by Umgeni Water, a capital investment programme was started for Darvill WWW, which amongst other items, addressed the need for:

- a formal anaerobic zone;
- protection of the anaerobic zone from the recycle of nitrate by provision of a pre-anoxic zone on the sludge recycle line and improved control of the return activated sludge recycle flows;
- a primary sludge fermentation-thickener system for generation of a VFA rich stream of primary supernatant which is pumped directly to the activated sludge anaerobic zone;
- a settled sewage balancing tank for dry weather flow conditions;
- two additional secondary clarifiers to increase the hydraulic capacity of the activated sludge plant;
- a dissolved air flotation plant for thickening waste activated sludge without significant release of phosphate.

In addition, a storm-dam (approximately equivalent in capacity to one day's dry weather flow) was built for storing excess raw or settled sewage under wet weather conditions and extensions were also made to the screening and grit removal system at Inlet Works.

While the above-mentioned capital upgrade project was underway, Umgeni Water took the decision to commence chemical dosing in the Darvill activated sludge plant in order to improve compliance with the Special P Standard. One of the reasons for this was the expectation of improvement in final effluent quality which had built up in the protracted period of negotiation prior to the take-over by Umgeni Water in 1992. Secondly, trade effluent control in the Pietermaritzburg area was weakened by the take-over. The take-over agreement inherently split responsibilities for sewage treatment and trade effluent *monitoring* (which was taken over by Umgeni Water) from the *powers* of trade effluent *control*, which remained vested with local government authority (i.e. Pietermaritzburg Municipality or the Transitional Local Council as it is today). The power to make the trade effluent by-laws, or to institute legal proceedings for contravention thereof, were not transferred to Umgeni Water; paradoxically, it was Umgeni Water which had a vested interest in achieving a high standard of treated effluent quality discharged from the Works[1]. The result appeared to be (and has continued to be) a tendency for an alarming number of cases of illegal trade effluent dumping to sewer, particularly waste from vegetable oil refiners/ soap and margarine producers in the catchment served by Darvill WWW. Five major edible oil industries are located in the Pietermaritzburg area. Illegal dumping of such trade effluent has had the effect of severely hampering process control at Darvill, to the point that attempts to achieve the necessary process control for biological N and P removal have been severely jeopardised. These problems were exacerbated by imperfections in the works infrastructure which existed at the time of the take-over in 1992 and which led to major process interruptions in the form of the subsequent civil and mechanical upgrade programme.

A third reason for opting for chemical removal at Darvill WWW, was the effect of large-scale stormwater and groundwater intrusion which has plagued the Pietermaritzburg sewer system since its earliest days. The strongly seasonal summer rains rapidly exert a diluting effect on the incoming sewage. The concomitant peak wet weather flows commonly exceed the average dry weather flow by five-fold or more (Figure 6.1a). The diluted sewage has a weaker biological P removal potential (Bagg *et al.*, 1985; de Haas *et al.*, 1995) and makes process control very difficult.

[1] After subsequent lengthy negotiations, the Municipality did devolve to Umgeni Water the authority for prosecution of offenders for contravention of the by-laws regulating discharge to sewer. However, numerous court cases followed which have failed to prevent further offences, either for technical/ legal reasons or due to the fines for admission of guilt being too low.

The purpose of this chapter is to briefly outline the history of biological P removal at Darvill and to summarise the full-scale experience to date with the use of aluminium sulphate (alum) and a ferrous-ferric chloride blend as simultaneous chemical precipitants. For reasons of space and direct relevance, a detailed chronology of all the variables affecting the full-scale operation of the plant to date has not been attempted; only the key areas of plant performance will be highlighted. Following this background, a description of the three-month full-scale trial conducted with the ferrous-ferric chloride blend will be given and compared with historical and subsequent plant performance using alum (see Table 1.3 of Chapter 3 for a summary of the plant trial). Unfortunately, because the mixed liquor of the Darvill activated sludge plant is common to the three aeration basins (with a common anaerobic basin and common secondary clarifiers - see section 6.2 and Fig. 6.2 below), it was impossible to conduct a controlled experiment at full-scale for comparing alum and iron blend dosing side-by-side in parallel modules.

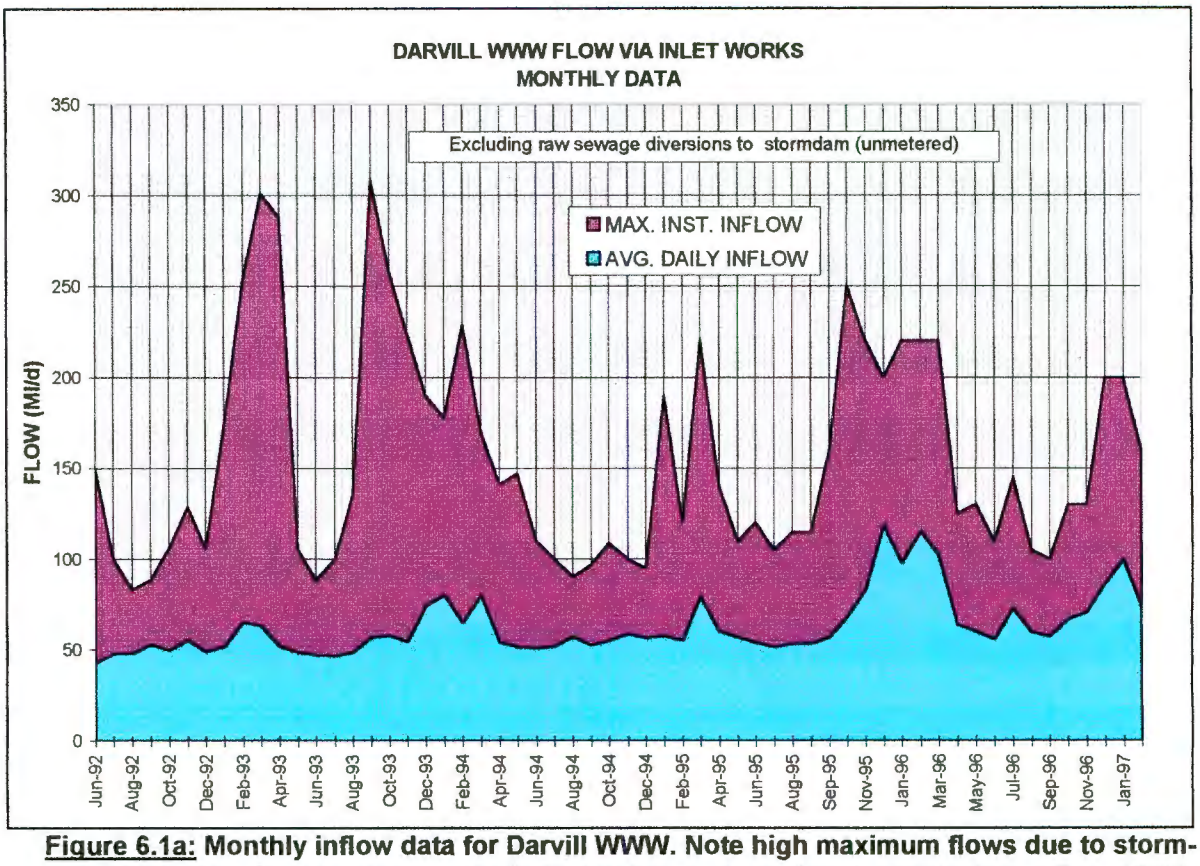


Figure 6.1a: Monthly inflow data for Darvill WWW. Note high maximum flows due to storm-water intrusion. Excess raw sewage is diverted to a storm-dam (commissioned Dec. 1992) and is partly unmetered (i.e. not reflected here). The true peak wet weather inflow is unknown, but exceeds 350 Mℓ/d (max. meter capacity).

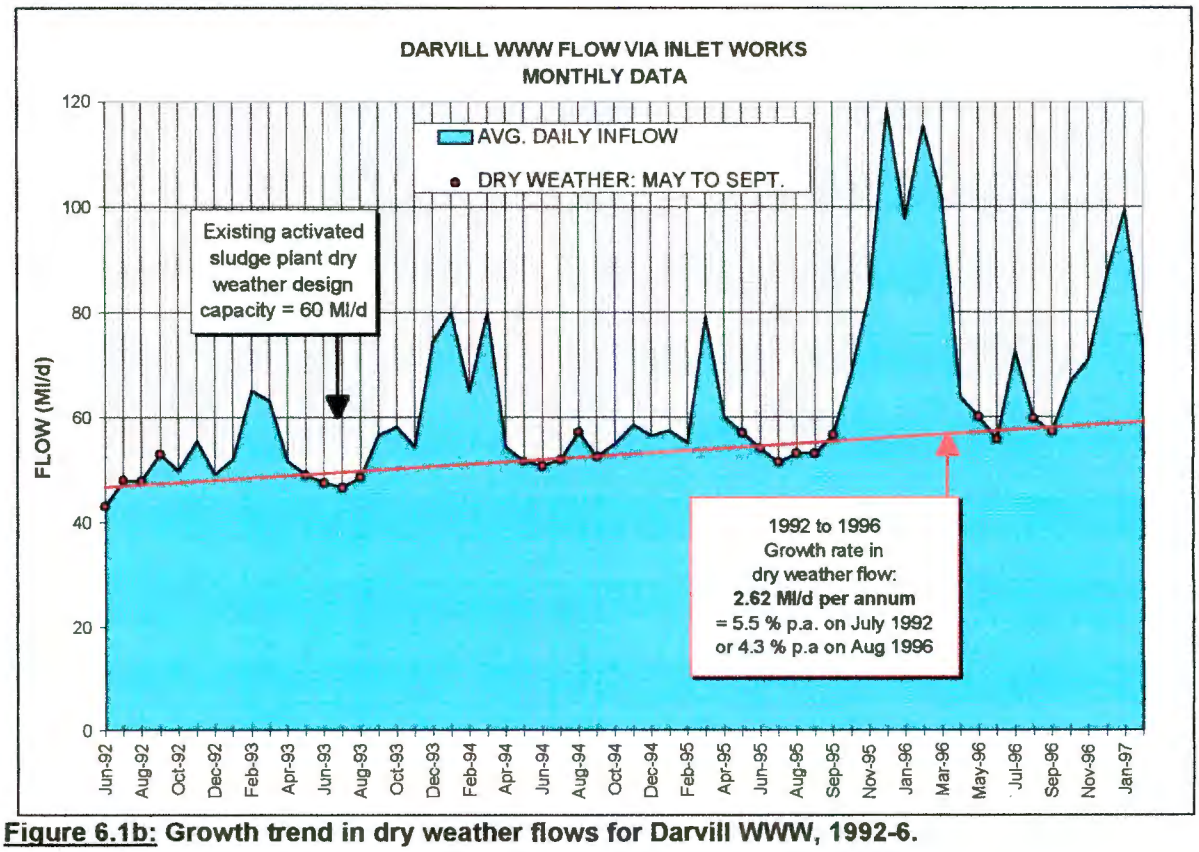


Figure 6.1b: Growth trend in dry weather flows for Darvill WWW, 1992-6.

6.2 BRIEF PROCESS DESCRIPTION OF ACTIVATED SLUDGE PLANT

Figure 6.2 gives the diagrammatic layout of the activated sludge process at Darvill WWW.

The activated sludge plant has been modified to conform approximately to the Johannesburg (or ISAH) process configuration. The original activated sludge plant consists of three aeration basins (total volume 19 600 m^3) in which a maximum of five out of the six original rows of 75 kW surface aerators are now operated. Stirrers have replaced the first row of aerators to create an informal anoxic zone. A pre-anoxic and anaerobic zones were added to stimulate biological P removal. Flows of settled sewage up to the average dry weather flow (ca. 60 Mℓ/d) are fed to the anaerobic zone along with a "VFA" stream of fermented primary sludge supernatant. (A minor fraction, ca. 4%, of the settled sewage is fed to the pre-anoxic zone to encourage denitrification of the return sludge. Flows in excess of the average dry weather flow are diverted to the anoxic/ aerobic zone in an attempt to secure a minimum hydraulic retention time for the mixed liquor passing through the anaerobic zone.

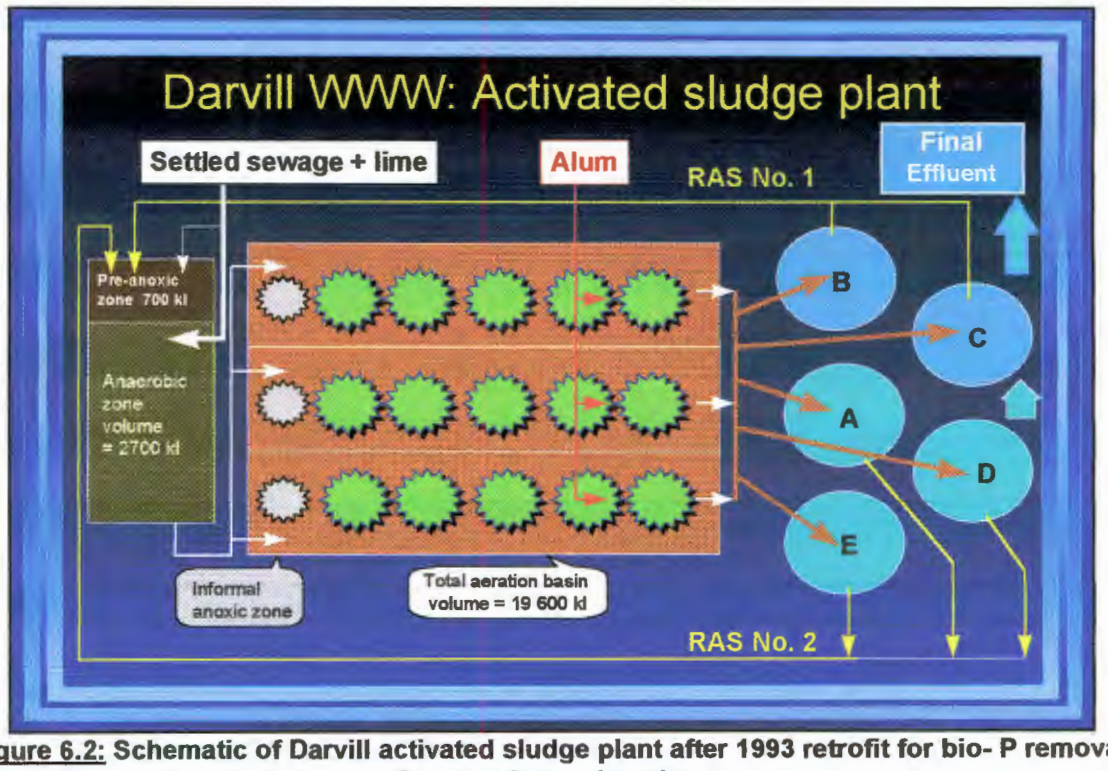


Figure 6.2: Schematic of Darvill activated sludge plant after 1993 retrofit for bio- P removal. See text for explanation.

The plant was originally supplied with three flat-bottomed (2.5 m side wall depth) suction-lift secondary clarifiers with an internal tank diameter of 35 m (nos. A, D and E in Fig. 1). Two deeper (4 m side wall depth) 35 m diameter centre-scraped secondary clarifiers (nos. B & C) were added in 1993. Clarifiers A, D and E have manual control of the sludge recycle (via six valves on the bridge of each), while clarifiers B and C each have a dedicated recycle pump with variable speed drives.

The operating range of the plant is given in Table 6.1. The annual growth trend in inflow is shown in Figure 6.1b above.

Alum (or ferrous-ferric chloride blend in the plant trial described below) is dosed into the splash zone of the fourth (or second-from-last) row of aerators via variable speed positive displacement dosing pumps. Both alum and the ferrous-ferric chloride blend were dosed undiluted. The dosage rate for alum is usually around 30 mg/ℓ (as $Al_2(SO_4)_3.14\ H_2O$), provided good biological P removal was also

achieved (see below). However, under conditions less conducive to bio-P removal, the alum dose may be increased, sometimes reaching ca. 70 mg/ℓ.

Lime is dosed into the settled sewage from a bulk lime silo (30t) in response to the secondary effluent alkalinity. Control of lime dosing is manual via a screw feeder equipped with a variable speed drive. Provided satisfactory *in situ* denitrification occurs in the activated sludge plant (secondary effluent nitrate 1 to 3 mgN/ℓ), a lime dose of 20 to 30 mg/ℓ as $CaCO_3$ is normally sufficient to maintain a secondary effluent alkalinity of 70 to 90 mg/ℓ as $CaCO_3$.

Table 6.2 gives a summary of inflow and influent composition data for settled sewage and fermented primary sludge supernatant (SNL) fed to the activated sludge plant over a two year period. The chemical data in Table 6.2 are based on the average of two daily grab samples taken 12h apart, except for TKN (weekly grab sample) and VFA (daily grab sample). The flow data were integrated by continuous recorders linked to ultrasonic meters.

Table 6.1: Approximate operating range of the Darvill activated sludge plant.

Design Average dry weather inflow:	60 Mℓ/d
Actual Average dry weather inflow (Aug. 1996): Actual Average dry weather inflow (Aug. 1997):	59.7 Mℓ/d 62.4 Mℓ/d
Design Max. wet weather inflow:	160 Mℓ/d
Actual Max. wet weather inflow (Mℓ/d):	100 to 120 Mℓ/d (MLSS and DSVI dependent)
Design MLSS (1992/3):	3800 mg/ℓ
Actual MLSS (Aug. 1996): Actual MLSS (Aug. 1997): Actual R_s (Aug. 1996): Actual R_s (Aug. 1997):	Ave. 5337 mg/ℓ Ave. 4409 mg/ℓ 7.6 d 7.8 d
Clarifiers B & C max. recycle:	2 x 17 Mℓ/d
Clarifiers B & C normal recycle:	2 x 12 Mℓ/d
Clarifiers A, D & E max. recycle:	3 x 14.5 Mℓ/d
Clarifiers A, D & E normal recycle:	3 x 12 Mℓ/d

Table 6.2 shows the strong seasonal trend with high summer flows (ca. October - April) diluting the sewage strength as a result of rainwater ingress. Due to solids loading constraints posed by the secondary clarifiers (Table 6.1), excess settled sewage is diverted to the storm-dam (along with excess raw sewage which cannot pass through Inlet Works). Overflow from the storm-dam passes to the receiving water (Umsunduzi River). The fact that the secondary clarifier hydraulic design capacity is fully utilised at times (Tables 6.1 and 6.2), indicates that the MLSS of the activated sludge plant needs to be reduced, either by extending the Works or by reducing the organic load of the settled sewage (e.g. chemical dosing ahead of primary sedimentation). Alternatively, any strategy which improves the settleability (lowers the DSVI) of the mixed liquor would also allow the hydraulic capacity of the existing secondary clarifiers to be more fully utilised.

6.3 HISTORICAL PERFORMANCE USING ALUM DOSING

6.3.1 Phosphorus removal

Figure 6.3 shows the effluent dissolved ortho P concentration for the Darvill activated sludge plant. Since July 1994 the secondary effluent has been passed through a tertiary stage (a so-called "maturation river") which provides about 16 h average hydraulic retention time and allows a degree of suspended solids removal as well as disinfection after chlorination. This creates the distinction between secondary effluent and final effluent (e.g. Fig. 6.3).

Alum dosing was commenced on a consistent basis in September 1992 and produced a marked reduction in effluent ortho P (Fig. 6.3). Earlier attempts (July and August 1992) at alum dosing (in the absence of alkalinity correction by addition of lime) had failed. Alum dosage was generally high to start with (50 to 70 mg/ℓ as $Al_2(SO_4)_3.14\ H_2O$ or 4.5 to 6.4 mg/ℓ as Al), but could be reduced to ca. 30 mg/ℓ once improved biological P was established following commissioning of the anaerobic basin and VFA system in July 1994 (Fig. 6.4). Final effluent compliance improved markedly in 1992 following the commencement of alum dosing, frequently exceeding 80% and sometimes reaching 100% (Fig. 6.4). During 1993-4, the Works was subject to a large number of process interruptions as a result of the capital upgrade project (see section 6.1) which hampered compliance. Furthermore, trade effluent problems commonly occurred, mainly in the form of illegal dumping of vegetable oil waste to sewer by local producers of cooking oil, margarine and by-products such as soap. Apart from serious primary sedimentation and scum removal problems produced by the excessive oil and grease from these wastes, it was noted that high secondary effluent ortho P concentrations frequently followed visual observations of vegetable oil waste entering the plant. Sometimes (but not always), this was accompanied by an increase in the secondary effluent ammonia concentrations; the latter suggested diminished aeration efficiency, as may be expected from the presence of oily emulsions in the activated sludge system. On other occasions, allowing for appropriate retention times, an increase in raw/ settled sewage phosphate concentrations coincided with the oily waste entering the plant and/or the high secondary effluent ortho P concentrations. This may be related to the fact that some of the vegetable oil industries use phosphoric acid in their refining process, or due to breakdown products from the seed cake used as raw material for the vegetable oil. Moreover, the presence of oily emulsions in the activated sludge plant generally gave rise to secondary sedimentation problems due to excessive scum formation. This was also linked to the visible formation of biological scum. These scums are formed by actinomycetes species (typically *Nocardia* spp.) which are known to proliferate in activated sludge systems which receive high concentrations of hydrophobic substances including fats, oil, grease and emulsions (Jenkins *et al.*, 1984; Lemmer and Baumann, 1988). The result is frequently that scum tends to get trapped in the system (e.g. inside the scum baffles of the secondary clarifiers). When the scum baffles were removed (ca. December 1993) as part of the original clarifier modifications at Darvill WWW, the scum tended to float out into the chlorine contact tank or maturation river. In doing so and being disturbed by cascading over the intervening weirs, part of the scum-associated solids settled to the floor of the chlorine contact tank where semi-anaerobic conditions allowed biological phosphorus release to occur. This is the most likely explanation for cases where mean final effluent ortho P concentrations exceeded the mean secondary effluent concentration (Fig. 6.3).

In an attempt to illustrate the effects of process disruption (including those resulting from vegetable oil waste discharges) on final effluent ortho P compliance, the period 1995/6 has been detailed in Figures 6.5a and 6.5b with annotation in Table 6.3a. Alum dosing ceased on 12 Aug. 1996 and the ferrous-ferric blend trial commenced a week later.

The data in Fig. 6.5 and Table 6.3a indicate that effective process control to achieve simultaneous nitrification-denitrification and combined biological-chemical phosphate removal is difficult in a single activated sludge system. A compliance level exceeding 90% is attainable (i.e. no more than one out-of-range result in a set of twenty (working day) daily results per month). However, consistent compliance to these levels requires an effective trade effluent control programme, which has not been achieved in the city of Pietermaritzburg over the years under consideration.

Table 6.2: Settled sewage and fermented primary sludge supernatant liquor (Primary SNL) flow and composition to Darvill activated sludge plant. N.D. = Not determined.

MONTH	Settled Sewage Mean COD	Settled Sewage Mean TKN	Settled Sewage Mean NH3	Settled Sewage Mean Alk.	Settled Sewage Mean TP	Settled Sewage Mean ortho P	Primary SNL VFA	Primary SNL COD	Primary SNL FLOW	Settled Sewage to activated sludge plant FLOW	VFA added to Settled Sewage based on inflow	COD (SNL) added to Settled Sewage based on inflow
	mg/ℓ	mgN/ℓ	mgN/ℓ	mg/ℓ CaCO3	mgP/ℓ	mgP/ℓ	mg/ℓ	mg/ℓ	Mℓ/d	Mℓ/d	mg/ℓ VFA	mg/ℓ COD
Jan-95	210	30.7	22.40	157	N.D.	5.57	435	N.D.	1.55	57.45	11.8	N.D.
Feb-95	275	30.6	22.15	154	N.D.	5.55	460	N.D.	1.36	54.04	11.6	N.D.
Mar-95	221	32.3	22.15	126	N.D.	4.22	450	N.D.	1.35	74.71	8.1	N.D.
Apr-95	237	33.0	20.55	125	N.D.	6.19	433	N.D.	1.17	58.57	8.6	N.D.
May-95	322	25.3	21.90	139	N.D.	6.85	616	N.D.	0.75	53.42	8.7	N.D.
Jun-95	381	33.5	23.80	140	11.91	8.15	664	N.D.	1.36	51.13	17.6	N.D.
Jul-95	334	27.4	25.00	226	9.14	6.22	770	N.D.	1.14	48.61	18.0	N.D.
Aug-95	314	27.0	26.35	157	10.39	7.71	835	N.D.	1.39	48.03	24.1	N.D.
Sep-95	307	32.8	24.15	161	6.57	6.57	970	N.D.	1.10	54.40	19.7	N.D.
Oct-95	307	16.8	22.00	139	6.41	6.41	832	N.D.	0.00	61.74	0.0	N.D.
Nov-95	253	22.4	18.90	142	N.D.	5.60	555	N.D.	0.25	72.90	1.9	N.D.
Dec-95	175	6.7	9.35	103	N.D.	3.97	224	N.D.	1.74	98.45	4.0	N.D.
Jan-96	151	8.9	11.62	113	N.D.	4.07	291	N.D.	1.88	88.94	6.1	N.D.
Feb-96	147	7.8	9.44	115	N.D.	3.34	361	N.D.	1.97	100.28	7.1	N.D.
Mar-96	130	6.9	11.72	111	5.42	3.56	357	440	1.79	91.97	6.9	8.6
Apr-96	242	12.3	14.31	140	N.D.	4.52	592	672	1.60	62.43	15.1	17.2
May-96	259	13.1	16.17	141	9.70	5.43	585	737	1.79	56.00	18.7	23.5
Jun-96	330	24.8	16.90	145	6.46	5.79	443	591	1.49	51.60	12.8	17.0
Jul-96	258	28.9	18.34	139	8.71	6.06	324	532	1.46	72.58	6.5	10.7
Aug-96	181	23.4	19.04	162	8.28	5.69	386	N.D.	1.49	55.81	10.3	N.D.
Sep-96	274	51.7	17.81	150	7.35	5.67	448	486	0.44	54.23	3.6	3.9
Oct-96	229	33.3	19.07	149	8.69	6.00	501	567	1.00	61.45	8.2	9.3
Nov-96	216	33.6	19.90	146	9.18	5.39	397	451	1.82	64.77	11.2	12.7
Dec-96	214	27.3	14.64	126	10.03	4.66	336	342	1.77	78.10	7.6	7.8
Jan-97	135	23.5	11.50	123	7.40	4.28	343	497	1.80	90.87	6.8	9.8
Feb-97	221	31.8	15.36	136	10.44	7.92	466	505	1.88	68.68	12.8	13.8
MEAN:	**242.9**	**24.8**	**18.2**	**141**	**8.51**	**5.59**	**503**	**529**	**1.36**	**66.58**	**10.3**	**12.2**
MEAN: MAY TO SEP.	**296**	**28.8**	**20.9**	**156**	**8.72**	**6.41**	**604**	**587**	**1.24**	**54.58**	**14.00**	**13.80**

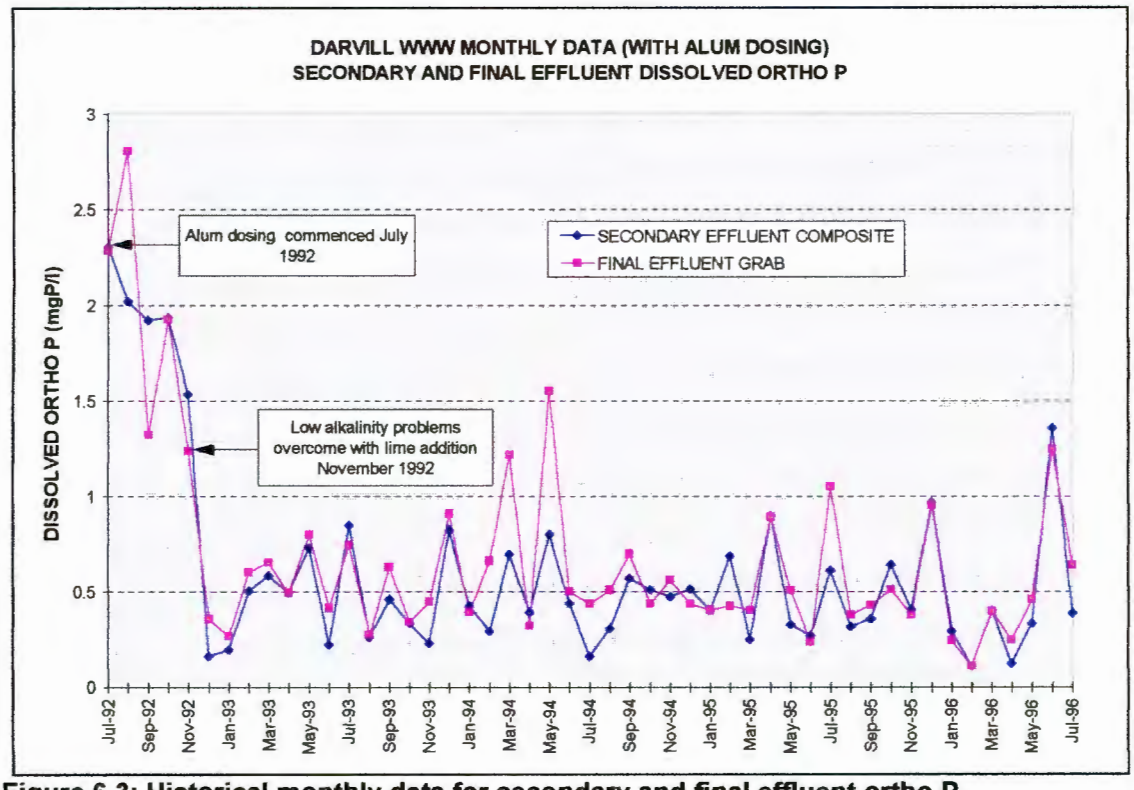


Figure 6.3: Historical monthly data for secondary and final effluent ortho P concentrations at Darvill WWW.

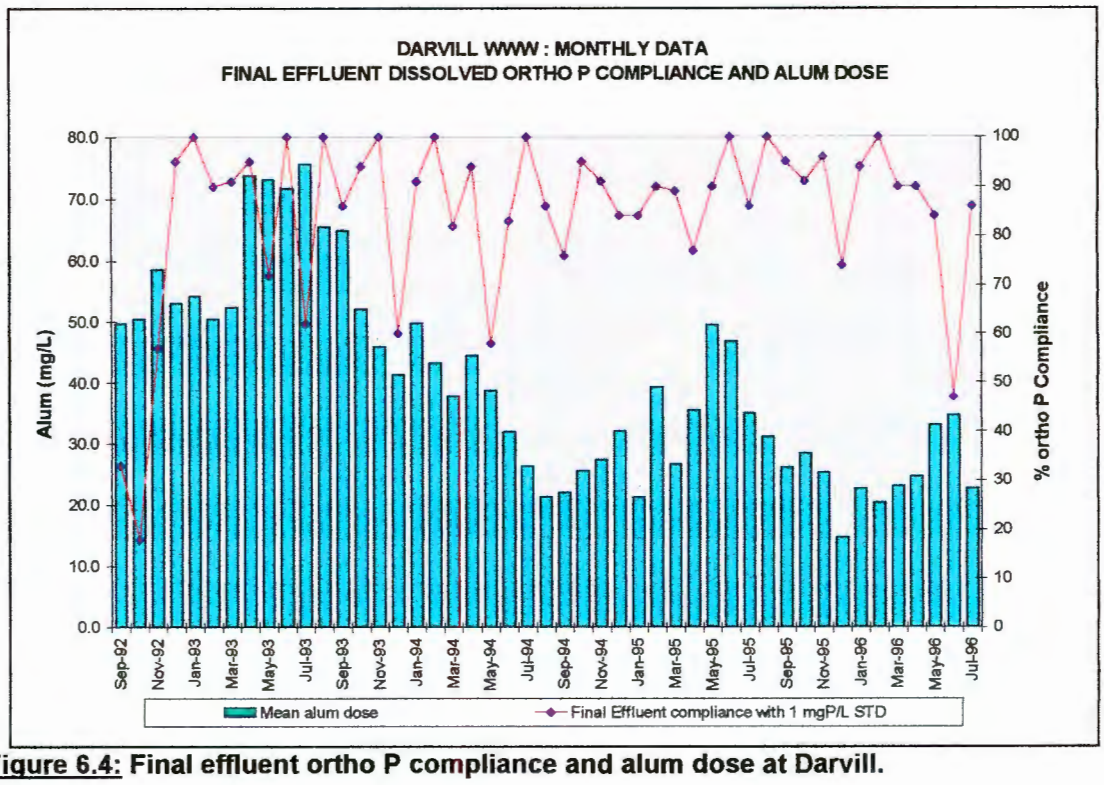


Figure 6.4: Final effluent ortho P compliance and alum dose at Darvill.

6.3.2 Sludge settleability and DSVI

Figure 6.6 shows the DSVI data for Darvill in the period Jan. 1995 to Aug. 1996. When combined with the annotations in Table 6.3a, it appears from Fig. 6.6 that severe trade effluent problems (e.g. July 1995; May-June-July 1996) are followed by an increase in the DSVI from a range of approx. 50 to 65 mℓ/g to >70 mℓ/g (up to 100 mℓ/g) over a one to four month subsequent period. The deterioration in settling was observed to coincide with outbreaks of *Nocardia*-type biological scum or foam which proved extremely difficult to eliminate from the plant.

Figure 6.7 shows average monthly DSVI data over a longer period (1992-6), corresponding to Fig. 6.4 which shows the average alum dose. From a comparison of these figures, several points become clear:

- Prior to the commissioning of the anaerobic zone (i.e. pre-July 1994), and particularly at higher alum doses (50 to 75 mg/ℓ) in the period Sep. 1992- Dec. 1993, the DSVI at this Works could be maintained at approx. 60 mℓ/g (range 50 to 70 mℓ/g);
- At lower alum doses (30 to 50 mg/ℓ), with the biological P removal extensions commissioned (but unfortunately also an increasing number of trade effluent problems), the DSVI tended to average in the range 60 to 80 mℓ/g, with occasional excursions as high as 100 mℓ/g, possibly due to trade effluent problems;
- Two wet seasons (ca. Oct. 1994 - Feb. 1995; and Nov. 1995 - Feb. 1996) brought a dramatic decline in the DSVI and this is most probably linked to the high storm and groundwater intrusion to this Works. It appears that fine silts and colloidal clay-type materials are washed into the sewage and these have a strong tendency to coagulate with or bind to the activated sludge flocs, thereby improving settleability [2]. This observation is supported by the fact that the volatile suspended solids (%VSS) content of the mixed liquor shows a similar seasonal trend to the DSVI for this Works (Fig. 6.7);
- Similarly, Nov. 1993 was a comparatively dry month (<50 mm rainfall) which saw an increase in DSVI, while summer rains occurred in Dec. 1994 - Jan. 1995, which appeared to be linked to a lower DSVI.

In summary, an operating DSVI in the range 60 to 80 mℓ/g appeared to be attainable at a minimum alum dose of approx. 30 mg/ℓ, but definite conclusions in this respect are obfuscated by abnormal external variables (trade effluent and stormwater or groundwater intrusion).

Figures 6.5a and 6.5b ...../

[2] The seasonal trend in DSVI may also be temperature-related since Pietermaritzburg predominantly receives summer rain. Unfortunately no records of mixed liquor temperature are kept at this Works. However, speculation that colloidal/ suspended soil material influences settleability was confirmed on at least one occasion by Operating staff at the Works who observed that the activated sludge colour turned an iron oxide red ("like mud") after flooding in the city caused the river to break its banks and silt/ mud- laden river water washed into the sewers. Both primary sludge and activated sludge settling and thickening improved markedly, but the high solids load blocked the primary settling tanks and sludge thickener.

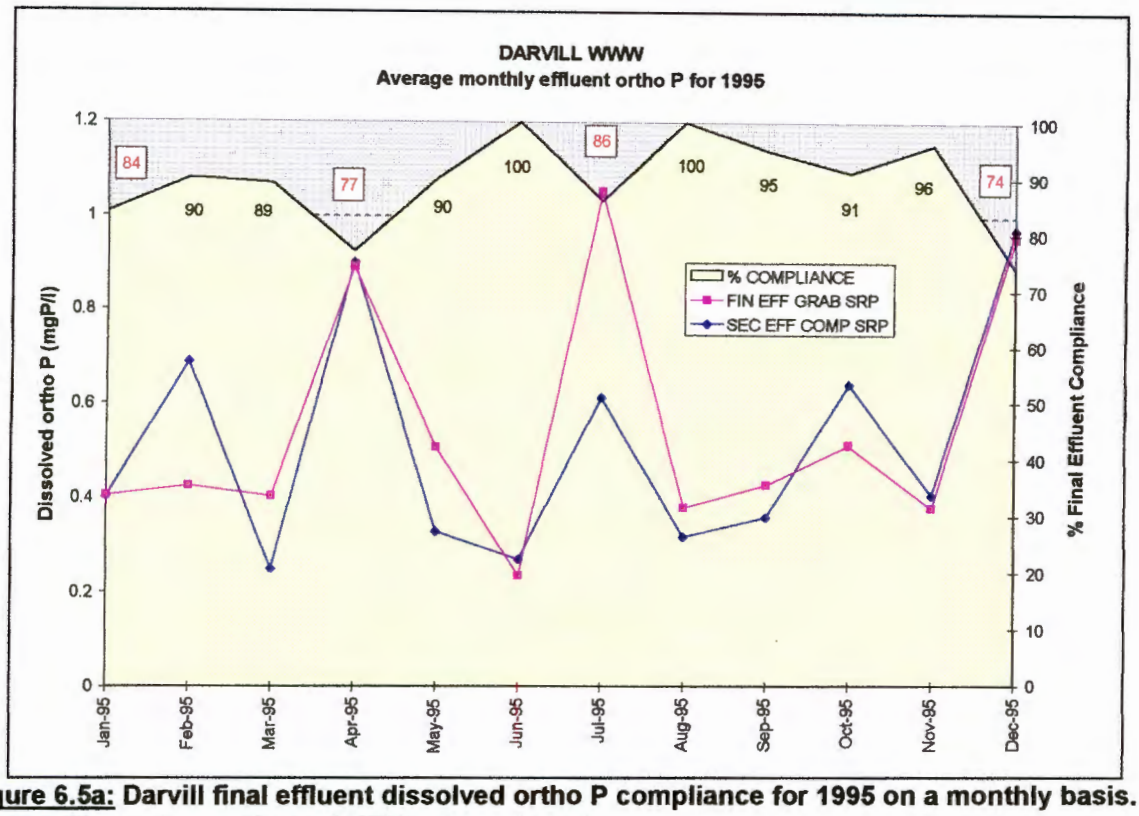


Figure 6.5a: Darvill final effluent dissolved ortho P compliance for 1995 on a monthly basis. Cases of lowest compliance (<87%) shown in red.

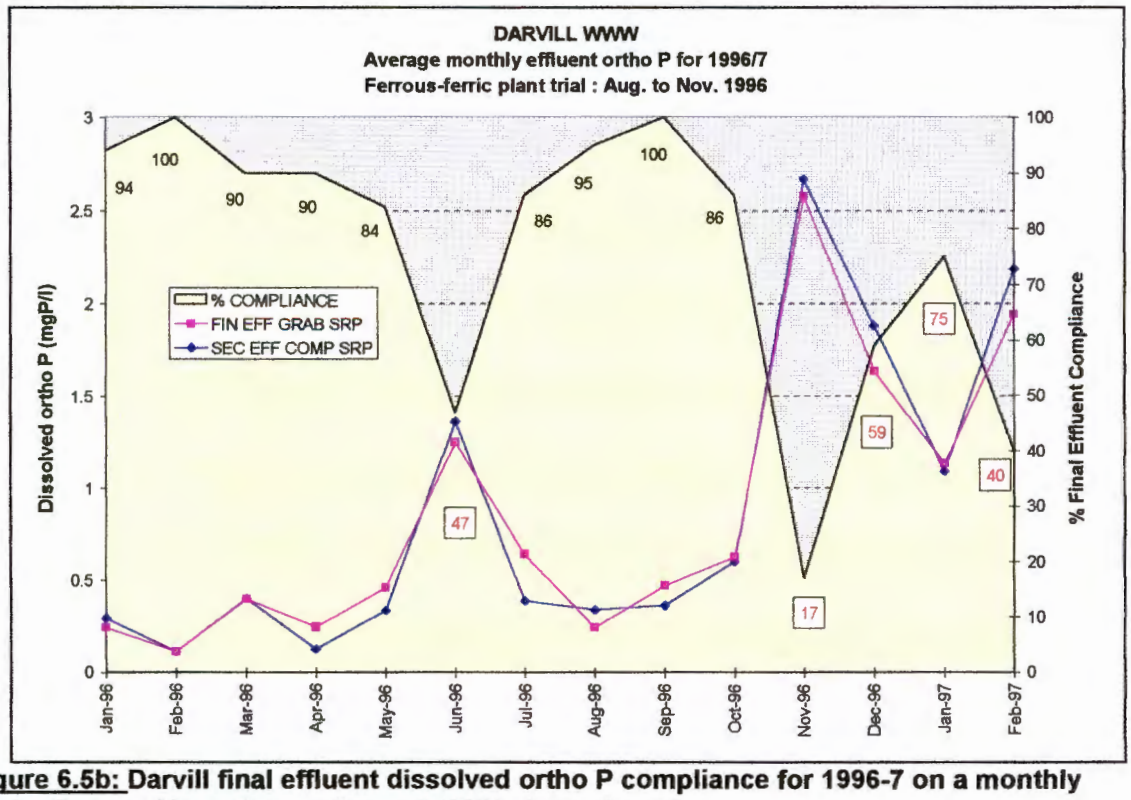


Figure 6.5b: Darvill final effluent dissolved ortho P compliance for 1996-7 on a monthly basis. Cases of lowest compliance (<75%) shown in red.

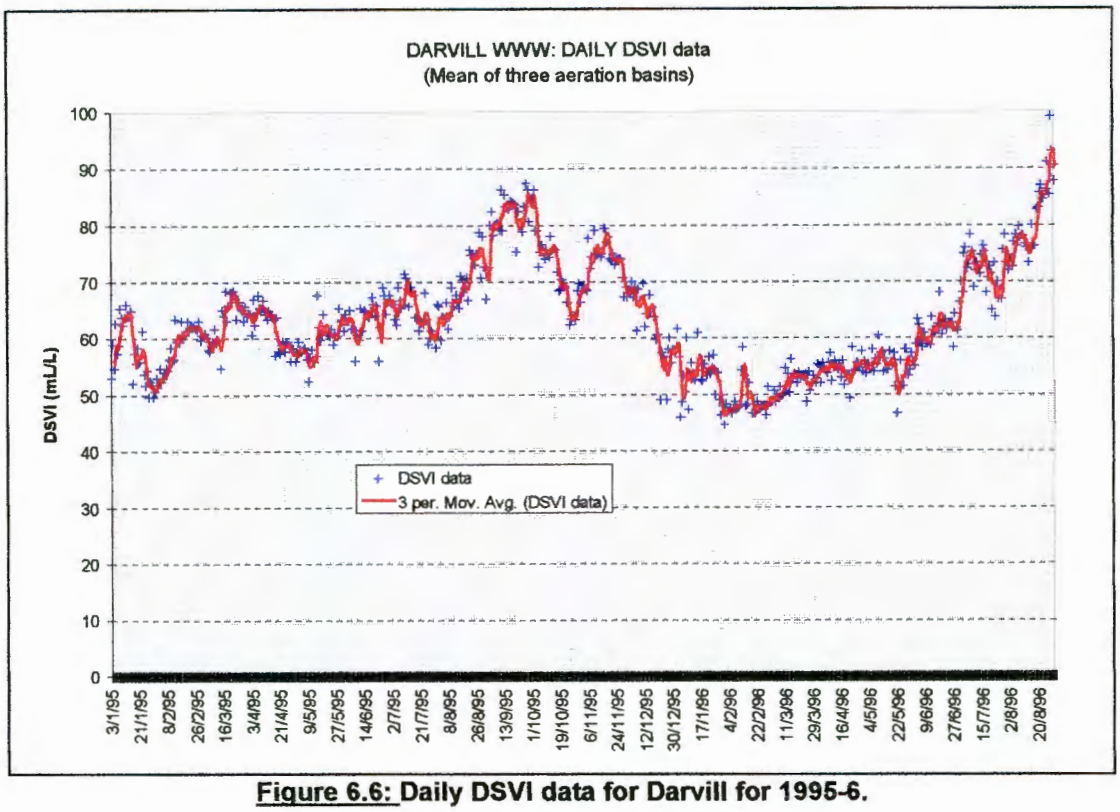


Figure 6.6: Daily DSVI data for Darvill for 1995-6.

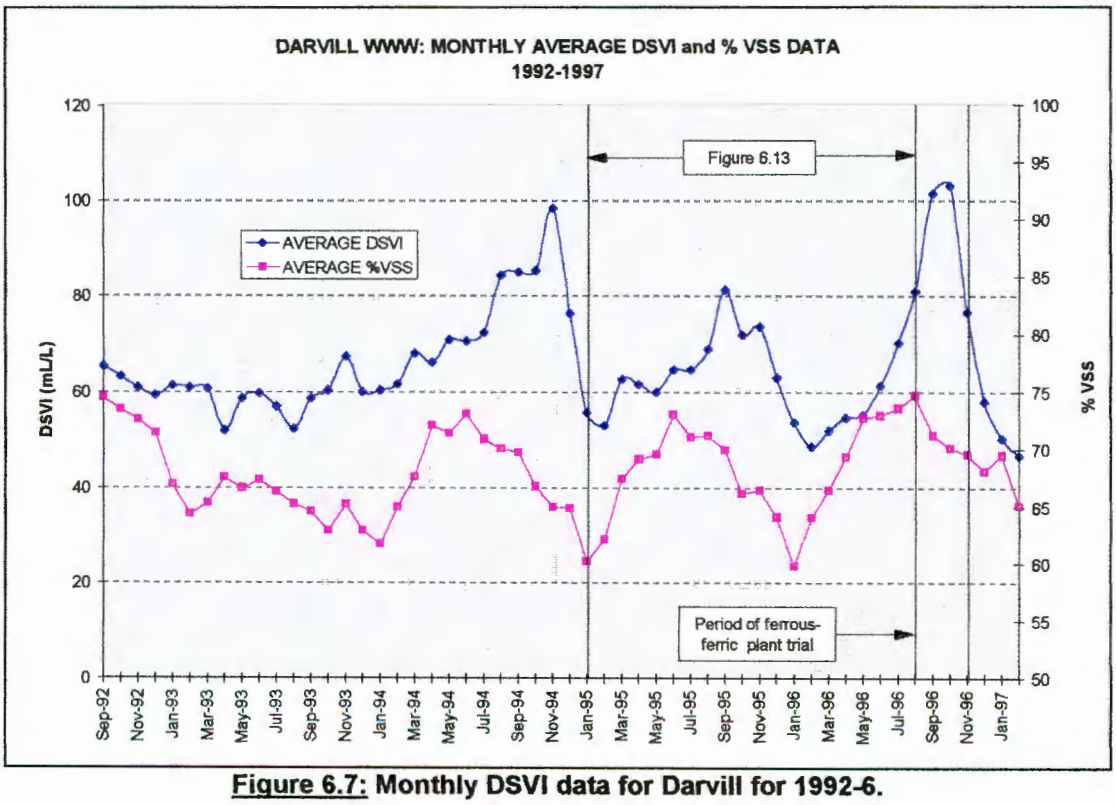


Figure 6.7: Monthly DSVI data for Darvill for 1992-6.

Table 6.3a: Annotations related to months of low effluent compliance for dissolved ortho P depicted in Figures 5a & 5b.

Period	Observations
January 1995	• Unsuccessful attempt at dissolved oxygen control of aeration while aiming to achieve simultaneous nitrification-denitrification. Under-aeration resulted. Control using nitrate and ammonia concentrations more successful. • Recycle of dissolved ortho P (biological release) from sludge settled in tertiary stage of "maturation river" and pumped back to activated sludge plant via DAF plant underflow during clean-out.
April 1995	• Primary sludge fermentation/ pre-thickener off-line. No "VFA" stream to anaerobic reactor weakened biological P removal. • Operator's nitrate method (*Hach* kit) found to be under-estimating nitrate, resulting in over-aeration. Higher-than-expected nitrate recycle via RAS weakened biological P removal. • Combination of reduced denitrification (over-aeration) and mechanical problems with lime feeder resulted in low alkalinity in activated sludge plant (46 to 70 mg/ℓ as $CaCO_3$), which weakened chemical/ biological P removal.
July 1995	Trade effluent problems • Five major *visible* discharges of vegetable oil and grease slick/ emulsion over period 23/6/95 to 23/7/95. • Build-up of scum on activated sludge and maturation river. • Inhibition of nitrification and aeration problems • Seven incidents of high influent pH (9.8 to 12.6) • Four incidents of high influent ortho P (10 to 15 mgP/ℓ; normally 5 to 8 mgP/ℓ - refer to Table 2)
December 1995	• City catchment has highest rainfall recorded this century with severe floods in Edendale valley. • Max. inflows to Works exceed 350 Mℓ/d (beyond metering capacity). • Sewage is very dilute; most of load is diverted via storm-dam directly to river. • Settled sewage COD drops to <100 mg/ℓ. Flows to activated sludge plant at solids loading limit of sec. clarifiers (ca. 130 Mℓ/d). Poor biological P removal under weak sewage conditions. Chemical dosing constrained by cost.
May-June-July 1996	Trade effluent problems • Eighteen major *visible* discharges of vegetable oil and grease slick/ emulsion over period 30/4/95 to 31/7/95. • Three *identified* incidents of high influent ortho P (14 to 16 mgP/ℓ). • Two incidents of high influent pH (9.2 to 12.9).
Aug. - Oct. 1996	• Trade effluent problems continue, to a variable degree. • Ferrous-ferric chloride plant trial appears to be successful with P removal but activated sludge plant develops a severe *Nocardia*-type biological foaming problem. Unsuccessful attempts are made to remove foam/ scum from reactor basins by manual physical methods using scum trap or by chlorination with HTH. • Mixed liquor DSVIs increase markedly (reaching nearly 120 mℓ/g).
November 1996	Trade effluent problems • Very large visible discharges of vegetable oil to Works occur. • Physical/ manual methods of foam/ scum trapping and removal are abandoned. Scum is released to final effluent via secondary clarifiers in greater amounts and mixed liquor DSVIs gradually decrease. Ferrous-ferric chloride dose is increased during the last 10 days of plant trial in attempt to reduce effluent ortho P concentrations.
December 1996	• Fewer discharges visible discharges of vegetable oil with factories closing for Christmas. No visible vegetable oil discharges after 18/12/96. • One high influent ortho P incident noted (20.7 mgP/ℓ). • Alum dosing is resumed after ferrous-ferric chloride plant trial. Biological foam/ scum problems virtually disappear completely and mixed liquor DSVIs recover to normal (ca. 60 mℓ/g).

Table 6.3a continued

January 1997	• Discharges of vegetable oil observed only in the third week of January. • Effluent ortho P consistently <0.75 mgP/ℓ until 19/1/97, which corresponds closely with the first observations (in 1997) of vegetable oil discharged to Works.
February 1997	Severe trade effluent problems resume • Large visible (and odorous) discharges of vegetable oil waste to Works. • At least three major incidents of high influent phosphate (ortho P ranging 13 to 63 mgP/ℓ; TP ranging 16 to 66 mgP/ℓ). • One high pH incident (raw sewage pH 11.5).

6.4 FERROUS-FERRIC CHLORIDE PLANT TRIAL

In preparation for the plant trial, alum dosing ended on 13 August 1996. The alum tanks were flushed out with tap water. New dosing pumps were installed which had the capability of resisting the increased corrosiveness of ferrous-ferric chloride compared to alum. Three identical dosing pumps were set up in such a manner as to pump an equal flow at a constant rate to each of the three activated sludge basins. Adjustment of the pumps was manual and the flow rate was checked on a daily basis by displacement from an in-line measuring cylinder. The flow rate of ferrous-ferric chloride was selected on the basis of on an assumed dry weather flow and such that the initial dose would be equivalent to a target of 0.1 mmol/ℓ as Fe (or Al in the case of alum at a dosage of 30 mg/ℓ) (Table 6.3b).

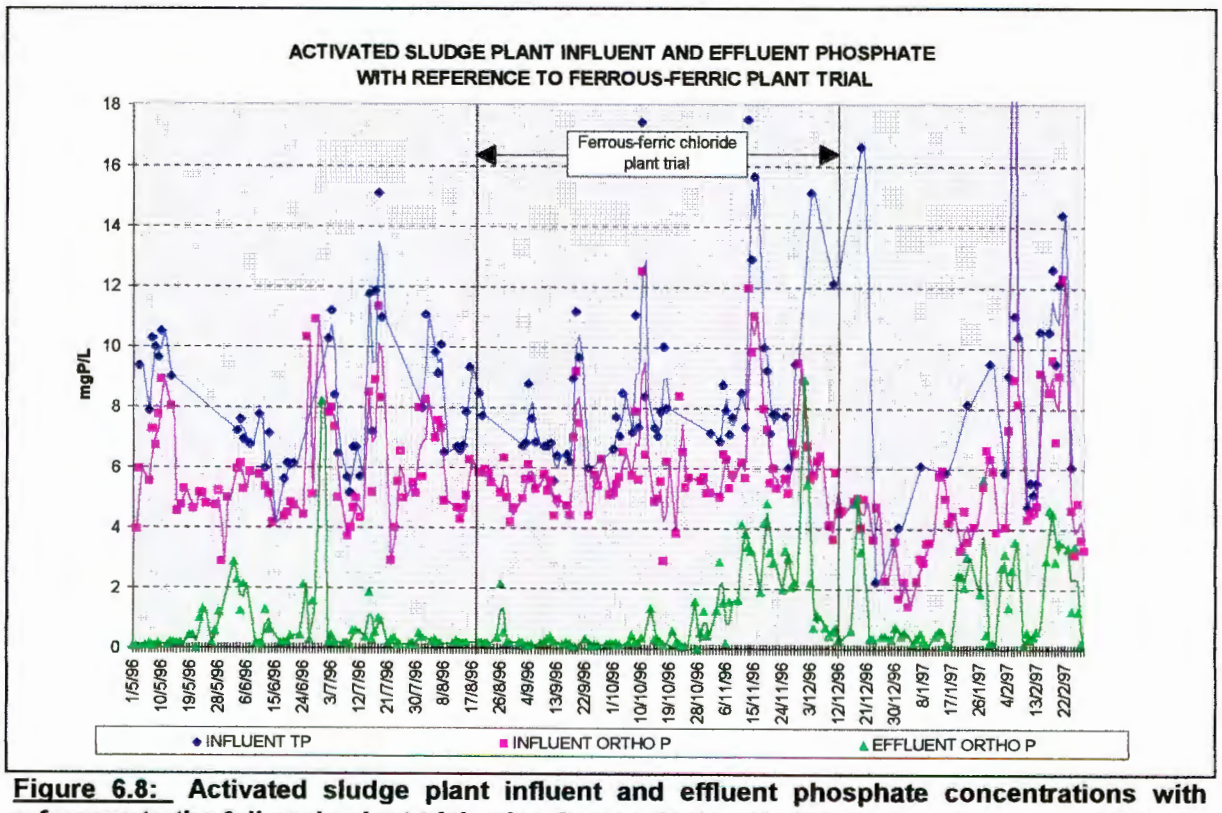


Figure 6.8: Activated sludge plant influent and effluent phosphate concentrations with reference to the full-scale plant trial using ferrous-ferric chloride as simultaneous precipitant. Two point moving averages plotted for data series.

Table 6.3b: Chemical dosing during the full-scale plant trial at Darvill WWW.

Period	Target dose mmol/ℓ as Al or Fe	Actual dose mmol/ℓ as Al or Fe	Actual dose as alum mg/ℓ as $Al_2(SO_4)_3.14H_2O$	Actual dose of ferrous-ferric chloride mg/ℓ Fe	Ave. daily flow rate of alum or ferrous-ferric chloride ℓ/d#	Ave. flow rate: ℓ/min per basin (three of)	Actual Ave. inflow rate to activated sludge plant Mℓ/d
1/5/96 to 31/5/96	0.1	0.103	30.7	0	3058	0.708	56.0
1/6/96 to 30/6/96	0.1	0.115	34.5	0	2958	0.685	51.6
1/7/96 to 31/7/96	0.1	0.082	24.3	0	2729	0.632	67.8
1/8/96 to 13/8/96	0.1	0.107	32.2	0	2981	0.690	55.8
20/8/96 to 31/8/96	0.1	0.102	0	5.7	1837	0.425	55.8
1/9/96 to 30/9/96	0.1	0.117	0	6.6	2055	0.476	54.2
1/10/96 to 31/10/96	0.1	0.109	0	6.1	2184	0.506	61.5
1/11/96 to 14/11/96	0.1	0.104	0	5.8	2187	0.506	64.8
14/11/96 to 20/11/96	0.14	0.135	0	7.5	2817	0.652	64.8
1/12/96 to 31/12/96	0.1	0.109	32.4	0	4199	0.972	78.1
1/1/97 to 31/1/97	0.12	0.117	34.7	0	5234	1.212	90.9
1/2/97 to 28/2/97	0.12	0.111	33.0	0	3773	0.873	68.9

Assumptions : Alum S.G. = 1.31 kg/ℓ; 46% m/m as $Al_2(SO_4)_3.14H_2O$
Ferrous-ferric chloride S.G. = 1.33 kg/ℓ; 13% m/m as Fe

6.4.1 P removal performance

Influent (settled sewage) phosphate concentrations were taken from the average of two grab samples daily: One sample was taken on the hour in a cycle from midnight to midday, advancing forward by one hour per day, and the other in a similar manner but in a cycle from midday to midnight. Ideally, these samples would have been taken as composites, but no refrigeration facilities were available for storing composite samples while being collected on the plant. (Experience had shown that raw or settled sewage samples kept at high ambient temperatures (ca. 25 to 42 °C) on the plant showed significant loss of COD, hydrolysis of organic nitrogen and loss of ammonia through volatilisation over the 24h period of collection. By contrast, the grab samples were refrigerated in the laboratory immediately after sampling and analysed within 48h).

The secondary effluent concentrations were taken as flow-weighted composite samples at a point where the effluent from all operational secondary clarifiers is combined and well mixed. Due to the low organic concentrations of the secondary effluent, no significant deterioration during the period of composite sample collection was expected.

Figure 6.8 shows the influent and combined secondary effluent ortho P concentrations (as well as influent total P, where available) for the activated sludge plant in three distinct periods:

- Alum dosing in the period prior to the plant trial (May-mid August 1996);
- Ferrous-ferric chloride dosing during the plant trial (August- late November 1996);
- Alum dosing in the period after the plant trial (December 1996 to February 1997).

Figure 6.5b shows the average monthly final effluent ortho P concentration and compliance with the 1 mgP/ℓ Special P Standard for the period spanning the plant trial.

It is clear from Figs. 6.8 and 6.5b that full compliance with the 1 mgP/ℓ standard was not achieved throughout the ferrous-ferric plant trial (13/8/96 to 20/11/96). However, P removal was good during the first two months of the plant trial, with effluent ortho P concentrations averaging 0.30 (± 0.34) mgP/ℓ during this period. The reason for the marked deterioration in P removal during the last month of the plant trial was not self-evident. However, it should be seen in the context of similar periods of deterioration in P removal in both the preceding and subsequent alum dosing periods. This suggests that factors other than chemical dosing also played a significant role in P removal.

Figure 6.9 shows the influent and effluent COD concentrations for the period corresponding to Figure 6.8, and Figure 6.10 similarly depicts the final effluent ammonia and nitrate.

Figure 6.11 shows that although there were some recorded instances of high or low influent and effluent alkalinity due to trade effluent discharges, in general the secondary effluent alkalinity remained in a desirable range of 70 to 100 mg/ℓ. This indicates satisfactory operator control of lime dosing. Similarly, Figs. 6.9 and 6.10 show that there is no obvious change in effluent COD, nitrate or ammonia which could be linked to the deterioration in P removal during the plant trial in the latter part of October and November 1996. Control of aeration was therefore satisfactory to achieve a balance between nitrification and denitrification (the latter in the informal anoxic zones created in these reactors). It is worth noting that Fig. 6.9 does show a reduction in influent COD during the latter part of October and into November 1996, as part of a gradual dilution in influent COD concentration which normally occurs at Darvill WWW with the onset of the summer rains and the attendant sewer ingress of rainwater. However, with the available data it is impossible to say whether this was a major factor contributing to the decline in P removal during the last month of the ferrous-ferric chloride plant trial. On the basis of operating experience at this plant, the impact of trade effluent on the plant is more likely to be the over-riding influence on P removal performance.

As has been stated elsewhere in this chapter, oil/grease and phosphate-rich industrial effluent dumping has become a regular problem in the Pietermaritzburg sewerage system. Some evidence of the sporadically high phosphate content of the settled sewage can be seen in Fig. 6.8 with concentrations of more than 12 to 18 mgP/ℓ total P (>10 mgP/ℓ ortho P) noted on several occasions. Such concentrations are 20 to 80% greater than the average and the measured peak concentrations may have been even higher on occasions, had more intensive sampling been routinely applied. Not only is an influent total P concentration of 12 to 18 mgP/ℓ very high for settled sewage by global standards, it also very high relative to the settled sewage COD of approximately 200 to 350 mg/ℓ for this Works (Fig. 6.9).

Using the steady-state BEPR of Wentzel et al. (1990), it can be shown that, for the following assumptions, the biological P removal potential of Darvill WWW (under dry weather conditions) can be shown to be about 8 mgP/ℓ. This model estimation is based on the following assumptions:

- Influent (settled sewage) COD : 300 mg/ℓ (excluding supernatant from primary sludge fermentation - see Table 2, data for dry months May to Sept.)
- Influent VFA : 20 mg/ℓ (as acetic acid)
- Unbiodegradable soluble COD fraction (f_{us}): 0.07
- Unbiodegradable particulate COD fraction (f_{up}): 0.04
- Readily biodegradable COD fraction (f_{bs}, as a fraction of biodegradable): 0.23

- Max. nitrate in return sludge: 1 mgN/ℓ [3]
- Return sludge ratio based on influent: 1:1
- Sludge age: 9 d
- Anaerobic mass fraction: 0.12
- No. of anaerobic reactors in series: 2.

It was established that the above assumptions have validity, notably :

- the influent VFA in the settled sewage is usually low [4] (de Haas and Adam, 1995);
- the biodegradable influent COD fraction of 0.23 could be supported by limited experimental data[5] and compares well with the default value of 0.24 commonly used for settled sewage (Dold *et al.*, 1991);
- the measured nitrate concentration in the pre-anoxic zone (which feeds return sludge to the anaerobic zone - Fig. 6.2) is routinely measured to be between 0.5 and 1.0 mgN/ℓ);
- a sludge age of 8 to 10d was recorded for this plant during 1996 (Fig. 6.17).

Hence, with approximately 8 mgP/ℓ biological P removal potential, and sufficient chemical precipitant dosed (0.1 mmol/ℓ) to remove up to an additional 2 mgP/ℓ at a projected ratio of P (removed):metal (dosed) = approx. 1.5:1 (Chapters 3, 4,& 5), it is clear that better than 10 mgP/ℓ removal cannot be expected on average unless a significant contribution of VFA to the influent comes from primary sludge fermentation.

From the data in Table 6.2, it can be seen that (under dry weather flow conditions, May to September) the fermented primary sludge supernatant liquor (SNL) contributes on average approximately 14 mg/ℓ VFA as COD based on the influent flow of settled sewage. This could increase the biological P removal potential from approximately 8 mg P/ℓ to approximately 9.5 mgP/ℓ, or a theoretical maximum P removal potential of approximately 11.5 mgP/ℓ with simultaneous chemical precipitation included. This estimate of P removal potential may explain to some extent the observations (Figs. 6.8 & 6.9) that periods of weaker P removal appeared to be associated with higher influent P concentrations (especially total P, where data was available) or lower influent COD. More detailed modelling of the results would only be possible if readily biodegradable influent COD had been measured on a routine basis.

University of Cape Town

Figures 6.9 & 6.10 ……/

[3] Nitrate concentrations of 0.5 to 1 mgN/ℓ are routinely measured in the pre-anoxic zone (refer to Fig. 6.2).

[4] De Haas and Adam (1995) reported an average of 35 (± 20) mg/ℓ VFA (mainly acetic and propionic acids) for Darvill settled sewage from 26 selected data pairs determined by HPLC. The original data set had 41 data pairs which gave 39 (± 43) mg/ℓ, but 15 data sets to be rejected as outliers.

[5] Unpublished data recorded in July 1993 for Darvill settled sewage gave an average of 102 (±15) mg/ℓ RBCOD determined using the square-wave loading method described by WRC (1984). The total COD for the corresponding period averaged 445 mg/ℓ. Assuming unbiodegradable fractions (particulate plus soluble) of 0.11, this gives an fbs value of 0.26. In April 1997, for 24 samples of Darvill settled sewage using the method of Mamais *et al.* (1993), an average f_{bs} value of 0.20 was determined.

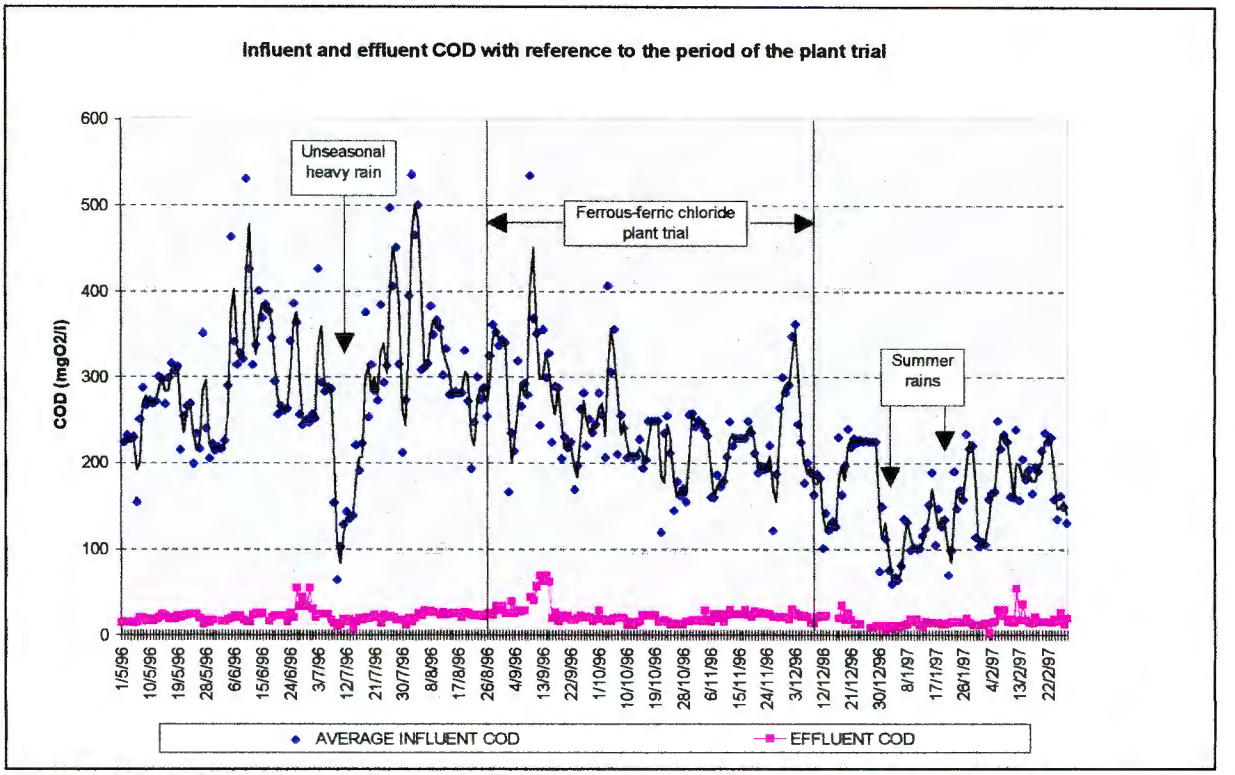


Figure 6.9: Influent and effluent COD for the activated sludge plant with reference to the ferrous-ferric chloride plant trial. Two point moving averages plotted for data series.

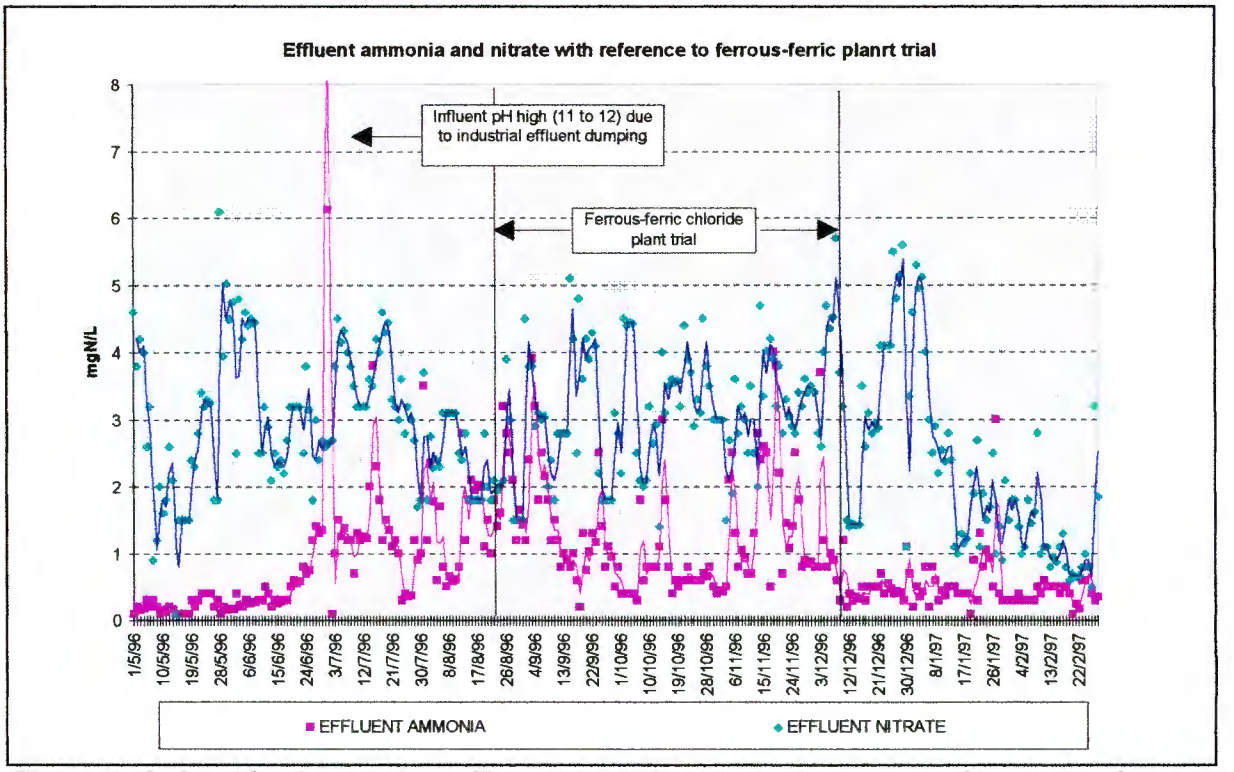


Figure 6.10: Combined secondary effluent ammonia and nitrate concentrations with reference to the ferrous-ferric chloride plant trial. Two point moving averages plotted for data series.

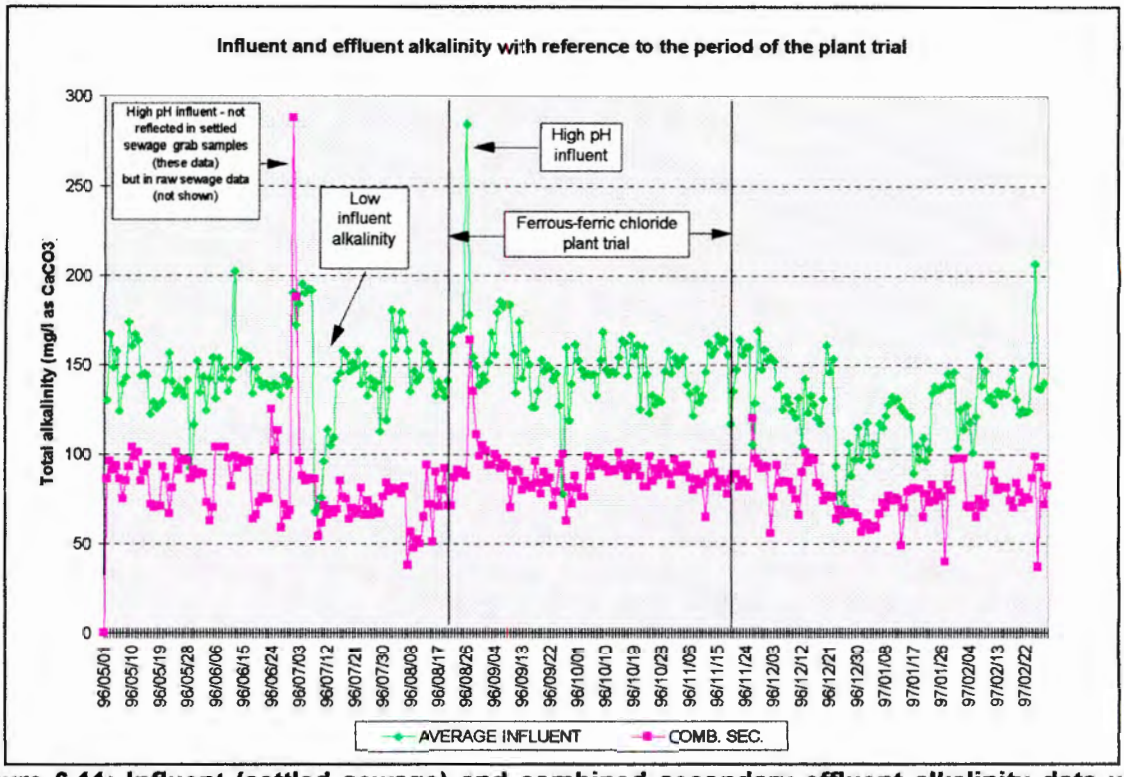


Figure 6.11: Influent (settled sewage) and combined secondary effluent alkalinity data with reference to the ferrous-ferric chloride plant trial.

6.4.2 Effect of trade effluent

The failure to find satisfactory explanations for the occasional failure of P removal on the basis of high influent P or low influent COD during the period of the plant trial (as well during the preceding and succeeding alum dosing periods), leads to the supposition that trade effluent discharged to Darvill WWW exerted an important or more complex effect. Since it is analytically difficult to differentiate between different trade wastes when diluted in a relatively large volume of domestic sewage, the only significant records kept at the Works in respect of trade effluent are influent pH and the presence of visible substances such as oils and dyes. Of these, the records of observed cases of floating vegetable oil, high influent phosphate and high influent pH are shown in graphical form in Figure 6.12. It should be noted that such data are dependent on the chance observation of floating oil by the Operators, or grab sampling in the case of pH and influent phosphate. Routine analysis for oil and grease is not carried out on the influent, owing to the difficulty and high cost of the analytical procedure and the fact that several vegetable oil refining industries discharge to Darvill WWW, which would make it very difficult to use the data obtained in such a manner (after dilution into the bulk sewage) for trade effluent prosecution purposes. Hence no record is kept of the influent *emulsified* oil and grease content. Many discharges from the vegetable oil refining industries contain emulsions of soap, oil and grease which could impact on the biological P removal process. Relatively small amounts of the visible (floating) oil fractions observed at Inlet Works (such as those recorded in Fig. 6.12) actually reach the activated sludge plant since these fractions tend to be trapped at the primary settling tanks. However, the emulsified fractions pass readily into the settled sewage which is pumped to the activated sludge plant.

Fig. 6.12 indicates that a large number of trade effluent-related incidents occurred during the months of May to August 1996, followed a marked reduction in September[6], a resumption during November, fewer in December 1996 and January 1997, and a sudden increase again during February 1997. Comparing this with the compliance records for final effluent ortho P in the corresponding period (Figure 6.5b), it can be seen that there is a degree of correlation:

- Poor effluent P compliance during May to July 1996, recovery through August with 100% compliance during September;
- Effluent P compliance was particularly poor during June 1996 and early July 1996 when several high pH and high influent phosphate incidents occurred;
- Similarly, one of the largest (most visible) illegal vegetable oil dumping incidents in the history of the Works occurred during early November 1996 when approximately 20 tons of waste oil and grease were removed from the PSTs. That month showed the lowest effluent P compliance (17%) for the period under discussion;
- The level of compliance improved over the December-January holiday period when industrial production is usually reduced.
- Three large oil-related incidents occurred during the third week of January 1997, which resulted in the effluent ortho P increasing from an average below 0.4 mgP/ℓ (1/1/97 to 18/1/97) to an average of 2.35 mgP/ℓ for the remainder of that month;
- February 1997 again saw a worsening of compliance (40%) with the final effluent ortho P averaging close to 2 mgP/ℓ. There were several visible vegetable oil discharges as well as high influent pH and phosphate incidents during February (Fig. 6.12).

Collectively, the phosphate data and observations in respect of trade effluent suggest that ferrous-ferric chloride appeared to be at least as effective for phosphate removal as alum, but no obvious full-scale process benefit was derived from the use of the iron salt compared to alum. More definite conclusions in this respect were obfuscated by the absence of parallel reactors for comparing the alum and iron salts, and by the nature of irregular trade effluent discharges which interfered severely with phosphate removal at Darvill WWW.

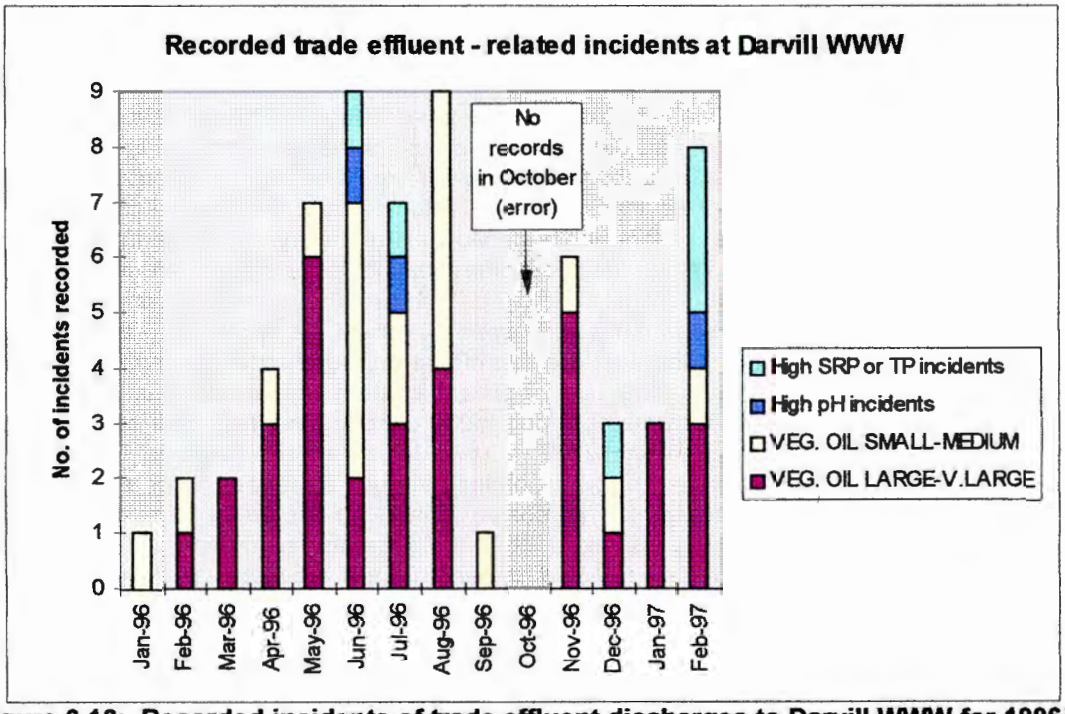


Figure 6.12: Recorded incidents of trade effluent discharges to Darvill WWW for 1996/7.

[6] No records were kept during October 1996 due to Operator error.

6.4.3 Foam, scum and settleability

One area of concern noted during the ferrous-ferric chloride plant trial was the apparent tendency for the iron salt to exacerbate biological foam or scum problems in the activated sludge plant. This effect had not been noted in the pilot plants. At high dose, ferric chloride had been found to weaken settleability in the pilot plants by producing a slow-settling pin-floc type sludge (see Chapter 4), but this effect disappeared when the pilot plants were switched to ferrous-ferric chloride dosing.

The full-scale biological scum and foam problem was suspected to be related to the high concentrations of vegetable oil and grease in the influent. The effect of this variable would not have been reflected in the pilot plants, partly because of the manner in which the settled sewage batches for the pilot plant were collected and cold-stored (the cold storage tank acting as a type of grease trap) and partly because of regular cleaning/ sieving of the mixed liquor in the pilot plants to remove debris which could have cause blockage of the feed and recycle tubes.

The photographic record in Appendix 6 shows the extent of the problem in the full-scale activated sludge plant in November 1996. Attempts to trap the foam/ scum in the anaerobic basin and remove it by a manual method were unsuccessful (e.g. pumping with trash or plunger pumps; utilising a rope skimmer; or by means of hand-held scoops). High pressure chlorinated water sprays were partially successful, but the foam reformed in the secondary clarifiers and resulted in severe solids carry-over problems in the secondary and final effluent. The suspended solids standard was compromised and a large tonnage of sludge had to be removed from the first maturation "pond" (or maturation "river"), which also provides disinfection contact time. The bacteriological standard for faecal coliforms was exceeded by a large margin in several samples (taken daily), with *E. coli* numbers reaching log 4 to log 5 per 100 mℓ. Increased numbers of *Giardia* and *Cryptosporidium* cysts were also detected in the final effluent at this time.

Microscopic examination of the foam/ scum confirmed observations with the naked eye that *Nocardia* was the dominant organism. Large numbers of spirochaetes were also found to be present in the scum.

On the basis of the previous discussion in respect of trade effluent, it seems most likely that the high concentrations of oil and grease in the sewage contributed to the growth of *Nocardia.* This is supported by research conducted on plants in the USA by Jenkins *et al.* (1984). However, the biological foam/ scum problem was greatly diminished when the plant was reverted to alum dosing. Moreover, the problems associated with vegetable oil and grease in the influent has been a regular feature at Darvill WWW since 1992 when alum dosing was first introduced. The *Nocardia* problem appeared to be significantly worse with dosing of the iron salt than with alum. According to Forster (1996), research on biological foaming in activated sludge plants in the UK has confirmed earlier work which associated foaming with the excretion by nuisance organisms of extracellular polysaccharide containing high concentrations of uronic acid. The same study (Kerley and Forster, 1995) suggested that the role of uronic acid in stabilising foams was through the formation of a three-dimensional structure with polyvalent metal ions such as calcium or aluminium, although iron ions were not tested in this regard by Kerley and Forster (1995). Unlike ideas prevalent in the 1970s, which separated surface chemistry from the role of filamentous micro-organisms, Forster (1996) proposed that a fully integrated model is required to explain the interactions between sludge microbiology and the sludge properties. This should involve the chemical nature of the settled sewage fed to the aeration tank, the dominant species of filament and their surfaces (Forster, 1996).

DSVI data suggested that *Nocardia* (or similar filamentous organisms associated with the biological foaming) was partly responsible for a deterioration in sludge settleability during the ferrous-ferric plant trial. Pilot plant data had suggested that ferrous-ferric chloride dosing would produce a *benefit* in terms of lower DSVIs, at least on a par with periods of alum dosing. The DSVI data for 1995-7 is shown in Figure 6.13 and can be compared to Fig. 6.6 (prior to ferrous-ferric chloride plant trial). Fig. 6.13 shows that the DSVI was in an increasing trend immediately prior to the commencement of the plant trial, but continued to increase during the plant trial to significantly higher values (approaching 120 mℓ/g) than in the previous late winter/ spring season. A turning point was reached in the latter part of October 1996, although the trend was difficult to discern for the Operators at that time. The

iron dose was increased at the start of November 1996 but it is unclear whether this contributed directly to the further decrease in DSVI which took place shortly thereafter. Certainly, after the plant was switched back to alum dosing, the DSVI decreased up to the end of January 1997. The decrease in DSVIs during Dec. 1996 - Jan. 1997 was recorded with a concomitant virtual disappearance of the *Nocardia*-type scum and foam problems which had been prevalent during the ferrous-ferric chloride plant trial.

As was discussed under 6.3.2 above, the DSVI data needs to be interpreted as part of what appears to be an annual cycle for this Works: increasing DSVIs through winter (the dry season), followed by a marked decrease with the onset of the summer (the wet season)[7]. Once again this trend was manifest during 1996/7, as monthly average data in Figure 6.14 indicate. It follows that ferrous-ferric chloride did not appear to produce a benefit of lower DSVIs compared to alum in the full-scale trial. The iron salt may even have been partly responsible for increased DSVIs which were apparently linked to the *Nocardia* scum/ foam proliferation during the plant trial.

Summarising, it appears that the absence of a control reactor makes it impossible to differentiate the respective impacts of chemical dosing and trade effluent interference with settling characteristics of the sludge. On the one hand, it may be significant that the *Nocardia* scum and foaming problems, as well as average monthly DSVI's in excess of 100 mℓ/g for two months in succession, occurred for the first time in the history of the Darvill activated sludge plant during the ferrous-ferric plant trial. On the other hand, the trade effluent problems experienced during this period were also amongst also the worst in the recent operating history of the Works and probably had a significant influence on the activated sludge settleability.

Figures 6.13 & 6.14 ...../

[7] As noted under 6.3.2, it is not clear whether this annual cycle in DSVI is temperature-related (e.g. in so far as temperature affects oil and fat separation in the mixed liquor), or flow-related (e.g. in so far as storm and groundwater ingress of the sewer system may wash clay-like colloidal soil material into the sewage, which could exert an influence on activated sludge flocculation). Temperature has been implicated as a potential stimulus for low F/M (anoxic-aerobic) filament bulking (Ekama, 1994).

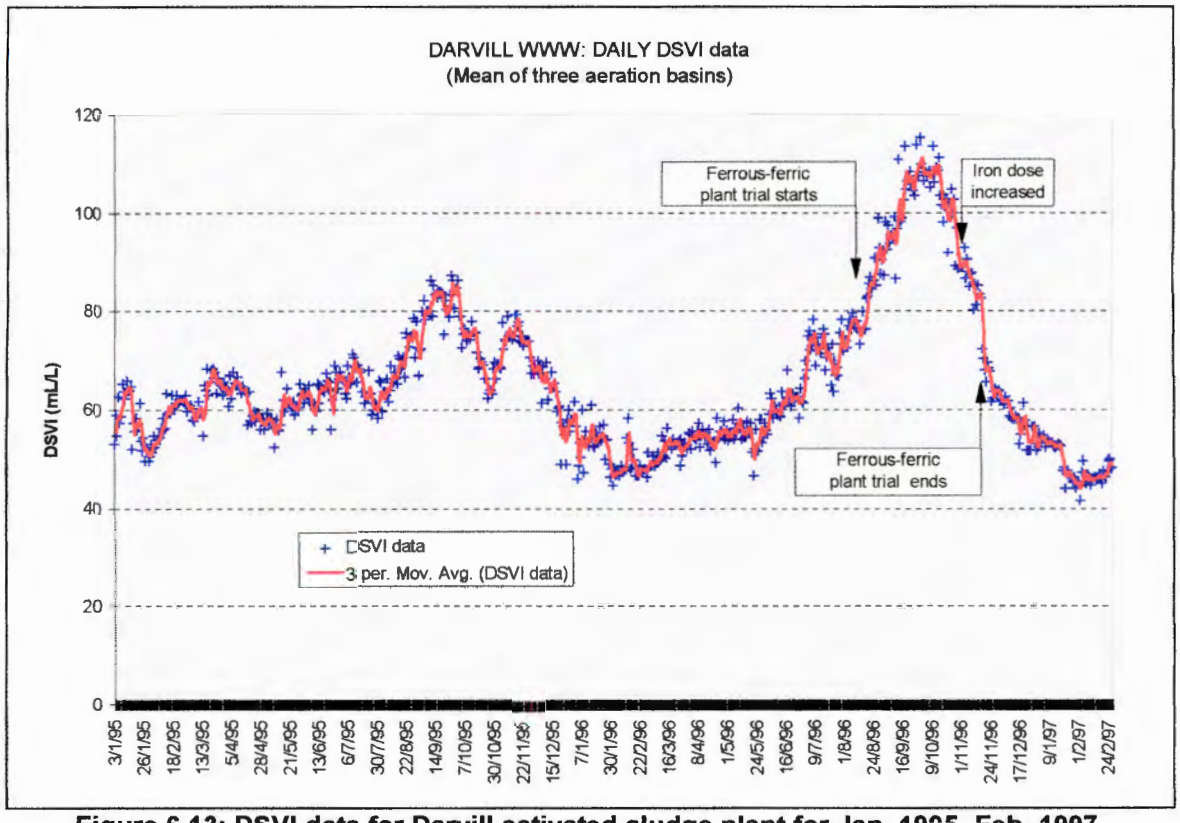


Figure 6.13: DSVI data for Darvill activated sludge plant for Jan. 1995- Feb. 1997.

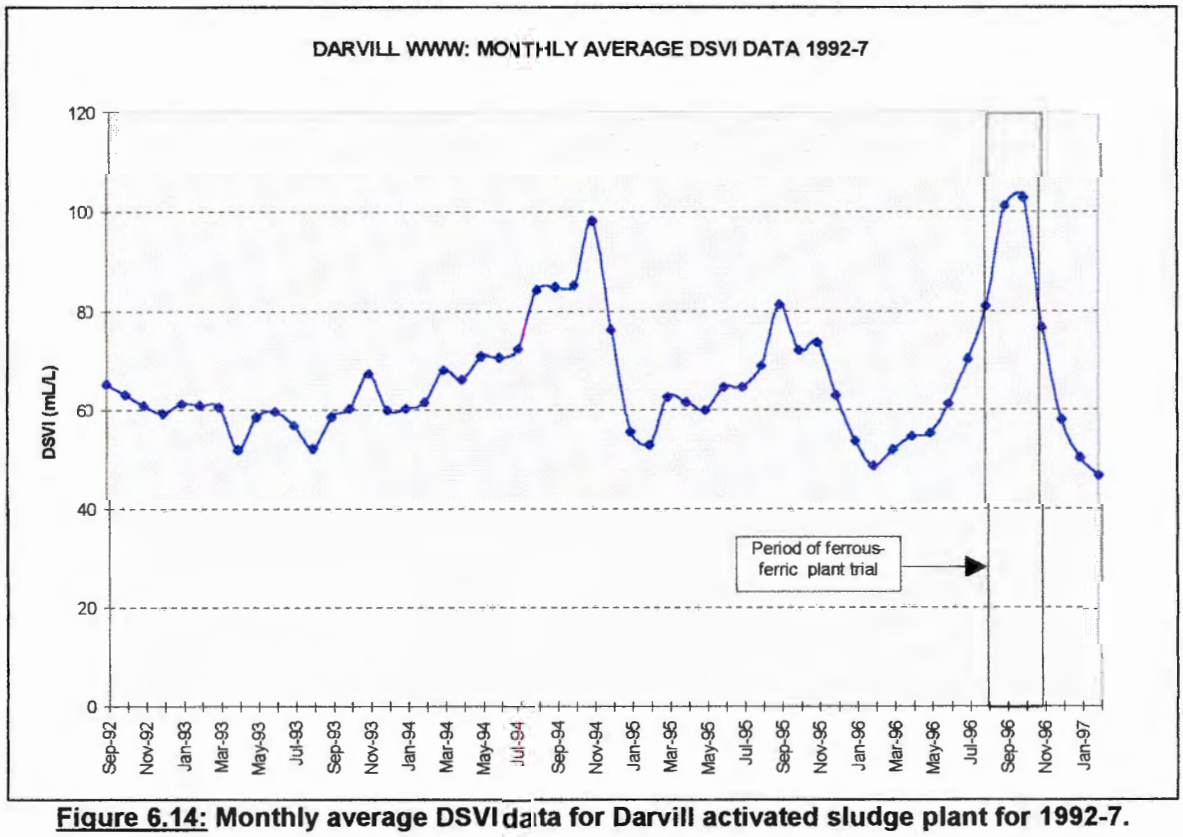


Figure 6.14: Monthly average DSVI data for Darvill activated sludge plant for 1992-7.

6.4.4 Fractionation results

Figures 6.15 and 6.16 give the relevant fractionation data using the method described in Chapter 2 (Table 2.11) which was applied to samples of mixed liquor from the pilot plants in Chapters 3, 4, and 5.

The fractionation results for mixed liquor withdrawn from the full-scale activated reactor both before, during and after the ferrous-ferric chloride plant trial showed broad similarities, namely:

- mixed liquor total P of approx. 60 to 80 mgP/gVSS;
- approx. 10 to 20 mgP/gVSS as chemically precipitated ortho P extracted into cold PCA, and a further possible 4 to 8 mgP/gVSS extracted as ortho P in NaOH;
- complex P of 32 to 45 mgP/gVSS (sum of PCA and NaOH fractions), implying that the biological mechanism still dominated;
- most of the complex P extracted into NaOH as opposed to PCA;
- residue TP of 5 to 10 mg P/gVSS (<15% of total P), indicating that most of the P was extracted in the fractionation procedure.

Figure 6.16 shows that most of the phosphate release could be accounted for from the NaOH extractable complex P, with the PCA extract complex P contributing to P release, as expected where it made a significant contribution to the mixed liquor total P. However, it is significant that in most cases the *net ortho P release* to the supernatant could only be accounted for by taking into account the apparent uptake into the PCA ortho P extract, and in some cases, into the supernatant complex P fraction. These observations suggest that metal precipitation sites were available in the sludge mixed liquor and a part of the ortho P released from the biological hydrolysis of complex (poly) P became trapped in a chemical form in the sludge matrix as a result. Metal hydroxide in the sludge matrix could have been the source of metal in such a precipitation reaction. The appearance of complex P in the supernatant in some cases further suggests that in some cases, colloidal forms of metal (hydroxy) phosphate may have formed which were not removed by low speed centrifugation.

The increased appearance of metal hydroxide as "stored" source of precipitant for phosphate in the mixed liquor suspended solids would be expected under conditions where phosphate is limiting in the supernatant (i.e. under real conditions where the effluent ortho P concentrations are required to be as low as possible). Such conditions prevailed during the first two months of the plant trial. It is therefore explicable that the batch P release and fractionation results for the plant trial resembled those for the pilot plants while dosed with ferrous-ferric chloride under conditions in which no phosphate was added to the influent and low effluent P concentrations prevailed. For example, the fractionation patterns of Figs. 6.15 and 6.16 are very similar to those in Figs. 5.11a and 5.14a of Chapter 5.

Figures 6.15 and 6.16 do not provide clear proof that the biological mechanism was inhibited by the dosing of iron in the form of ferrous-ferric chloride. However, it may be significant that the *relative* proportion of biological (complex P) to chemical (ortho P) fractions decreased during the course of the plant trial. Taking into account the actual total P recoveries in the fractionation experiments (see Fig. 6.15), the following summary of P fractions may be made:

- Alum (before): 24% chemical; 59% biological; residue 17% from 63 mgP/gVSS Total P;
- Iron (1 month): 21% chemical; 62% biological; residue 13% from 70 mgP/gVSS Total P;
- Iron (3 mo.): 42% chemical; 47% biological; residue 9% from 69 mgP/gVSS Total P;
- Alum (after): 33% chemical; 54% biological; residue 9% from 63 mgP/gVSS Total P

Like the effluent P data (section 6.4.1), these data suggest that the ferrous-ferric salt initially produced an improvement in the biological mechanism, followed by a deterioration over two months of continuous iron dosing, with the chemical mechanism becoming stronger in that time. A reversion to alum dosing appeared to reverse this trend. The biological (complex P) fractions varied from 32 to 45 mgP/gVSS, and it may be significant that these fractions were smallest after three months of iron dosing. This may be linked with evidence from the pilot plants that depression of the biological (complex P) sludge fractions, appeared to be more marked under low effluent P conditions (Chapter 4, section 4.3.; Chapter 5, sections 5.3.5.2/3 and 5.3.6). It is noteworthy that the full-scale plant showed secondary effluent alkalinity of ca. 60 to 120 mg/ℓ as $CaCO_3$, which is similar to that from

the pilot plant Test unit for the low effluent P conditions without supplemental sodium bicarbonate in the influent (Chapter 4, section 4.3.11.2).

In summary, some evidence was gained from the full-scale ferrous-ferric plant trial to support pilot plant observations that a greater degree of inhibition of the biological mechanism is caused by iron dosing than by alum dosing. However, in the absence of a full-scale control reactor and confounding extraneous variables such as the effects of trade effluent (see sections 6.4.2 and 6.4.3), it is not possible to determine to what extent partial inhibition of the biological mechanism was the cause of the elevated effluent P concentrations from the full-scale plant during the latter part of the trial with ferrous-ferric chloride.

Figures 6.15 & 6.16 ...../

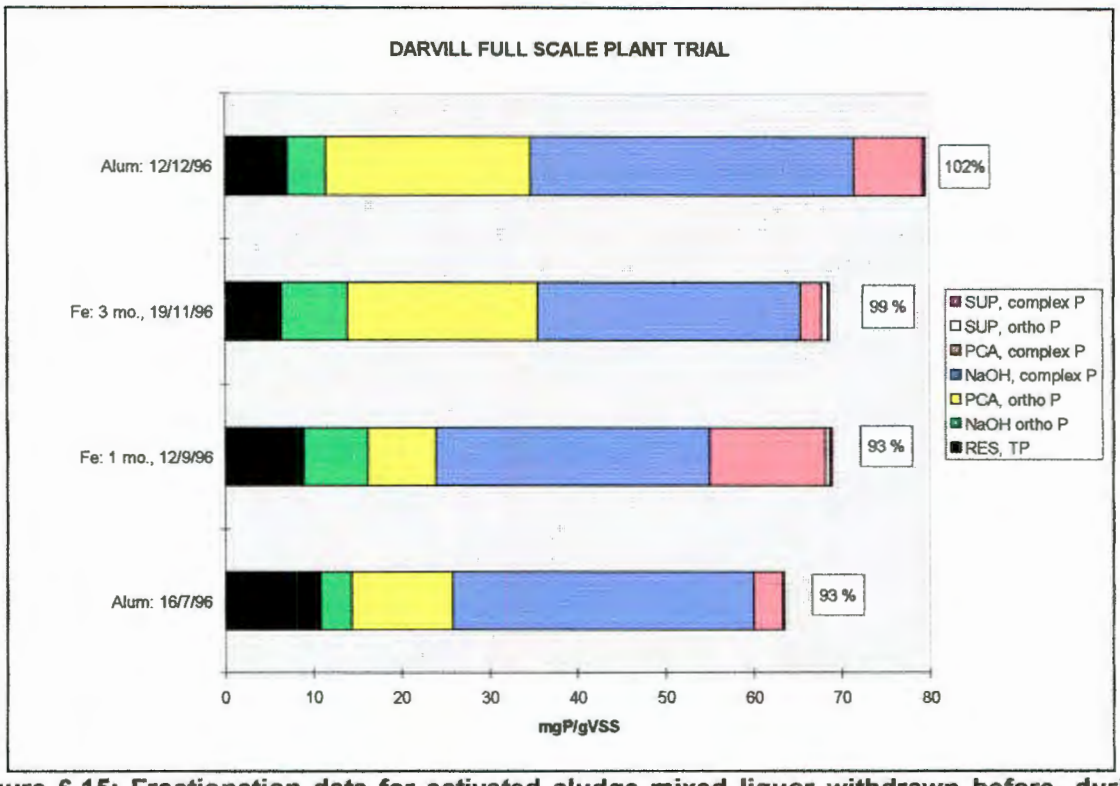


Figure 6.15: Fractionation data for activated sludge mixed liquor withdrawn before, during and after the ferrous-ferric full-scale plant trial at Darvill.
Percentage figures quoted are for Total P recovery in fractionation procedure.

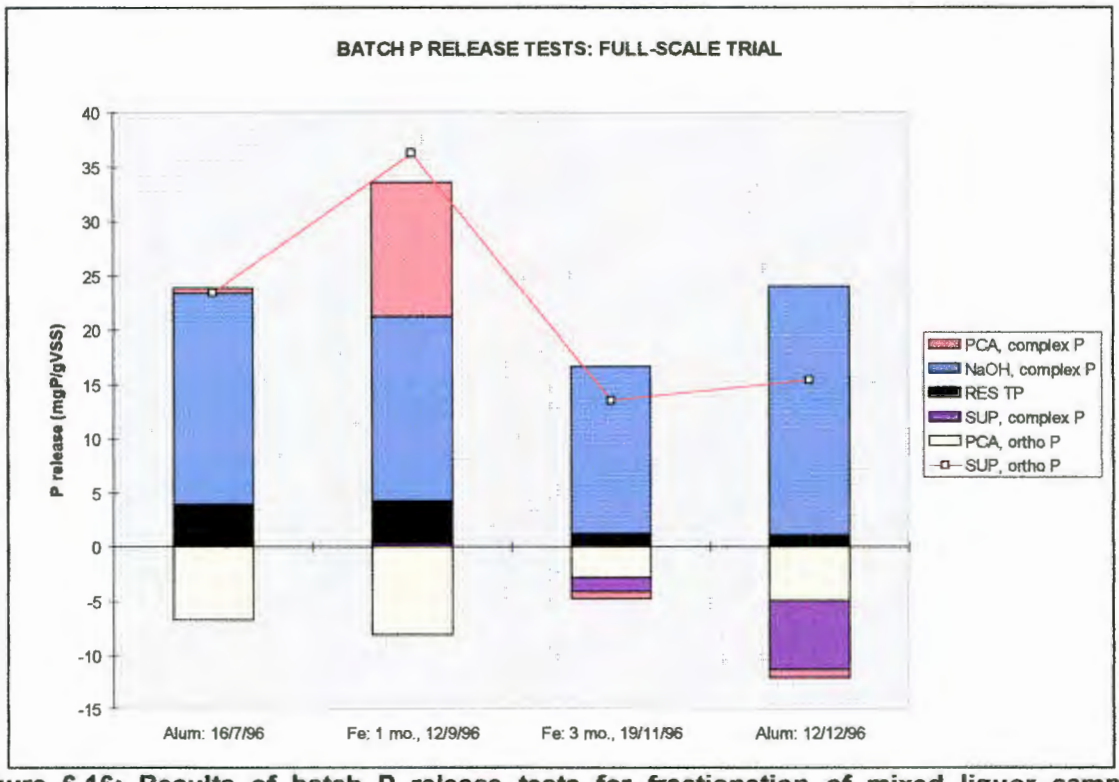


Figure 6.16: Results of batch P release tests for fractionation of mixed liquor samples corresponding to Fig. 15. *Note: Negative P release result implies P uptake in that fraction.*

6.5 SECONDARY SETTLING TANK STRESS TESTS

Secondary settling (or clarification) is fundamental to the activated sludge process. Three 35m diameter, 2.5m deep secondary settling tanks (SSTs) with suction lift return sludge lines were originally built at Darvill WWW (in 1974) for a design average dry weather flow (ADWF) of 54 Mℓ/d. These three SSTs had proved inadequate under wet weather flow conditions when at least three times dry weather flow needed to be passed through the activated sludge plant. Accordingly, Meiring and Barnard (1990) recommended that additional SSTs be built for this plant and that the old SSTs be modified. The recommended modifications included removal of two inner launders (the original design incorporated both an outer peripheral and two inner launders), leaving only a single peripheral launder per SST, and the installation of baffles. These recommendations for the old SSTs were carried out; the details of the baffles are recorded by Umgeni Water (1993) and will be discussed below. Furthermore, two additional 35m diameter SSTs were built (area = 962 m^2 each), which are centre-scraped, with a side-wall depth of 4m, and each equipped with a dedicated variable speed drive return sludge pump (max. capacity ca. 220 ℓ/s or 19 Mℓ/d). A new splitter box was built to serve the five SSTs (two "new" and three "old") - refer to Footnote 10 in section 6.5.1 below). Furthermore, the screw pumps, which originally provided for sludge recycle from the old SSTs, were replaced by a bank of four centrifugal pumps operated on level control from the sump to which the siphons from the recycle lines of these SSTs jointly discharged. The design capacity for these four pumps collectively was ca. 500 ℓ/s or 43.2 Mℓ/d.

The five SSTs at Darvill were designed for a maximum surface solids loading rate of 7.5 kg SS/(m^2.h) at a DSVI of approximately 80 mℓ/g (or less) and an MLSS of 3800 mg/ℓ and a peak wet weather flow of 3 x 54 = 162 Mℓ/d (Barnard, 1992)[8]. From mass flux considerations (WRC, 1984):

$$G_{ap} = X_o \cdot (Q_i + Q_r)/ A \qquad \text{..... Eqn. 6.1}$$

where G_{ap} = applied solids flux (kg/m^2/d)
X_o = operating reactor MLSS (kg/m^3)
Q_i = influent wastewater flow to process (m^3/d)
Q_r = underflow (sludge recycle) rate (m^3/d)
A = area of clarifier (m^2)

Applying Eqn. 6.1 for five Darvill SSTs and the above-mentioned design criteria:

if G_{ap} = 7.5 x 24 = 180 kg/(m^2·d), X_o = 3.8 kg/m^3 , Q_i = 162 000 m^3/d, A = 4810 m^2 ,

then Q_r = 65 842 m^3/d.

Hence, the design calls for ca. 13.2 Mℓ/d recycle from each of the five SSTs under peak wet weather conditions. Under these conditions, the recycle ratio (s) would be 0.41, the overflow rate (Q_i / A) would be 33.7 m/d and the underflow solids concentration (X_r) would theoretically be 13.1 kg/m^3. In practice, successful solids separation under these conditions would be largely dependent on the actual settling and thickening characteristics of the sludge. These characteristics are not adequately described by the DSVI alone, but can be more fully described by the flux theory constants V_0 and n (refer to WRC, 1984).

Operating experience at Darvill WWW (Figure 6.17) has shown that the reactor MLSS can increase during winter (when little or no stormwater intrusion occurs and the diversion facility to the storm

[8] On 19/12/94 (during hand-over at the end of the upgrade contract), a stress test was conducted on the two new SSTs. The average DSVI on the day of the test was 74 mℓ/g (three observations). The average MLSS was 5579 mg/ℓ (three observations on the day of the test and three observations on the previous day). A constant actual influent flow rate of 89.2 (± 1) Mℓ/d was achieved over a five hour period during which the test was conducted. The flow was split equally between five SSTs, including the two SSTs being tested. The recycles from each of the two SSTs being tested was set at a constant 18 Mℓ/d, while the combined recycle from the other three (old) SSTs remained close to 40 Mℓ/d. (The total volume of one new SST was estimated to be ca. 4.3 Mℓ, implying that at least 4 x nominal HRT would be spanned by the five hour test period). The average effluent suspended solids concentration over the five hour period was 3 mg/ℓ (1ℓ samples filtered) for both SSTs (S.D. < 1 mg/ℓ). The applied flux was calculated to be 7.98 kg/(m^2.h), which exceeded the design criterion of 7.5 kg/(m^2.h) by a small margin. The recycle ratio was close to 1:1, which was considered acceptable for the operating conditions tested (ca. 1.5 x ADWF). The performance of the SSTs was therefore considered to be satisfactory.

dam is not used, leaving all influent sewage to be treated in the activated sludge plant). For example, in August 1996, the reactor MLSS averaged ca. 5300 mg/ℓ, in spite of the sludge age being kept to ca. 8 days. Additional reactor solids places a severe operating constraint on the secondary clarifiers. From Eqn. 6.1 it can be shown that for an MLSS of 5000 mg/ℓ, and the same Q_r calculated from the design (65 842 m^3/d), influent flow (Q_i) would need to be restricted to 107 Mℓ/d, if the design criterion of max. 7.5 kg SS/(m^2.h) is not to be exceeded. Under these conditions, the underflow solids concentration (X_r) would theoretically be 17.2 kg/m^3. Operating experience has shown that such high underflow solids concentrations are difficult to achieve (because they are primarily dependent on the inherent thickening characteristics of the sludge). As a result, the Works Operators frequently were faced with a dilemma over what maximum pumping rate (and recycle rates) to choose for the Works.

In view of the above, it was considered to essential to evaluate the settling characteristics of the Darvill activated sludge in the context of the ferrous-ferric plant trial. Some data from the literature (e.g. D'Elia, M and Isolati, 1992) indicated that an improvement in settling may be expected with the dosing of iron salts. Moreover, the need was identified to evaluate the sludge settling characteristics in terms of DSVI (which is a easily measured and suitable for routine use by Operating staff) as well as flux theory (which has been well researched and from which operating charts can be drawn up for use by Operating staff).

In order to measure and test the settling characteristics of the Darvill activated sludge, flux constants were measured and a series of stress tests conducted before, during and after the ferrous-ferric plant trial. The results of these tests are described in this section.

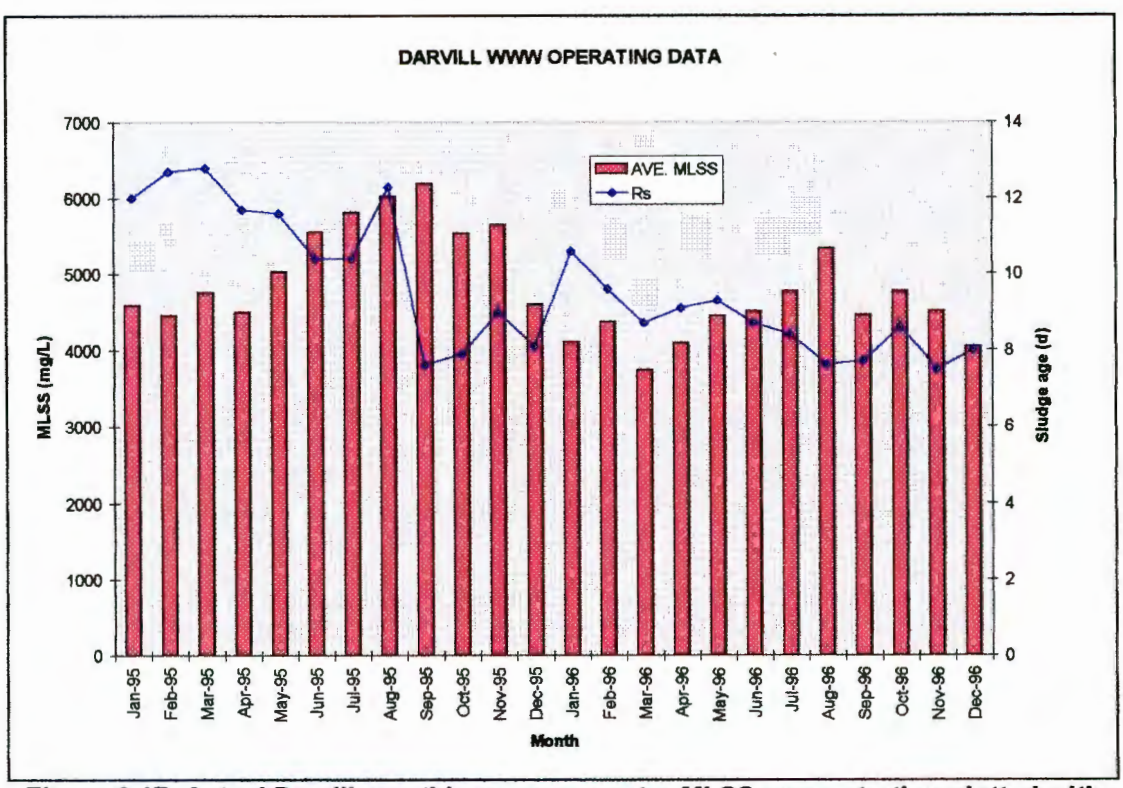


Figure 6.17: Actual Darvill monthly average reactor MLSS concentration plotted with calculated sludge age (taking effluent suspended solids into account).

6.5.1 First stress test: End of alum dosing

Alum dosing to the Darvill activated sludge reactors was formally stopped on 14 August 1996 in preparation for the plant trial using ferrous-ferric chloride blend. Informally, alum dosing continued until 16 August as the alum tanks were cleaned out. In order to assess the activated sludge settleability ahead of the plant trial, settling tests using Mallory settlometers (2 ℓ) were conducted to determine the flux theory constants V_0 and n, as described by WRC (1984). To assess secondary settling tank (SST) performance, flux theory constants (V_0 and n) were measured on 12 August (as described by WRC, 1984) and the first stress test was carried out on 15 August.

The stress test was conducted by taking one SST off line, leaving two flat-bottomed 2.5 m deep suction-lift tanks (nos. A and E, see Fig. 6.2) and two scraped, centre draw-off 4 m side wall depth tanks (nos. B and C) on line. As noted in the overall plant description above, all the SSTs have an internal tank diameter of 35 m. Recycles on Tanks A and E must be controlled manually by setting the valves on each of six vertical sludge draw-off pipes per tank. Normally the flows are visually "tapered" such that the draw-off pipe closest to the central stilling well is closed, while that nearest the perimeter of the tank is fully open. Recycles on Tanks B and C are controlled by a programmable logic controller (PLC) operating one variable speed pump dedicated to each of the sludge recycle lines. Finally, since the settled sewage inflow to the activated sludge plant at Darvill is pumped from a balancing tank via two variable speed pumps and either one or two optional fixed speed pumps (all pumps have a capacity of ca. 45 to 55 Mℓ/d, depending on operating conditions), the overflow rate of the SSTs could be automatically controlled via a manual setpoint to PLC.

Samples of mixed liquor feeding the settling tanks were taken at a point common to all the tanks, namely the mixed liquor splitter box. Samples of the return activated sludge (RAS) were taken at available points immediately downstream of the recycle pumps, namely: one point common to Tanks A and E; and one point common to Tanks B and C. Unfortunately, no readily accessible sample point existed on the individual RAS lines of Tanks B and C, which led to the decision to compare the "old" (A and E) versus "new" (B and C) tanks in the manner described. Sludge blanket levels were detected by means of an electronic infra-red detector (manufactured by the Instruments Dept., Inland Regional Workshop, Umgeni Water). The instrument had been roughly calibrated to set off an audio signal when immersed into a mixed liquor solids concentration of >1000 mg/ℓ. The average of at least three readings across the radius of the each clarifier was recorded at the designated times (allowing approx. 15 min. for completing the procedure of taking the readings on the four operational tanks).

Flux theory constants V_0 and n were measured on 30 July 1996 and 12 August 1996 (and had previously been measured on 23 December 1994 and 19 May 1993). The results are given in Table 6.4.

Table 6.4: Flux theory constants determined by settling tests using the method described by WRC (1984) for Darvill full-scale activated sludge plant. Data collected on 12 August 1996 was applied to first stress test (15/8/96).

DATE	MLSS range tested (kg/ m^3)	Correlation coefficient (r^2) of semi-log plot ln V_s vs. MLSS	Result V_0 m/d	Result n m^3/kg	DSVI (Ave. of five daily results preceding)
19 May 1993	1.256 to 7.458	0.981	366	0.452	53
23 December 1994	0.715 to 11.109	0.943	195	0.439	70
30 July 1996	1.594 to 10.982	0.975	232	0.406	71
12 August 1996	1.474 to 10.828	0.988	185	0.393	78

Table 6.4 shows that considerable variability in the V_0 and n data has been observed. The significantly higher V_0 (and to some degree n) value recorded in May 1993 may have been due to the higher alum dose in use at that time (Fig. 6.4). However, no simple relationship between flux theory parameters (V_0 and n) and the typical DSVI values recorded for the plant at the time was apparent from Table 6.4. For the purpose of the stress test on the secondary clarifiers conducted on 15 August 1996, the settling data of 12 August 1996 (Table 6.4) was used to construct operating charts, based on the flux theory (WRC, 1984) and modified flux theory (Ekama and Marais, 1986).

On the day prior to the clarifier stress test, the average MLSS in the three activated sludge basins at Darvill was 5.306 kg/m^3 and that in the RAS (Tanks A, D and E) was 10.596 kg/m^3 to 11.366 kg/m^3 (Tanks B and C). Accordingly, an operating chart was initially constructed for MLSS values in the range 4.9 to 5.3 kg/m^3 and the overflow and underflow rates set such that the SSTs would be close to overload conditions at the lower MLSS concentration of 4.9 kg/m^3 for the modified flux theory [9]. Following completion of the test on 15 August, it transpired that the MLSS recorded on that day ranged 4.3 to 4.9 kg/m^3. This meant that the actual solids loading rate on the SSTs was lower than the target solids loading based on the higher MLSS assumed. Figure 6.18a shows that on the operating chart constructed from modified flux theory (Ekama and Marais, 1986)[10], the operating points selected lie close to the line for approx. 5.0 kg/m^3 MLSS (X_o).

Figure 6.19 shows the actual MLSS and underflow suspended solids concentrations recorded during the stress test. The average MLSS in the period 11h30 to 17h00 was 4.5 kg/m^3 (min. 4.3; max. 4.6 kg/m^3), implying that the operating points recorded were within the "safe" envelope beneath the curve for an MLSS up to 4.9 kg/m^3. At 18h45, the operating point moved lower and was therefore still within the safe operating range for an MLSS of 4.9 kg/m^3 which materialised at that time.

Figure 6.20 records the actual flow rates and recycle rates recorded during the test. Three main time domains were identified:

- From the start of the test (shortly after 10h00) up to 11h00, the overflow rate was increased from 15.6 to 20.8 m/d (60 to 80 Mℓ/d) in two steps (slight over-pumping occurred at ca. 11h00, due to the PLC selecting a fixed speed pump at that point and then gradually correcting by slowing the variable speed pumps);
- From 11h20 to 15h00, when the overflow rate was held constant at 20.8 m/d (80 Mℓ/d);
- From 15h10 to 18h15, when the overflow rate was held constant at 19.5 m/d (75 Mℓ/d).

Over the last half hour of the test (18h15 to 18h45), the overflow rate began to decline due to the balancing tank reaching a low level (<20%), at which point the PLC began to over-ride the manual flow set-point to protect the pumps from eventually running dry.

Figure 6.20 also shows the recycle flow patterns. The target recycle rates for all four of the SSTs was 16 Mℓ/d (giving a target recycle ratio of 0.8 on 80 Mℓ/d overflow rate and 0.85 on 75 Mℓ/d overflow rate). With the variable speed pumps on SSTs B and C, the target recycle rate was readily achieved (Fig. 6.20), whereas with the manual valve adjustments on the bridges of SSTs A and E, control was more difficult. Nevertheless, it was possible to maintain a recycle ratio in the range 0.8 to 0.9 for most of the duration of the test, except in the final half hour when the ratio increased to between 0.9 and 1.0, due to the drop in overflow rate (see above).

Figure 6.21 shows the sludge blanket levels of the SSTs during the test. From Fig. 6.20 it can be seen that SST A and SST E had the higher blanket levels throughout the test, which would be expected considering the 2.5m side wall depth. SST C commenced with a higher sludge blanket than SST B and it remained so throughout the test. One possible reason for this was the tendency of an

---

[9] In the modified flux theory, the applied flux of the overflow and underflow rates are both reduced by 25% (or 1/0.80), compared with the flux theory (Ekama and Marais, 1986).

[10] Conventional flux theory (WRC, 1984) states that the limiting clarifier overflow rate (Q_i/A) to meet both the thickening and clarification criteria is the lesser of :

$Q_i/A = V_0 (1+\alpha)/\{s.(1-\alpha)\} \exp [-n.(1+s).X_0.(1+\alpha)/\{2s\}]$ where $\alpha = \sqrt{[1 - 4s/\{n.(1+s).X_0\}]}$ and

$Q_i/A = V_0 \exp (-n.X_0)$

(Equations 8.27 and 8.29 of WRC, 1984).

The modified flux theory sets the permissible applied solids loading rate at that calculated by reducing the overflow and underflow rates by 25% (or 1/0.80) for operation, or increasing the surface area by 25% for design, while leaving the recycle ratio and feed concentration unchanged (Ekama and Marais, 1986; Ekama *et al.*, 1996).

open scum release hole in the mixed liquor splitter box to set up a velocity gradient such that the flow to SST C was favoured slightly over that to SST B. Photographic evidence of this problem is shown in Appendix 7. This was corrected at ca. 12h45 by shutting the remaining scum hole which had been open up to this time[11]. Considering the depth of SSTs B and C (SWD 4 m), the occurrence of relatively high blankets in these clarifiers may have produced some storage of solids, thereby explaining the lower-than-expected MLSS on 15/8/96 compared to the previous day's results (see above). At the reported average MLSS for the previous day (5.3 kg/m^3), Fig 6.18a shows that the clarifiers would have been operating in a safe condition with 11 Mℓ/d recycle per SST for an expected balanced overflow rate of (12.5 m/d or 12 Mℓ/d per SST; total 60 Mℓ/d for 5 SSTs), giving a recycle ratio of 0.92. Fig. 6.18a shows that this recycle would have been "safe" up to an overflow rate of 15.0 m/d (14.4 Mℓ/d per SST; 72 Mℓ/d for five SSTs; recycle ratio 0.76) at an MLSS of 5.3 kg/m^3 . Operating data for the previous day showed the overflow and recycle rates were well within these limits. Hence, the fact that some solids were apparently being "stored" in SSTs B&C was probably related to the splitter box bias favouring flow to these clarifiers, and SST C in particular [12].

For operational purposes, a sludge blanket depth of 1 m below top water level (TWL) was regarded as the minimum tolerable. Noting that SST E had shown an increase in blanket level from the start of the test, when the SST A blanket rose from 1.05 m to 0.75 m at ca. 15h00, the decision was taken to slightly reduce the overflow rate from 20.8 m/d (80 Mℓ/d) to 19.5 m/d (75 Mℓ/d) (Figs. 6.20 and 6.21). This appeared to result in a drop in the blanket level in SST A (stabilised at 1.2 m) and a stabilisation of the blanket level in SST E (at 0.75 m).

Taken as a whole, the blanket level data in Fig. 6.21 suggests that in the period from ca. 11h00 to 15h00, the SSTs were operating fairly close to their critical condition, with an increase in sludge blanket level registered for all the tanks during that period. In reality it would not be practical to operate the clarifiers much closer to this critical condition since the risk and consequences of failure would be serious in terms of final effluent compliance with the discharge standard.

The results in Fig. 6.21 are in broad agreement with the *modified* flux theory operating chart drawn up for the day of the test (Fig. 6.18a), which suggests that for MLSS at or near 5000 mg/ℓ, the Darvill clarifiers would have operated at or close to their critical loading condition. The fact that the blankets did not rise still further was probably due to the lower-than-expected actual MLSS on the day of the test. The results are *not* in broad agreement with the standard flux theory operating chart (Fig. 6.18b) which suggests that during the stress test the clarifiers were all operating even further into the "safe condition" envelope of the chart, even at 5300 mg/ℓ MLSS.

Figure 6.22 shows the secondary effluent suspended solids concentration measured by taking random samples at the V-notch overflow weirs of each of the four operational SSTs during the stress test. Considerable difficulty was experienced with obtaining suitable random samples since the activated sludge plant had developed a moderately severe biological (*Nocardia*) foam problem in the preceding month, which resulted in increased solids loss via the effluent due to foam carryover. Since random collection of foam carryover would not have been representative of the settling behaviour in the tanks, an effort was made to avoid the plume of scum carried in a given direction by the prevailing wind. Four random samples (500 mℓ) were collected from at different points on each clarifier in this manner to make a composite sample (2ℓ) for effluent suspended solids analysis. Potential bias in this sampling method weaken the validity of data in Fig. 6.22 to some extent. Nevertheless, the overall conclusion may be drawn that SSTs A and E performed significantly better in terms of effluent suspended solids, which was surprising considering that SSTs B and C are deeper. The difference may lie in the benefits of suction lift sludge collection across the floor of the "old" tanks (A and E), as well as the size of the stilling/ flocculating well (Wahlberg *et al.*, 1995). In

[11] Refer to Appendix 7. The scum holes on this splitter box are 500 mm square (three of) and may have been unnecessarily large in the design, allowing too much flow through, which causes turbulence in the splitter region, thereby resulting in unequal splits. All the scum holes were closed for the remainder of the test. This practice was not encouraged on a permanent basis since it can lead to a worsening of *Nocardia* foam problems by trapping scum in the activated sludge reactor.

[12] It is worth noting that the original design made provision for a deliberately unequal split of flow to the five SSTs. The new SSTs (B & C) were considered capable of taking a higher solids loading rate and were allocated a weir length of 4.40 m each (or 23.5% each), compared to the old SSTs (A, D and E) which were allocated a weir length of 3.30 m each (or 17.7% each). However, this led to severe operating problems, with frequent solids carryover from SSTs B & C. Eight months after commissioning, the weir plates were modified to equalise the flow split (20% each). This overcame the problem.

respect of the latter, all three "old" SSTs (A, D, and E) were retrofitted with a circular baffle at a radius of 3.0 m which served to increase the size of the stilling/ flocculating well and produced an improvement in performance which was immediately apparent to operating staff[13]. The new SSTs (B and C) were designed with a fairly large stilling well (at radius 3.5 m) but the details of the outlet ports from this well differ from the baffle design for SSTs A, D and E. Detailed discussion of the merits of the two designs falls outside the scope of this study. However, it should be noted that unequal flow division due to splitter box scum hole design problem (see above) probably contributed to the relatively poor performance of SST C in terms of effluent suspended solids (Fig. 6.22).

In summary, the stress test and modified flux theory appeared to indicate that the safe operating limit of the Darvill secondary sedimentation tanks in August 1996 at the end of a period of sustained simultaneous alum dosing (ca. 30 mg/ℓ as dry alum) was approx. 20 m/d (overflow rate) at a recycle ratio of approx. 0.85 and an operating MLSS of 5000 mg/ℓ. A lower MLSS would allow a higher overflow rate (Table 6.5).

The results in Table 6.5 agree with the general observation by operating staff at the Works during the summer season of 1995/6 that the maximum overflow rate which could be achieved with all five clarifiers operating and recycle rates close to maximum pumping capacity, was of the order of 20.8 to 24.9 m/d (100 to 120 Mℓ/d), depending on sludge settleability and reactor MLSS. Attempts to pump 130 Mℓ/d on a sustained basis sometimes resulted in blanket carryover.

Table 6.5: Summary results from modified flux theory operating chart and first SST stress test of 15 August 1996 (end of alum dosing) at Darvill WWW.

MLSS	Max. Q_t/A (m/d)	Max. Q_t (Mℓ/d) per SST	Max. Q_t (Mℓ/d) for five SSTs	Required minimum recycle ratio	Required min. recycle ratio for SST B and C [Max. recycle capacity] (Mℓ/d, two SSTs)	Required min. recycle ratio for SST A, D and E [Max. recycle capacity] (Mℓ/d, three SSTs)
5000	21	20	100	0.9	36 [38]	54 [ca. 43]*
4500	25.5	24.5	123	0.75	37 [38]	55 [ca. 43]*
4300	27.5	26.5	132	0.7	37 [38]	56 [ca. 43]*
3800	33.5	32	160	0.6	38 [38]	58 [ca. 43]*

* : Recycle pumping capacity limitation noted

Figures 6.18a & b ...../

[13] Peripheral (Stanford) baffles were also retrofitted to the old SSTs. These consist of horizontal plates which protrude 1.2m from the side wall along the entire inner perimeter if the tank. The new SSTs were equipped with a similar baffles at the design stage. In the case of the new SSTs, the Stanford baffles protrude 1.7m from the side wall.

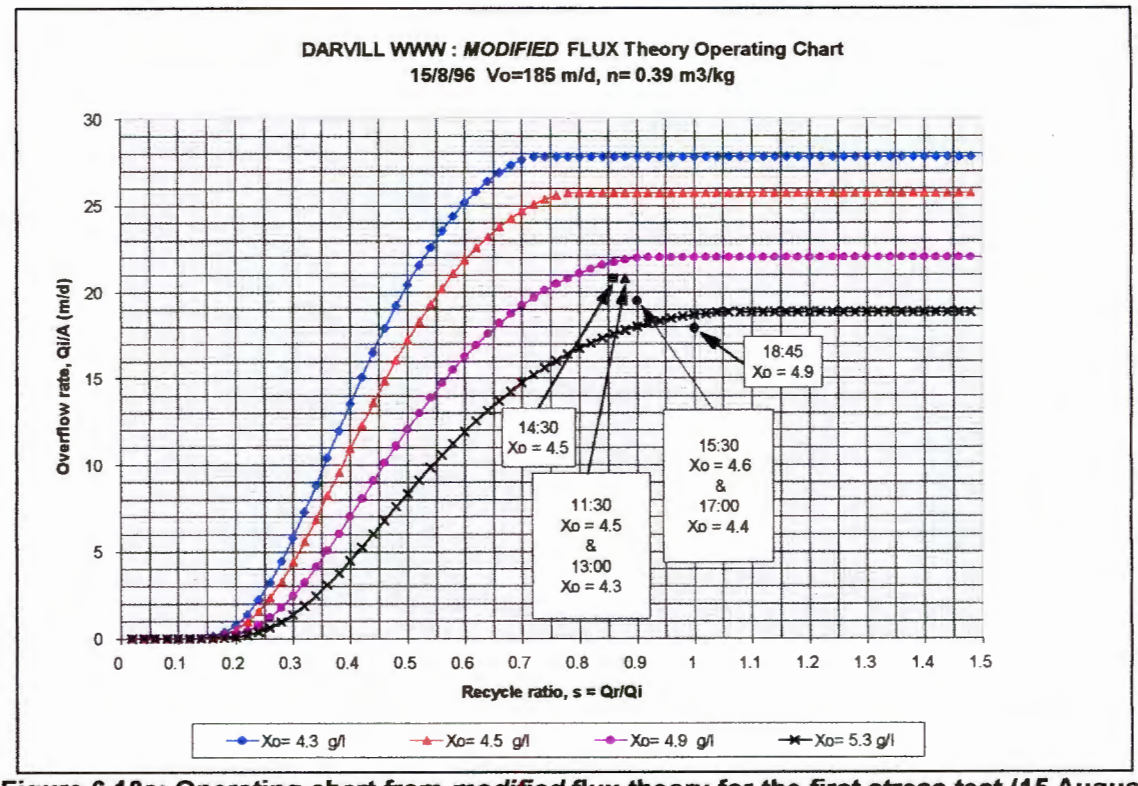


Figure 6.18a: Operating chart from *modified* flux theory for the first stress test (15 August 1996). Refer to Figure 6.19 for actual X_o (MLSS) values recorded during the test.

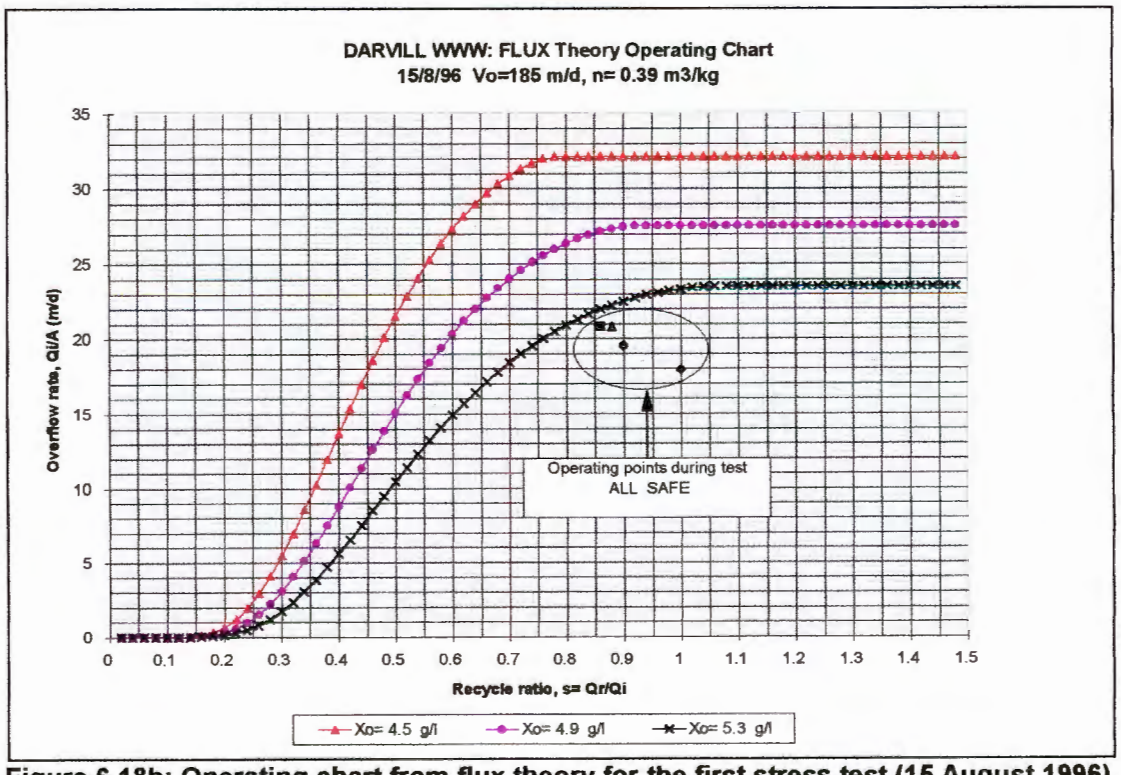


Figure 6.18b: Operating chart from flux theory for the first stress test (15 August 1996). Refer to Figure 6.19 for actual X_o (MLSS) values recorded during the test.

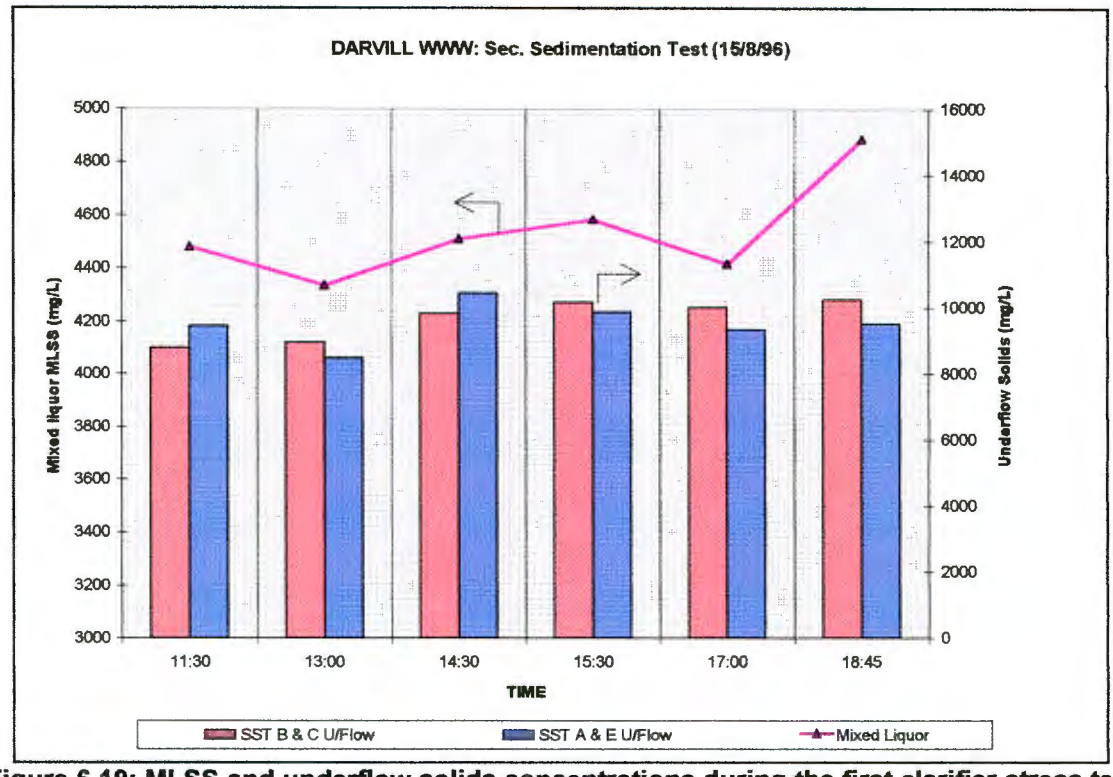


Figure 6.19: MLSS and underflow solids concentrations during the first clarifier stress test (15 August 1996).

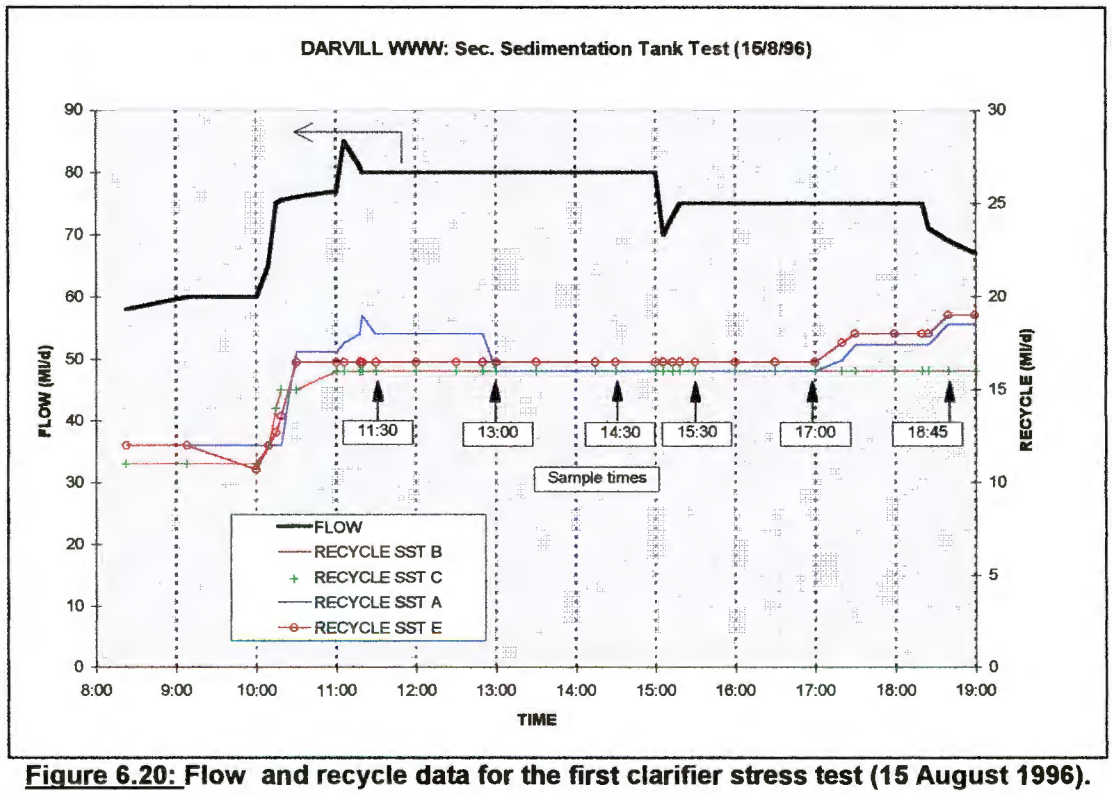


Figure 6.20: Flow and recycle data for the first clarifier stress test (15 August 1996).

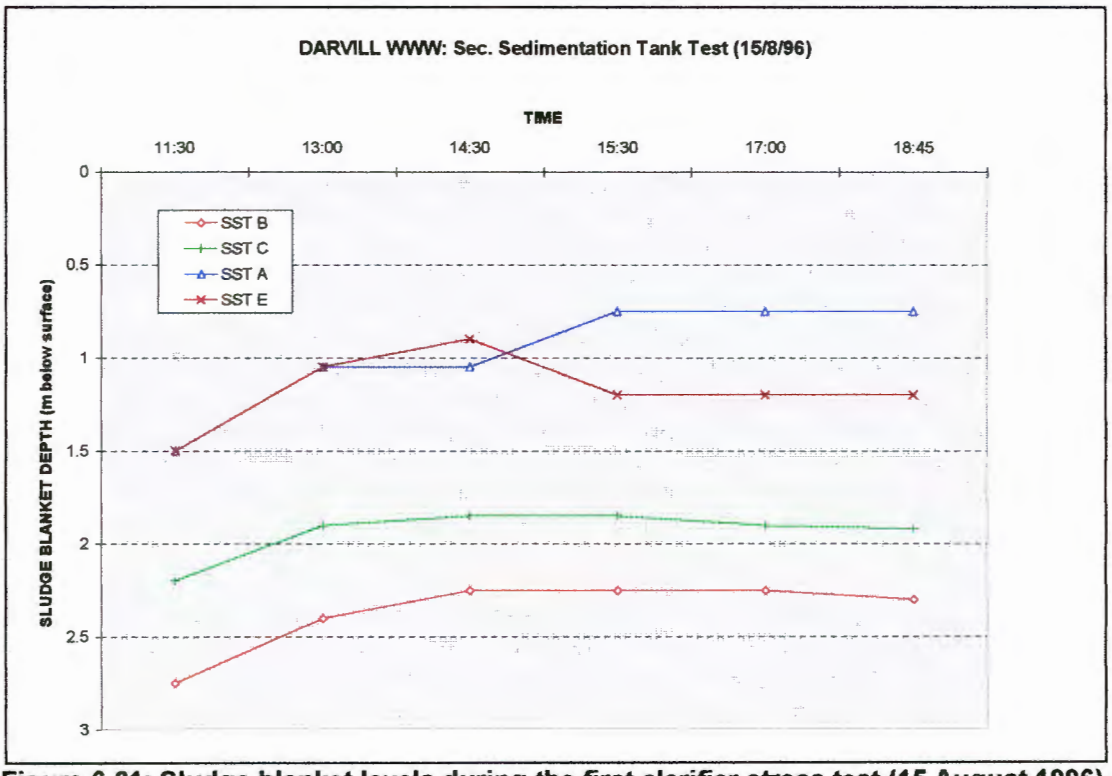


Figure 6.21: Sludge blanket levels during the first clarifier stress test (15 August 1996).

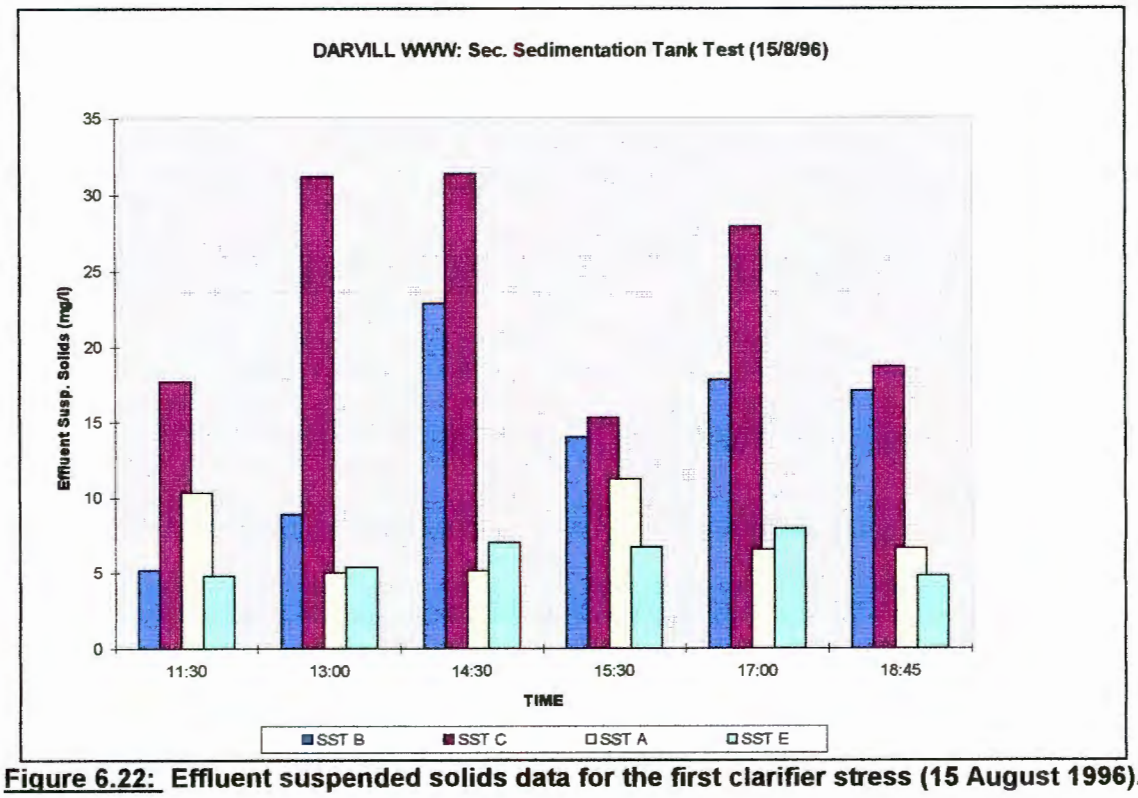


Figure 6.22: Effluent suspended solids data for the first clarifier stress (15 August 1996).

6.5.2 Second stress test: During ferrous-ferric chloride dosing trial

Ferrous-ferric chloride dosing was commenced on 20 August 1996. At this time, the Darvill activated sludge plant experienced a fairly severe *Nocardia* scum/ foam problem. The problem appeared to stem from frequent discharges to sewer of trade effluent containing a concentration of emulsified oil and grease (see 6.4.2/3 above) The foam tended to carry through to the secondary clarifiers (SSTs), from where it escaped into the secondary effluent, carrying high concentrations of suspended solids[14] into the final effluent. In an effort to alleviate the problem, two steps were taken by the operating staff: a floating boom was installed in the anaerobic basin with a skimming device through which foam could be removed via a trash pump; and the "scum holes" on the mixed liquor splitter box which allow scum to pass out of the activated sludge plant to the SSTs, were temporarily closed off. Whilst these measures did allow a large quantity of scum/ foam to be manually removed, the *rate* of removal appeared to be too slow to keep up with biological growth of the nuisance organism. This problem was discussed under 6.4.3 above. The *Nocardia* problem seemed to contribute to a deterioration in sludge settleability in the time intervening between the first SST stress test (see 6.5.1) and the second test described in this section. The scum holes on the splitter box were later re-opened and the floating boom removed from the anaerobic basin to allow foam/ scum to leave the plant via the SSTs.

In order to quantify the combined effect of the apparent *Nocardia* problem and the ferrous-ferric chloride dosing, activated sludge settleability was measured in a series of settling tests on 26 September 1996 using Mallory settlometers (2 ℓ) to determine the flux theory constants V_0 and n (WRC, 1984). To assess secondary sedimentation tank (SST) performance, a stress test was carried out on 2 October 1996.

The results for determination of the flux theory constants on 26 September are given in Table 6.6. From a comparison with the results for 12 August (Table 6.4), it is clear that the poorer settleability was manifest by an increase in n (and DSVI) but little change in V_0.

Table 6.6: Flux theory constants determined by settling tests using the method described by WRC (1984) for Darvill full-scale activated sludge plant. Data applicable to second stress test (2/10/96).

DATE	MLSS range tested (kg/ m^3)	Correlation coefficient (r^2) of semi-log plot ln V_s vs. MLSS	Result V_0 m/d	Result n m^3/kg	DSVI (Ave. of five daily results preceding)
26 September 1996	1.52 to 10.25	0.993	188	0.513	104

From flux and modified flux theory, operating charts (Figures 6.23a & 6.23b) were constructed in the MLSS range 4.2 to 4.9 kg/m^3 which had been recorded for the activated sludge plant in the week preceding the stress test. The initial target operating point selected was an overflow rate of 15.6 m/d (15 Mℓ/d per SST, total 60 Mℓ/d for four SSTs) with a recycle ratio as close as possible to 1.0. From modified flux theory (Fig. 6.23a) this would set up a critically loaded condition at an MLSS of ca. 4.3 kg/m^3, and from standard flux theory it would set up a critically loaded condition at an MLSS of 4.9 kg/m^3.

The stress test was commenced by taking SST B off line, thus leaving four SSTs in operation: two of the new type (B & C) and two of the retrofitted old type (A & E) (refer to 6.5.1). The problematic scum holes on the mixed liquor splitter box (see above) were closed for the duration of this test.

[14] The suspended solids may be pathogen-bearing. Routine monitoring data for the Darvill WWW final effluent suggests a higher incidence of *E. coli* indicator organisms and indicator organisms , Cryptosporidium and Giardia cysts at times of high effluent suspended solids concentrations (*Umgeni Water*, Pietermaritzburg, unpublished data).

Figure 6.24 shows the flow data for the second stress test. Commencing shortly after 09h00, the overflow rate was increased from 11.4 to 14.3 m/d (44 to 55 Mℓ/d for the 4 SSTs) by 10h00 and remained at 14.3 (55 Mℓ/d) until shortly after 11h00 when one of the variable speed pumps pumping settled sewage to the plant tripped and had to be de-selected in favour of a fixed speed pump, followed by correction of the operable VSD by the PLC. At 11h30, the overflow rate setpoint was increased to 15.6 m/d (60 Mℓ/d for 4 SSTs) and flows remained constant until 15h50 when it was further increased to 17.2 m/d (66 Mℓ/d for 4 SSTs). Again, flows remained constant until ca. 21h15 when the test was stopped.

Recycles were set shortly after 09h00 to a constant target of 15 Mℓ/d per SST. This target was easily achieved for SSTs B & C and (variable speed pumps controlled by PLC) and was achieved on average to within 0.5 Mℓ/d for SSTs A & E until ca. 16h00 (Fig. 6.24). At that time it was found that the blanket in SST A had risen to 1.0 m below top water level (the maximum level judged to be "safe"). Accordingly, the recycles on SSTs A and E were increased at ca. 16h00 to 16.7 and 16.2 Mℓ/d respectively for the remainder of the test.

Figure 6.25 shows that the actual MLSS concentrations recorded during the test were in the range 4.9 to 4.2 kg/m^3 , with a fairly steady decrease in this range over the first seven hours of the test, followed by a stabilisation in the range 4.2 to 4.3 kg/m^3 . Figure 6.25 also shows that the underflow solids concentrations remained fairly constant in the range 9.0 (± 1) kg/m^3. Taken collectively, the feed and underflow solids data suggest that a degree of solids storage was established in the SSTs over the first seven hours of the test.

When the actual operating points are plotted on the operating chart developed from *modified* flux theory (Fig. 6.23a), it may be concluded that at all times during the test, the SSTs were operating in an over-loaded condition, with minor variations in the *degree* of over-loading, as judged by the distance of the operating point plotted from the relevant curve. By contrast, when plotted on the chart for standard flux theory (Fig. 6.23b), all the operating points were within the "safe" envelope below the relevant curves. The only possible exception was the point for 09h30 which plotted on the 4.9 kg/m^3 curve. However, the actual MLSS (X_o) was in a decreasing phase at 09h00 (Fig. 6.25), which implies that a curve between those for 4.9 and 4.6 kg/m^3 should be related to this point.

The data for sludge blanket levels solids are presented in Figure 6.26. These data indicate that the clarifiers were operating close to the critical condition, but not in a failure (or over-loaded) condition. The sludge blankets showed a significant detectable increase in three of the four SSTs (A, B & C), and a detectable (though small) increase in the fourth (SST E). In the case of SST A, the blanket rose to just less than one metre from top water level. As in the first stress test (15 August), SST E performed better than SST A in terms of blanket level, despite the same design and a very similar recycle rate, which suggests that the feed flow split may not be equal or some other factor may be important (e.g. length of feed pipe from mixed liquor splitter box). SSTs B & C behaved in a similar manner in terms of sludge blanket level.

Effluent suspended solids (Figure 6.27) were significantly lower throughout this test, compared to the first test (c.f. Fig. 6.20). The first test gave effluent suspended solids in the range 5 to 12 mg/ℓ for SSTs A & E, and 5 to 30 mg/ℓ for SSTs B & C; this test gave results consistently below 10 mg/ℓ for all the SSTs, and mostly below 6 mg/ℓ. The average results were : 2.5; 3.7; 3.9; and 2.6 mg/ℓ for SSTs B, C, A and E respectively. However, for three effluent samples from SST E, in which the suspended solids result was zero (one litre filtered through Whatman GF/C), a result of 0.5 mg/ℓ was recorded for graphical purposes in Fig. 6.27.

It is not clear to what extent the lower effluent suspended solids results can be ascribed to the flocculating properties of ferrous-ferric dosed as phosphate precipitant. The pilot plant studies (Chapter 5) had indicated that an improvement in DSVI should be expected with the use of ferrous-ferric blend, compared to no precipitant/ flocculant addition. This improvement appeared to be correlated partly with the mass of phosphate stored in the mixed liquor (Chapter 5, section 5.3.9). By contrast, the full-scale plant DSVI had in fact *deteriorated* in the time intervening between the first and second SST stress tests, and it follows that the improvement in effluent suspended solids concentrations was probably at least partly related to the increase in DSVI. Ironically, extremely clear

effluents with a low suspended solids content are a feature of bulking (poor settling) sludges with a high DSVI (Jenkins *et al.*, 1984), provided the clarifiers are not over-loaded.

Summarising, it can be concluded that the increase in DSVI from ca. 75 to 104 mℓ/g (or combined effect of a decrease in V_0 and increase in n) resulted in a significant decrease in the performance of the Darvill SSTs. From the performance of the SSTs in the second stress test and Fig. 6.23a, it may be concluded that a "safe" operating overflow rate at DSVI 104 mℓ/d would be ca. 15 m/d at a recycle ratio of ca. 1.1 and an MLSS of 4.5 g/ℓ. For the five SSTs, this converts to a maximum Q_i of 72 Mℓ/d with recycles of 16 Mℓ/d for each of the five SSTs. Comparing these results to those in Table 6.5 for the first stress test (at DSVI ca. 75 mℓ/g, is can be seen that this represents a 40% reduction in maximum Q_i; in fact, a max. Q_i of 72 Mℓ/d is less than 1.5 times average dry weather flow for this works[15] (see Fig. 6.1b). It follows that the Darvill activated sludge plant needs to be operated to a target DSVI of <75 mℓ/g and MLSS of <4 g/ℓ in order to realise the wet weather design capacity of 160 Mℓ/d for the five SSTs available.

Figures 6.23a & b ...../

[15] Since the maximum possible recycle achievable for the old SSTs (A, D & E) is ca. 14.4 Mℓ/d (due to pump constraints), in practice, the max. Q_i achievable at a DSVI of 104 mℓ/g and MLSS of 4.5 g/ℓ may be lower still (ca. 70 Mℓ/d).

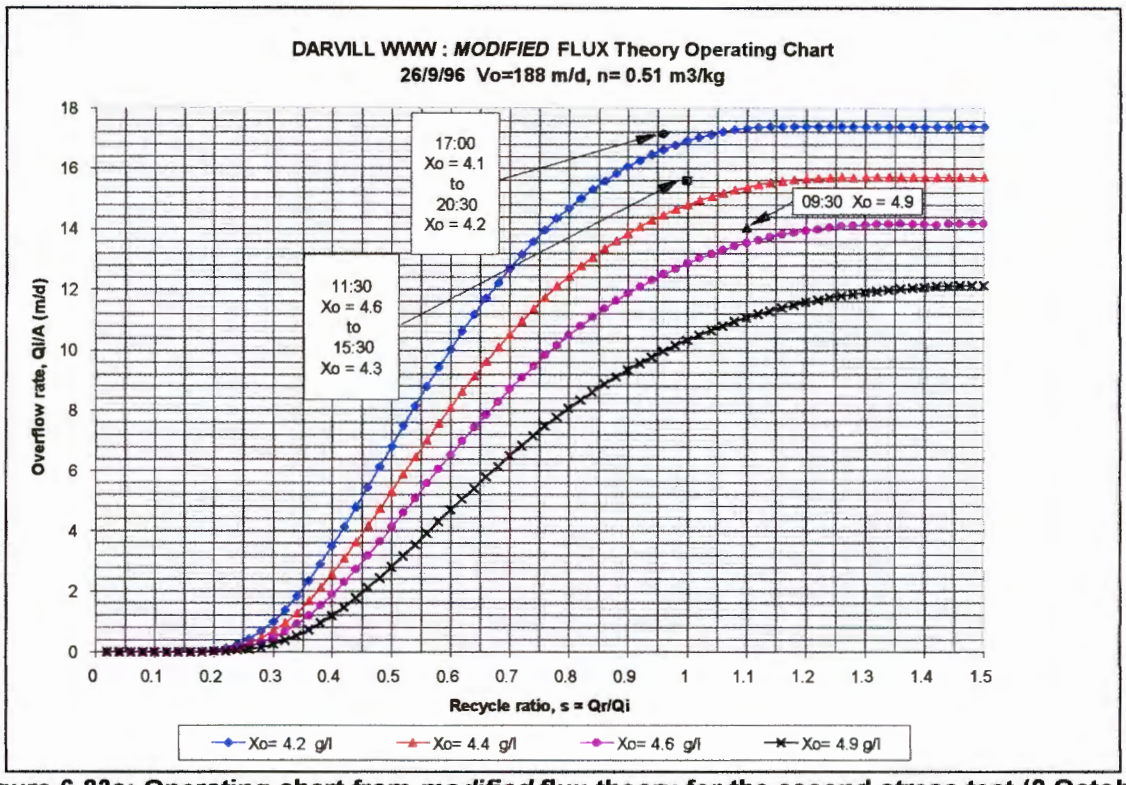


Figure 6.23a: Operating chart from *modified* flux theory for the second stress test (2 October 1996). Refer to Figure 6.26 for actual X_o (MLSS) values recorded during the test.

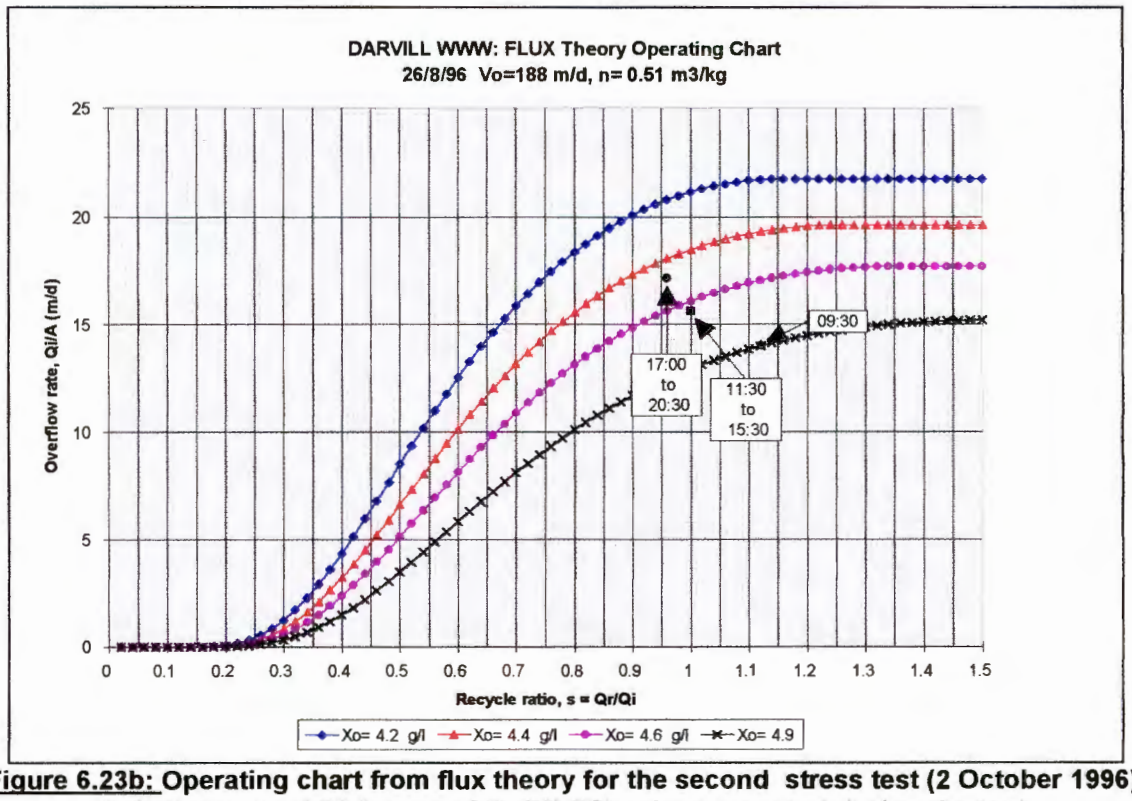


Figure 6.23b: Operating chart from flux theory for the second stress test (2 October 1996). Refer to Figure 6.26 for actual X_o (MLSS) values recorded during the test.

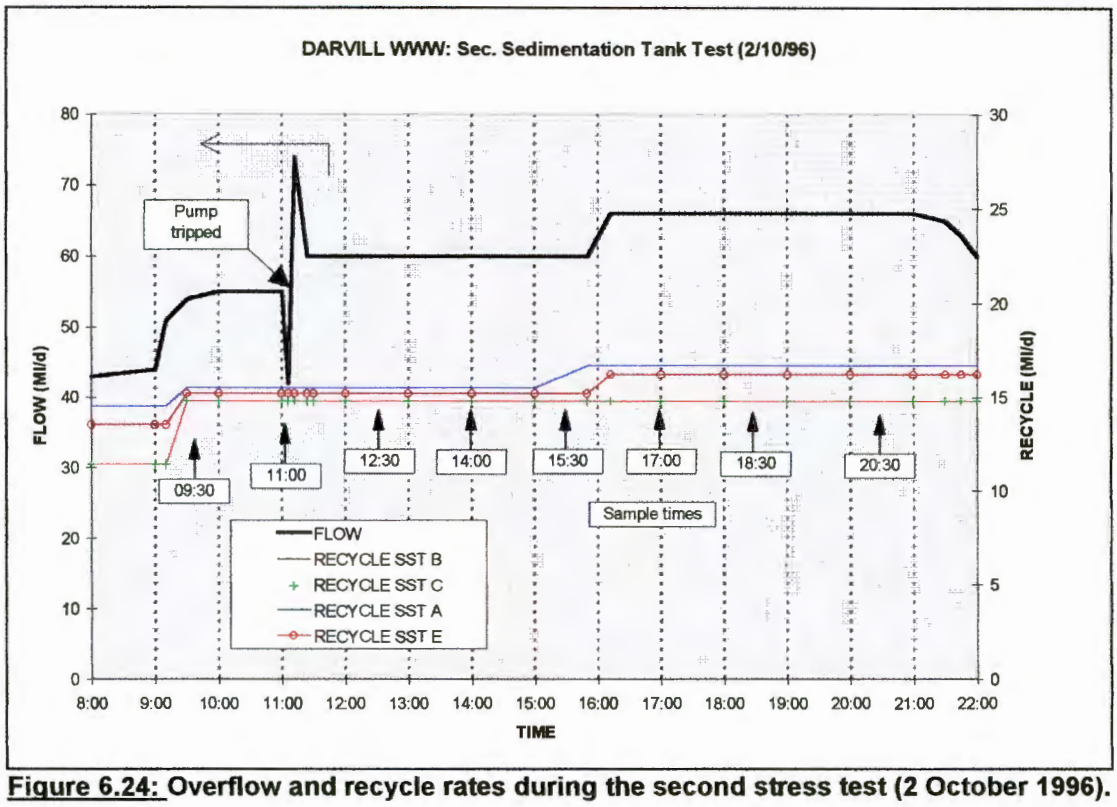


Figure 6.24: Overflow and recycle rates during the second stress test (2 October 1996).

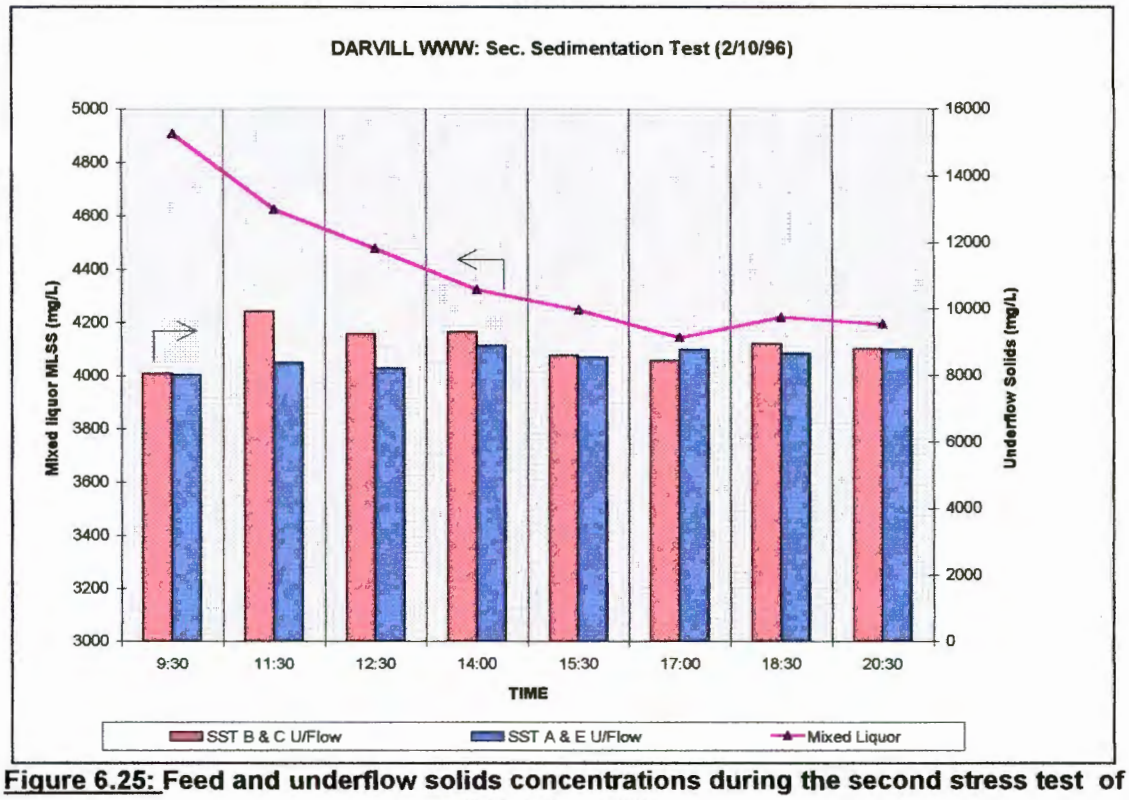


Figure 6.25: Feed and underflow solids concentrations during the second stress test of 2 October 1996.

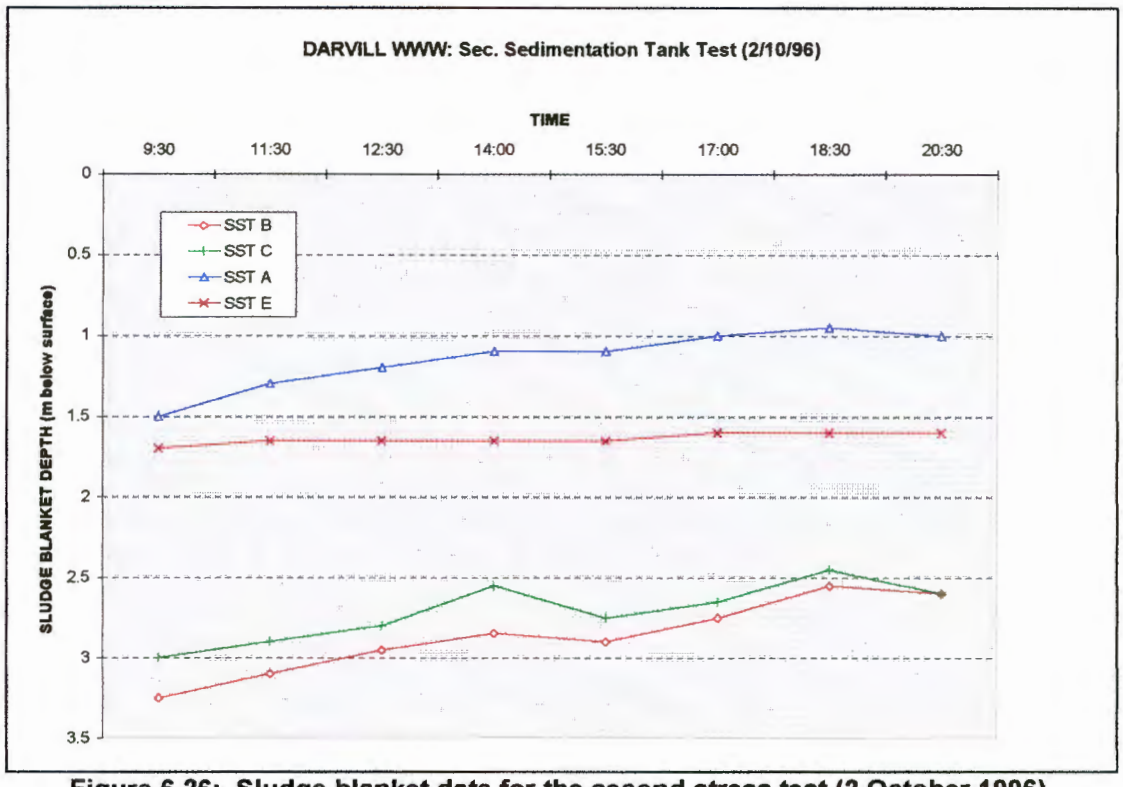


Figure 6.26: Sludge blanket data for the second stress test (2 October 1996).

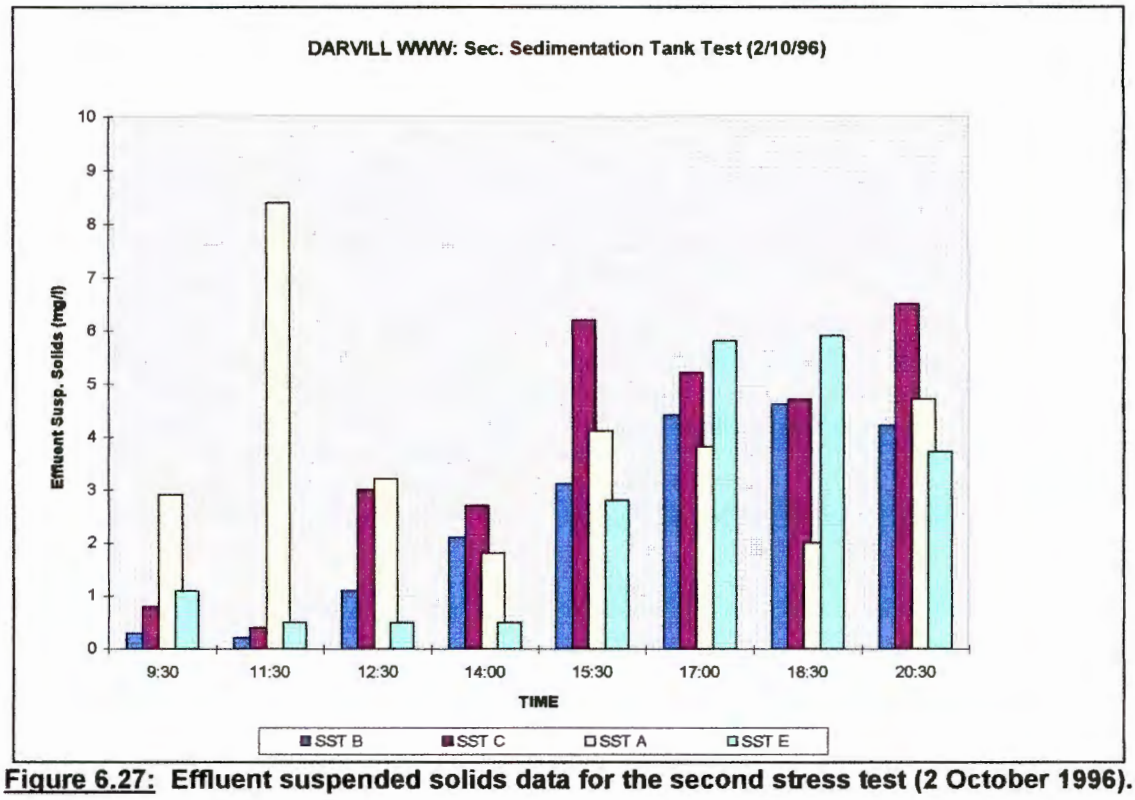


Figure 6.27: Effluent suspended solids data for the second stress test (2 October 1996).

6.5.3 Third stress test: End of ferrous- ferric chloride dosing

Contrary to the first two months of the plant trial, DSVI data (Fig. 6.13) indicated that sludge settleability had improved by the end of the ferrous-ferric plant trial. For this reason, it was decided to carry out a third stress test on the secondary clarifiers at this time.

Activated sludge settleability was measured in a series of settling tests on 13 November (shortly after the iron dose was increased) and 25 November 1996 (the last day iron dosing). A degree of improvement in DSVI appeared to materialise from the increased iron dose but the overall rapid downward trend in DSVI may have been influenced by other factors too (refer to section 6.4.3). The sludge settling tests were carried out as described in section 6.5.1 to determine the flux theory constants V_0 and n. To assess SST performance, a stress test was carried out on 20 November 1996.

The results for determination of the flux theory constants on 13 and 25 November are given in Table 6.7. From a comparison with the results for 26 September (Table 6.7), it seems that improved settleability (lower DSVI) was manifest by an decrease in n and (to a lesser degree) an increase in V_0. However, it is worth noting that in previous tests (Tables 6.4 and 6.6), good correlation was obtained in the semi-log plot used to determine V_0 and n for all points up to ca. 11 kg/m^3 MLSS. However, in the test results reported in Table 6.7, better correlation was obtained by ignoring the two points determined at highest MLSS concentration (ca. 9.5 to 14.0 kg/m^3). On the basis of the better correlation (Table 6.7), the measured V_0 was greater, but the n values was also greater; this appeared to be inconsistent with the lower DSVI results (Table 6.7). For consistency with previous stress tests, the V_0 and n values determined for the entire MLSS range were used to construct the flux curves.

Table 6.7: Flux theory constants determined by settling tests using the method described by WRC (1984) for Darvill full-scale activated sludge plant. Data applicable to third stress test (20/11/96).

DATE	MLSS range tested (kg/ m^3)	Correlation coefficient (r^2) of semi-log plot ln V_s vs. MLSS	Result V_0 m/d	Result n m^3/kg	DSVI (Ave. result for two days preceding)
13 November 1996	1.04 to 11.18 [1.04 to 6.96]	0.894 [0.972]	192 [272]	0.43 [0.54]	82
25 November 1996	1.43 to 13.97 [1.43 to 8.91]	0.982 [0.991]	224 [287]	0.36 [0.43]	62

From flux and modified flux theory, operating charts (Figures 6.28a and 6.28b) were constructed in the MLSS range 3.6 to 4.3 kg/m^3. On the day prior to the stress test, an average reactor MLSS of 4.6 kg/m^3 was recorded. This was used to establish the initial target operating point, namely an overflow rate of 21 m/d (20 Mℓ/d per SST, total 80 Mℓ/d for four SSTs) with a recycle ratio as close as possible to 0.8 (16 Mℓ/d per SST). From modified flux theory (Fig. 6.28a) this would have set up a critically loaded condition at an MLSS of 4.6 kg/m^3. From actual recorded results on the day of the test, lower reactor MLSS concentrations were measured, which resulted in some of the operating points falling within the "safe" envelope.

Figures 6.28a & b ...../

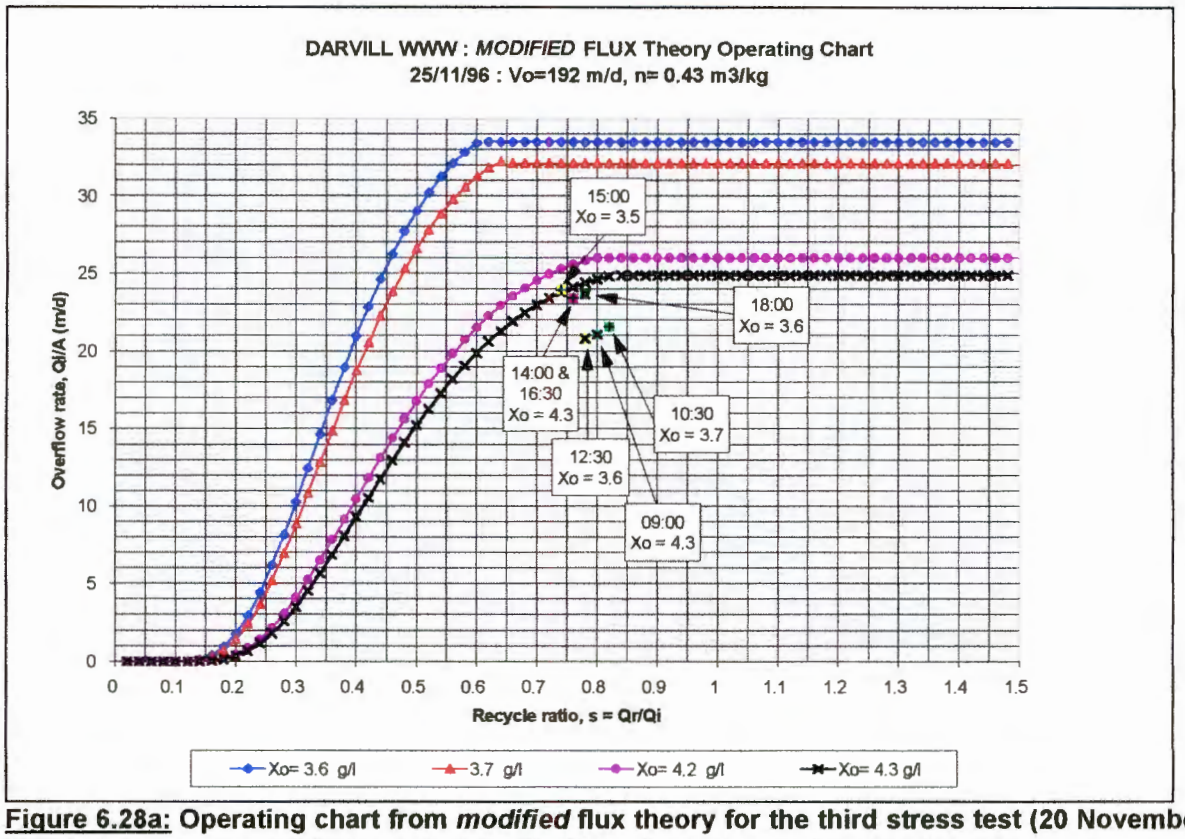


Figure 6.28a: Operating chart from *modified* flux theory for the third stress test (20 November 1996). Refer to Figure 6.30 for actual X_o (MLSS) values recorded during the test.

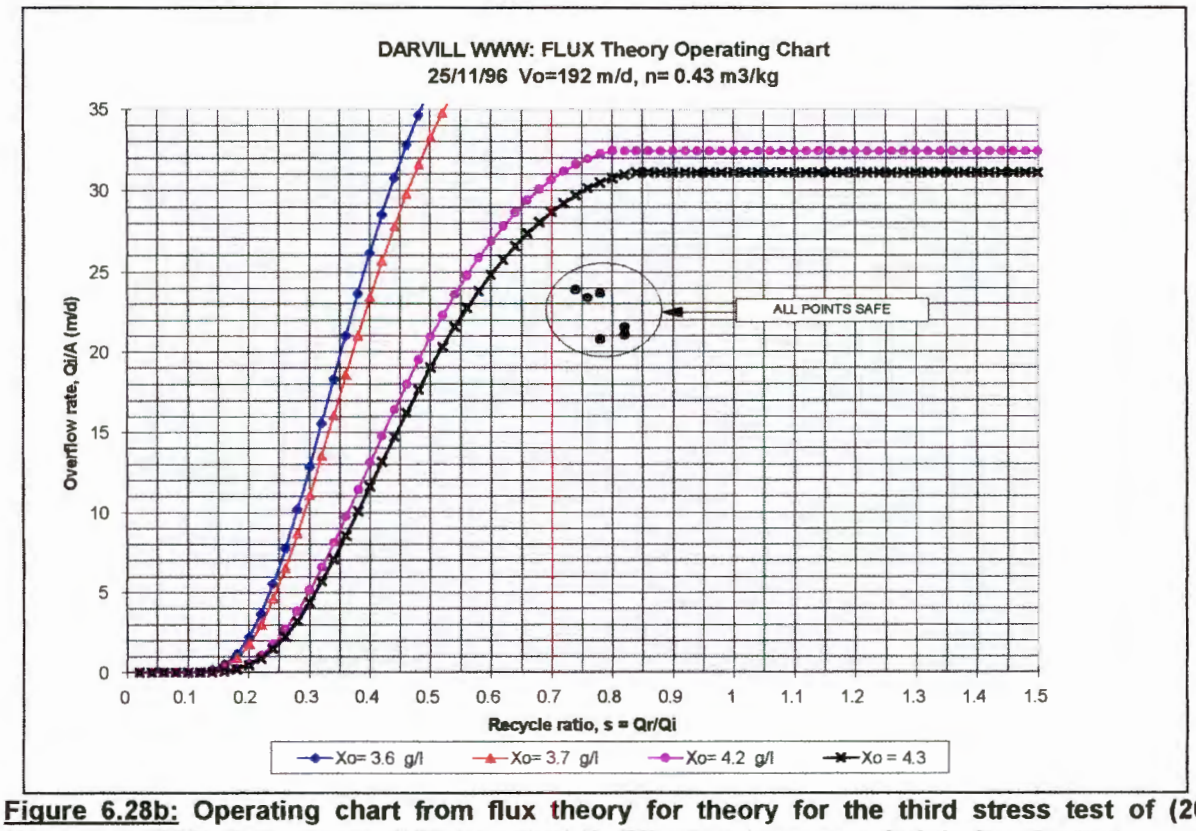


Figure 6.28b: Operating chart from flux theory for theory for the third stress test of (20 November 1996). Refer to Fig. 6.30 for actual X_o (MLSS) values recorded during the test.

The third stress test was commenced by taking SST B off line, thus leaving four SSTs in operation: two of the new type (B & C) and two of the retrofitted old type (A & E) (refer to section 6.5.1). The problematic scum holes on the mixed liquor splitter box (see above) were largely closed for the duration of this test, with the exception of a slot of greatly reduced size to allow scum to escape. (Any flow bias this may have created would have tended to favour SSTs A and E in that order, due to the configuration of the splitter box).

During the stress test, between 08h10 and 08h30, the overflow rate was increased from 18.5 to 21.3 m/d (71 to 82 Mℓ/d for 4 SSTs) by adjusting the setpoint for the main pump-station to the activated sludge plant (Fig. 6.29). A setpoint in the range 20.5 to 21.8 m/d (mean 21.0) (79 to 84 Mℓ/d, mean 81 Mℓ/d) was maintained until 13h30. At that point, a brief power failure caused the pumps to trip, followed by a start-up and readjustment of the flow setpoint. The setpoint was increased to 23.4 m/d (90 Mℓ/d) and this flow was achieved by 14h00. Apart from minor variations due to power supply problems, an overflow rate of 23.4 to 23.9 Mℓ/d (90 to 92 Mℓ/d) was maintained for four hours until 18h00. At this stage the balancing tank had reached 27% capacity. An unsuccessful attempt was made to pump a higher flow rate over the last hour of the test (18h00 to 19h00), during which the balancing tank was further emptied to 19% capacity. From experience it was known that a rapid pumping rate below 20% balancing tank capacity would not be possible, so the test was ended at this point. The data for the last hour (18h00 to 19h00) was not used in the results since the pumping rate were erratic.

The SST sludge recycles (Fig. 6.29) were set at ca. 08h30 to a constant target of 17.7 m/d (17 Mℓ/d per SST). This target was easily achieved for SSTs B and C (variable speed pumps controlled by PLC) and was achieved on average to within 1.6 m/d (1.5 Mℓ/d) each for SSTs A & E with exception of a period between 12h00 and 14h00 when the recycle from SSTs A & E dropped to 14.6 m/d (14 Mℓ/d), and a period from 17h00 to 18h00 when SST A recycle rose to 19.8 m/d (19 Mℓ/d).

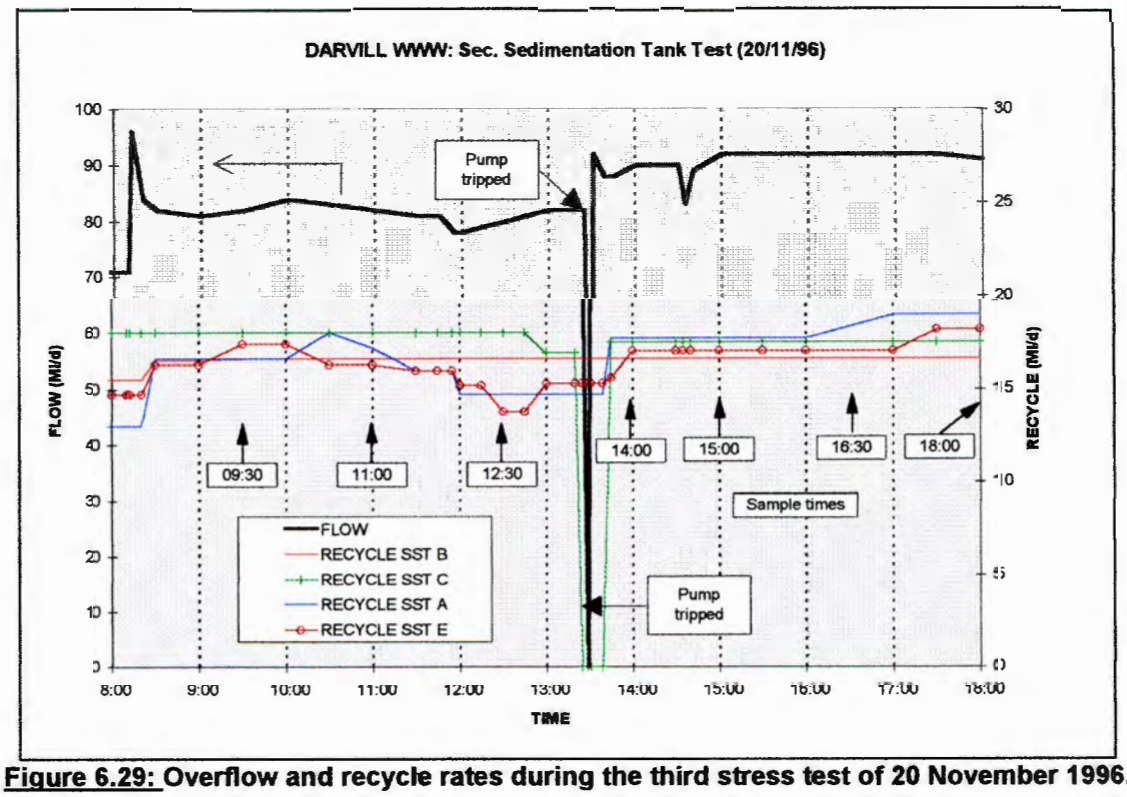


Figure 6.29: Overflow and recycle rates during the third stress test of 20 November 1996.

Figure 6.30 shows that the actual MLSS concentrations recorded during the test were in the range 3.5 to 4.3 kg/m^3, with significant variability in this range. Fig. 6.30 also shows that the underflow solids concentrations remained fairly constant in the range ca. 8.0 to 9.0 kg/m^3.

When using the recorded MLSS concentrations to plot the actual operating points on the chart developed from *modified* flux theory (Fig. 6.28a), it can be seen that the operating condition ranged from "safe" (09h00, 10h30 ,15h00 and 18h00) to "critical" (14h00 and 16h30). Hence the lower-than-expected MLSS concentrations weakened the stress test to some extent.

The data for sludge blanket levels and effluent suspended solids are presented in Figs. 6.30 and 6.32. Taken together, these data suggest that the clarifiers were operating close to the critical condition, but not in an over-loaded condition. The sludge blankets of the centre-scraped SSTs (B & C) showed a small but noticeable increase in level over the first 7 hours of the test (up to 15h00) and then appeared to stabilise. The sludge blanket levels in the older suction lift SSTs (A and E) remained largely constant (Fig. 6.30). The effluent suspended solids data (Fig. 6.32) showed a small increase during the test, with a suspected flow bias due to the small remaining scum slot on the splitter box showing up with a trend toward higher effluent solids from particularly SST A. It is noteworthy that the effluent suspended solids showed increases despite sludge blanket levels increasing only slightly. In a similar manner to the first stress test (15 August 1996), it can be concluded that sludge blanket levels alone are not directly related to effluent suspended solids concentrations in a pre-failure operating condition for these secondary clarifiers.

In overall terms, the third stress test appeared to validate the modified flux theory operating chart, but conditions did not permit the upper operating load limit of the clarifiers to be tested on this occasion. Substantially higher overflow rates were achieved during this test compared to the second stress test without a substantial deterioration in effluent suspended solids and with only a small relative decrease in reactor MLSS. This confirmed that settleability had improved, as indicated by the lower DSVI. As discussed in section 6.4.3 above, this improvement may have been part of a seasonal trend, but was partly mediated by the doubling of iron dose during the closing stages of the ferrous-ferric plant trial.

Figures 6.30 & 6.31 ...../

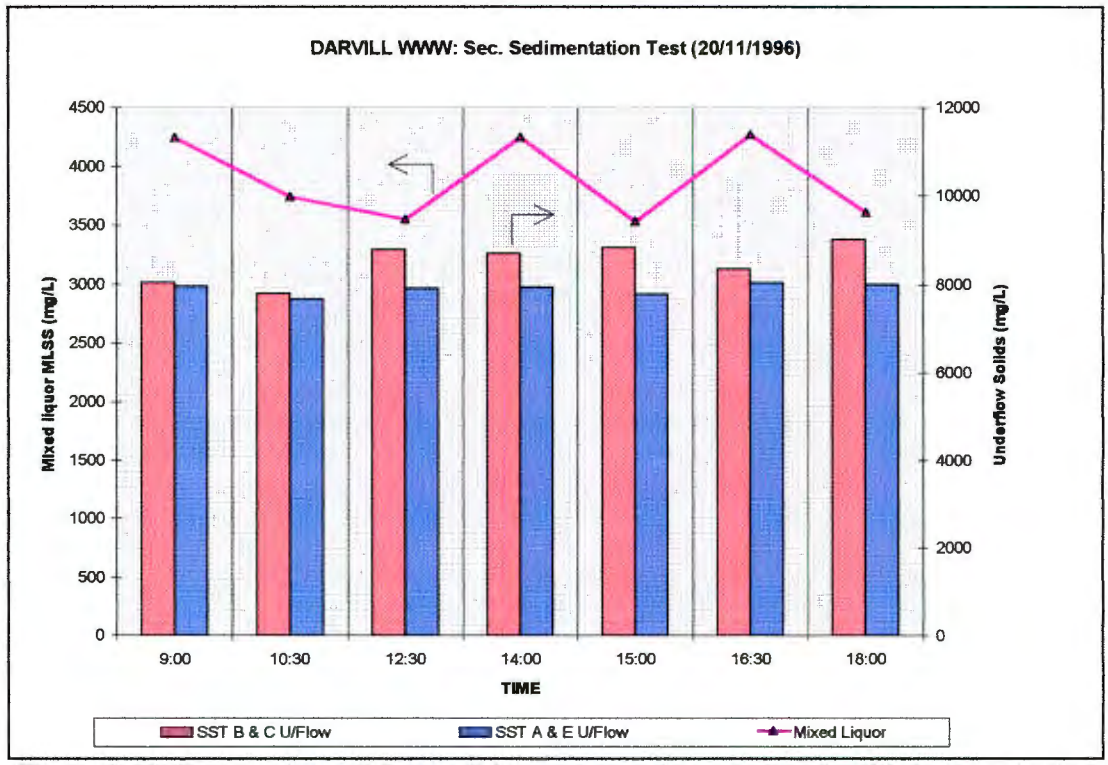


Figure 6.30: Feed and underflow solids concentrations during the third stress test of 20 November 1996.

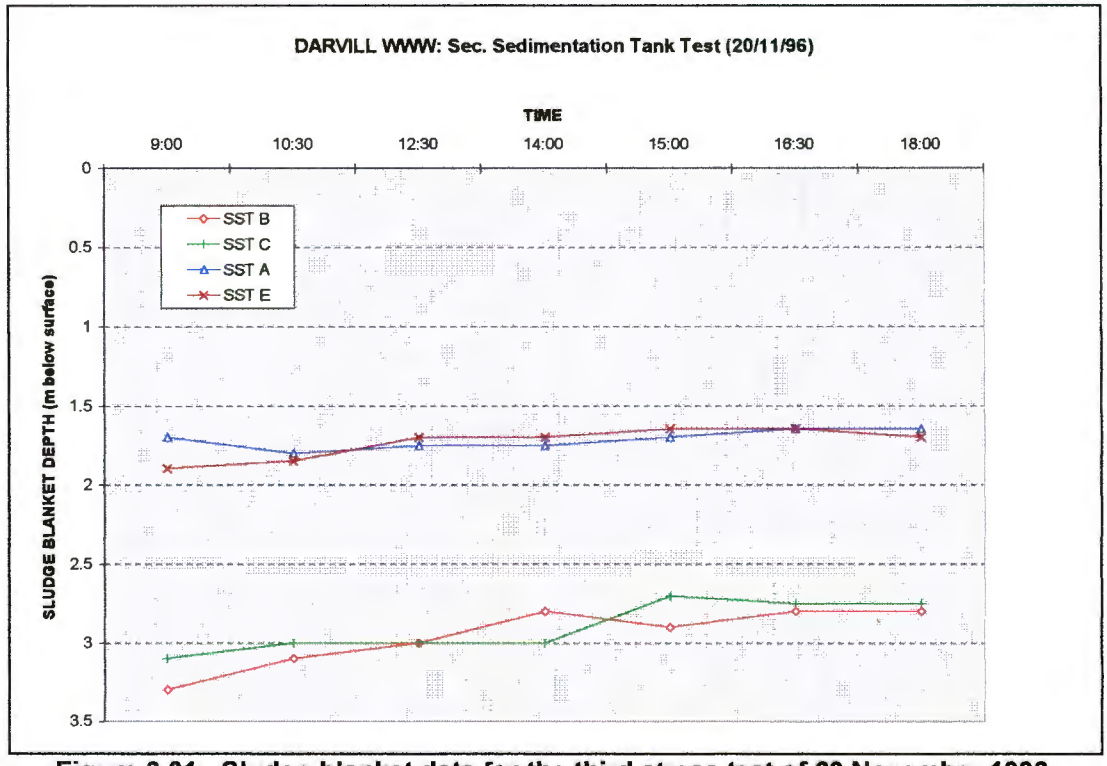


Figure 6.31: Sludge blanket data for the third stress test of 20 November 1996.

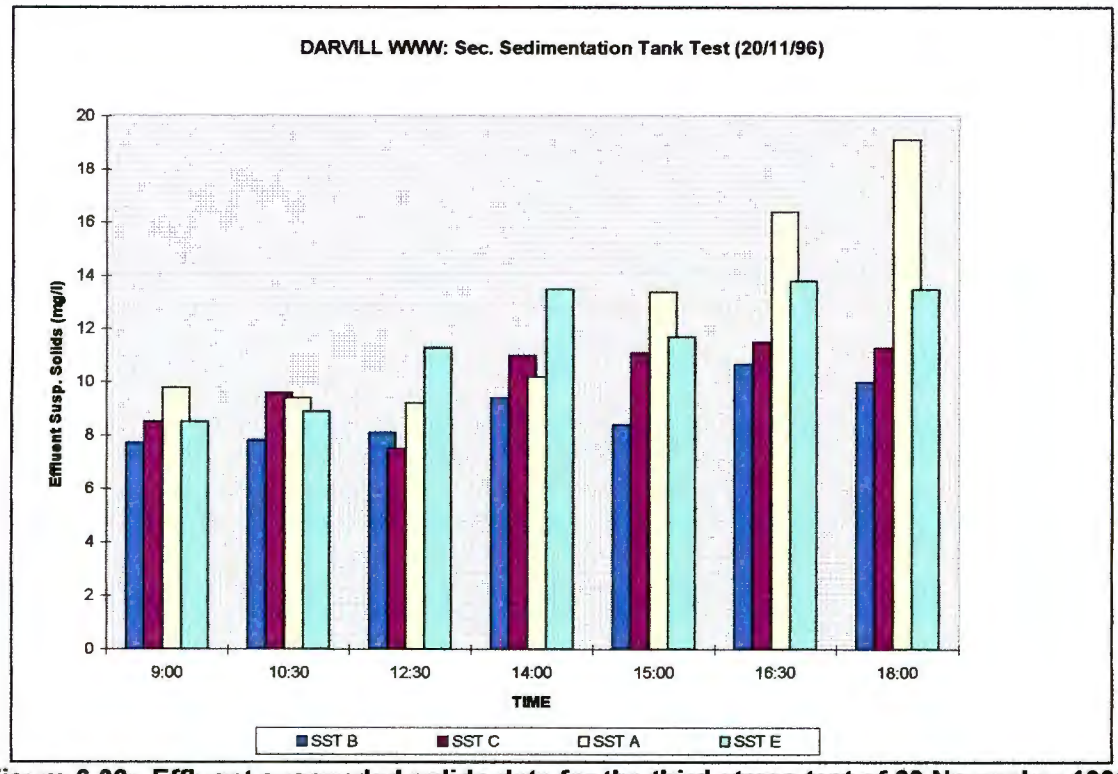


Figure 6.32: Effluent suspended solids data for the third stress test of 20 November 1996.

6.5.4 Fourth stress test: Alum dosing resumed

Alum dosing was resumed in December 1996, at the end of the ferrous-ferric chloride plant trial. The average monthly alum dose (based on influent flow) for the first three months of 1997 were:

- Jan. 1997: 32 mg/ℓ
- Feb. 1997: 31 mg/ℓ
- Mar. 1997: 37 mg/ℓ

The good sludge settleability which emerged in January- February 1997 (refer to Fig. 6.13) continued through March and April 1997 and the DSVI appeared to stabilise at around 50 mℓ/g at this time. Accordingly, a fourth and final clarifier stress test was conducted in April 1997. For this stress test, unlike the first three tests (see sections 6.5.1 to 6.5.3 above), the aim was to stress the clarifiers to the point of failure. In this manner, the validity of the operating chart based on flux theory (as opposed to *modified* flux theory) for defining the upper working limit of secondary clarifiers, could be tested.

Settling tests were conducted on 9 April 1997 using the method described before (see 6.5.1 to 6.5.3). The V_o and n results are given in Table 6.8.

It can be seen from a comparison between Tables 6.6, 6.7 and 6.8 that the improvement in sludge settleability during 1996/7 (registered by the lower DSVI) was manifest mainly by an improvement in the flux theory constant n, which implies that sludge thickening or "compactibility" was the limiting criterion for the Darvill secondary clarifiers.

Using the data in Table 6.8, operating charts based on flux theory (WRC, 1984) and modified flux theory (Ekama and Marais, 1986) were constructed (Figs. 6.33a and 6.33b).

Table 6.8: Flux theory constants determined by settling tests using the method described by WRC (1984) for Darvill full-scale activated sludge plant. Data applicable to fourth stress test (23/4/96).

DATE	MLSS range tested (kg/ m^3)	Correlation coefficient (r^2) of semi-log plot ln V_s vs. MLSS	Result V_0 m/d	Result n m^3/kg	DSVI (Ave. of five daily results preceding)
9 April 1997	1.59 to 17.39	0.972	218	0.290	49

The stress test was conducted on 23 April 1997. The relevant influent and recycle flow data are shown in Fig. 6.34. The mixed liquor feed to SSTs C, D and E was shut off at ca. 07h15 and the recycles from these three SSTs were cut at ca. 08h00. At 09h00, the influent flow rate was 80 Mℓ/d, giving an overflow rate of 41.6 m/d for the two operational SSTs (A and B); the recycle flows for SSTs A and B were 17.7 and 15.0 m/d (17 and 14.4 Mℓ/d) respectively (Fig. 6.34). (The aim was to commence with a recycle of 14.4 Mℓ/d on each; whereas the variable speed drive setpoint was readily achieved in the case of SST B, the siphon on SST A (old) was difficult to set accurately in the available time).

Samples were taken at 09h15. Immediately thereafter, at 09h20, the influent pump rate was increased to give a target overflow rate of 59.8 m/d (115 Mℓ/d for two SSTs) (Fig. 6.34). The recycle on SST B was increased to 17.7 m/d (17 Mℓ/d), thus equalising the recycle rates for the two operational SSTs. This operational mode was sustained for approx. 100 minutes. With estimated total volumes of 4.3 and 2.4 Mℓ for SSTs B and A respectively, and at an influent flow rate of 115 Mℓ/d, the 100 min. test period would have allowed 2 and 3.3 times the nominal hydraulic retention time to elapse respectively for the two SSTs. During this period, samples were taken at 10h15, 10h45 and 11h00. The results are shown in Figs. 6.35, 6.36 and 6.37.

For the modified flux theory, Fig. 6.33a shows that initially (09h15), SSTs A and B were operating just within the safe "envelope" below the 4.1 kg/m^3 curve. In the period 09h20 to 11h00, the MLSS concentration (sampled at the mixed liquor splitter box feeding the SSTs) decreased steadily (Fig. 6.35), tending to toward 3.4 kg/m^3. Coupled with the increased influent flow rate (Fig. 6.34), slightly overloaded conditions (tending back toward critically loaded conditions) were established in both SSTs during the period 09h20 to 11h00.

For standard flux theory, Fig. 6.33b shows that at all times during the fourth stress test, the operational SSTs (A & B) were in a "safe" loaded condition, with the operating points plotting below the envelope below the applicable curves on the chart.

Figure 6.35 shows that the underflow recycle solids concentrations was high in both SSTs, reaching ca. 16 kg/m^3, which was close to the highest concentration (ca. 17.4 kg/m^3) found during settling tests in the laboratory (Table 6.8). As the flux theory operating chart also indicates (Fig. 6.35), this suggests that the thickening criterion was limiting under these conditions.

Figure 6.36 shows that the blanket levels increased markedly in both SSTs during the period after the inflow was increased (observations at 10h15 to 11h00). Whilst the blanket in SST B was still ca. 1.6m below the water surface (due to the greater side wall depth of this SST, compared to SST A - see introduction to section 6.5 above), the test had to be stopped at 11h00 due to the failure of SST A. High carryover of solids from SST A began at ca. 10h45 (Fig. 6.36) when the blanket rose to $\leq$ 0.3 m of the water surface (Fig. 6.35). Attempts to further increase the recycle rate on this SST proved fruitless due to hydraulic constraints. As a result, the test was stopped before the final height of the sludge blanket of SST B could be established. Conditions in SST B were fairly turbulent and by 11h00 the effluent suspended solids had already exceeded the 25 mg/ℓ standard. Moreover, judging from the similar rise rates of the sludge blankets (Fig. 6.36), it seems that SST B would also have eventually shown gross solids loss as a result of a sludge blanket very near to the water surface. As

a result of its greater sludge storage capacity (due to its greater depth) this event was postponed relative to SST A.

In summary, the fourth stress test showed that the greatly improved settling characteristics associated with the lower DSVI and return to alum dosing at Darvill WWW increased the solids loading capacity of the to 14.8 kg SS/(m^2.h). This is approximately double the nominal design solids loading capacity of 7.5 kg SS/(m^2.h) for the new SSTs (B and C). As noted in previous sections, seasonal DSVI trends, the effects of trade effluent and the absence of a Control reactor at full-scale precludes the conclusion that the improved settling resulted purely from a resumption of alum dosing. However, this test does appear to validate the use of modified flux theory for design and operation of secondary clarifiers. The modified flux theory (Ekama and Marais, 1986) reduces the maximum permissible overflow rate (and attendant underflow rate) by 25 % (a factor of 1/0.8), compared to standard flux theory (WRC, 1984). During the fourth stress test, the clarifiers failed when operated at the limit predicted from standard flux theory. In previous stress tests, the SSTs were operated within the "safe" region (or, in some cases, in a critically-loaded to marginally overloaded region) based on modified flux theory, and the effluent suspended solids were generally well within the 25 mg/ℓ standard for this Works [16]. In practice, it is undesirable to design or operate a plant without a safety margin since allowance should be made for sub-optimal operating conditions (e.g. variation in settling characteristics and a practical limit to the frequency with which most operators are prepared to conduct settling tests and update operating charts; or operational constraints in settling optimal recycle rates, such as noted here in the case of manually adjusted suction lift clarifiers). Moreover, compliance with discharge standards is usually frequency-based (e.g. 95th percentile), which makes it virtually mandatory to operate the plant in a "safe" region with effluent suspended solids concentrations substantially lower than the required standard. Therefore, accepting the modified flux theory operating chart as a basis, with low DSVI (ca. 50 mℓ/g), the operating limit for the Darvill secondary clarifiers are given in Table 6.9. Compared to Table 6.5 (which was based on settling data when DSVI = 78 mℓ/g - refer to Table 6.4), the maximum overflow rates in Table 6.9 are 72 to 100% higher. However, in practice, such high overflow rates would not be achievable since operation of the plant would be constrained by the hydraulic limitations, and the recycle pumping capacity in particular (Table 6.9).

Table 6.9: Summary conclusions from modified flux theory operating chart and SST stress test of 23 April 1997 (alum dosing resumed) at Darvill WWW.

MLSS	Max. Q_i/A (m/d)	Max. Q_i (Mℓ/d) per SST	Max. Q_i (Mℓ/d) for five SSTs	Required minimum recycle ratio	Required min. recycle ratio for SST B and C [Max. recycle capacity] (Mℓ/d, two SSTs)	Required min. recycle ratio for SST A, D and E [Max. recycle capacity] (Mℓ/d, three SSTs)
5000	40	38	190	0.54	41 [38]*	62 [ca. 43]*
4500	47	45	225	0.46	41 [38]*	62 [ca. 43]*
4300	50	48	240	0.43	41 [38]*	62 [ca. 43]*
3800	58	56	280	0.35	39 [38]	59 [ca. 43]*

* : Recycle pumping capacity limitation noted

Figures 6.33a & b ...../

[16] Exceptions in this regard were noted previously to have been due to sub-optimal plant operation (e.g. unequal flow splitting between the clarifiers).

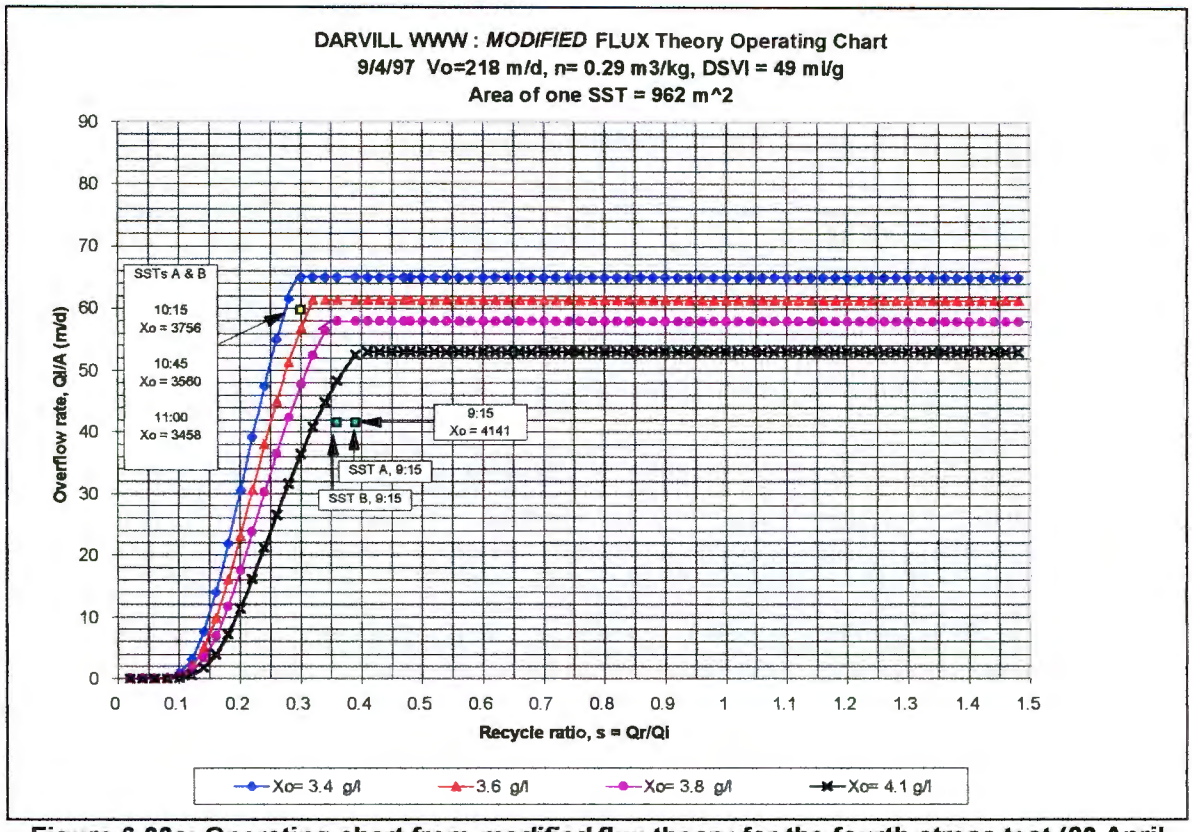


Figure 6.33a: Operating chart from *modified* flux theory for the fourth stress test (23 April 1997). Refer to Figure 6.35 for actual X_o (MLSS) values recorded during the test.

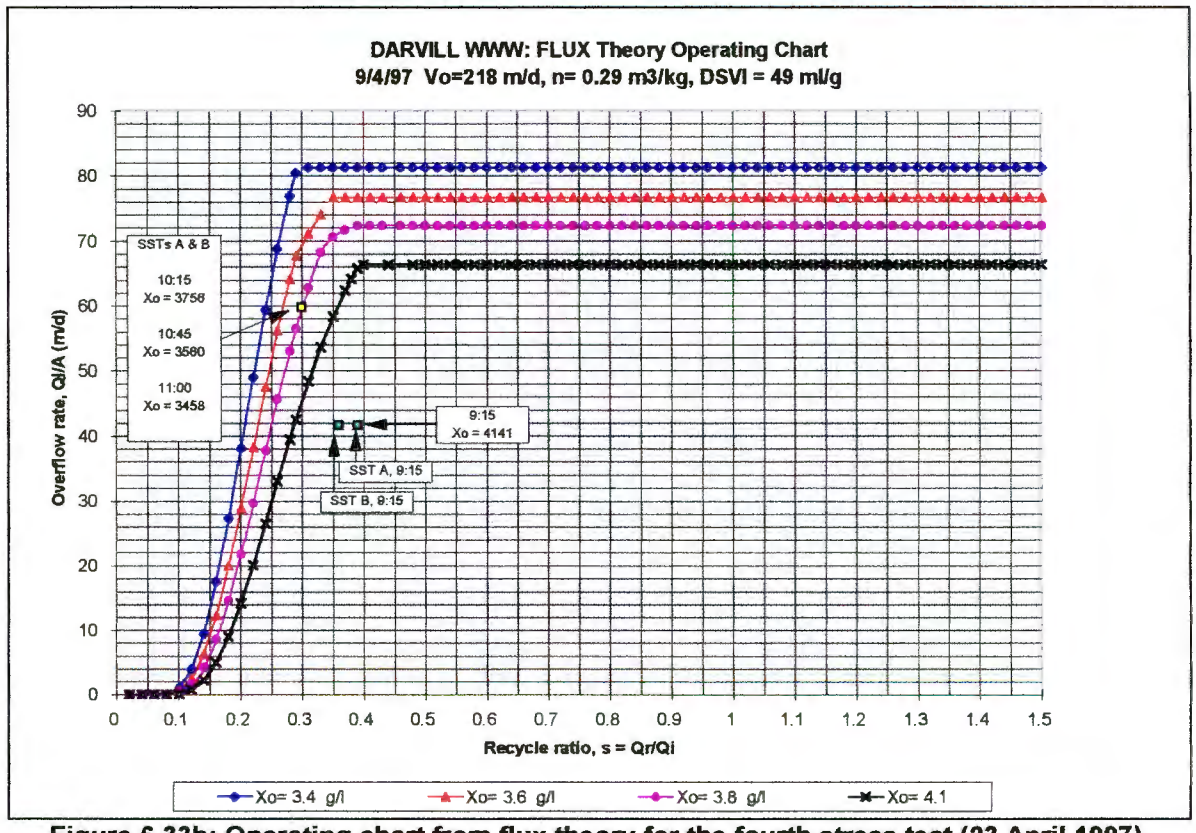


Figure 6.33b: Operating chart from flux theory for the fourth stress test (23 April 1997). Refer to Figure 6.35 for actual X_o (MLSS) values recorded during the test.

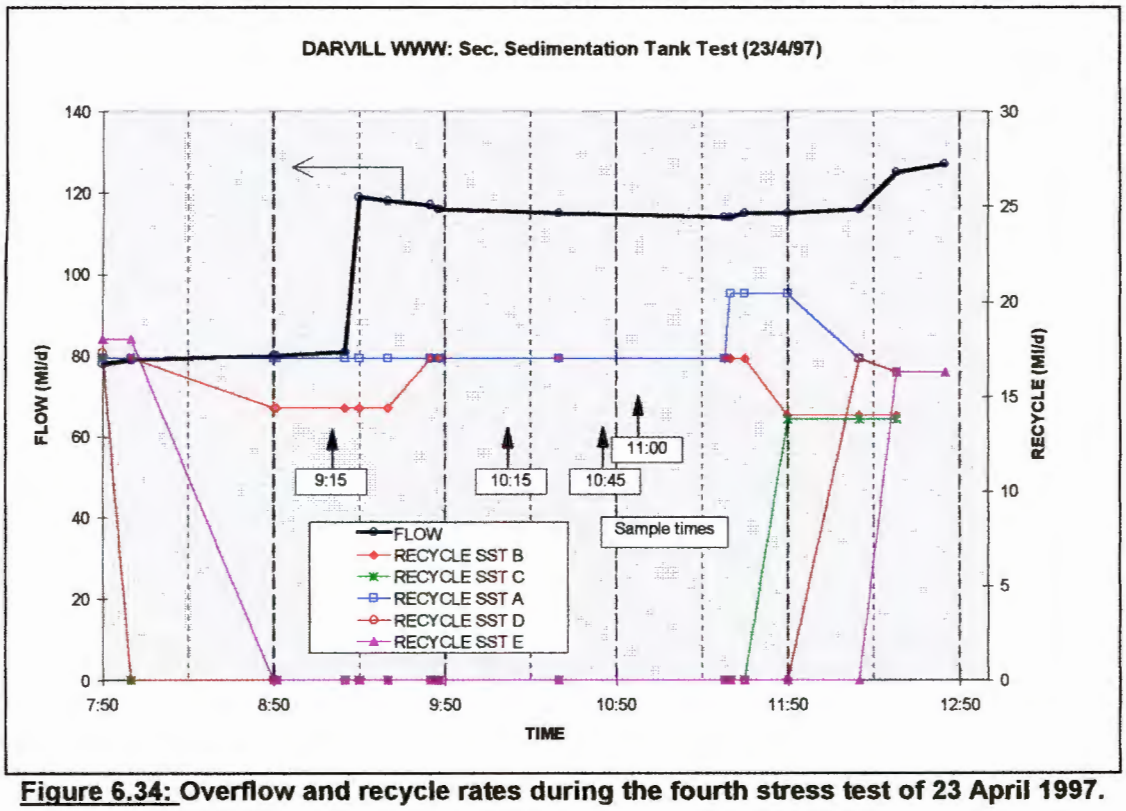


Figure 6.34: Overflow and recycle rates during the fourth stress test of 23 April 1997.

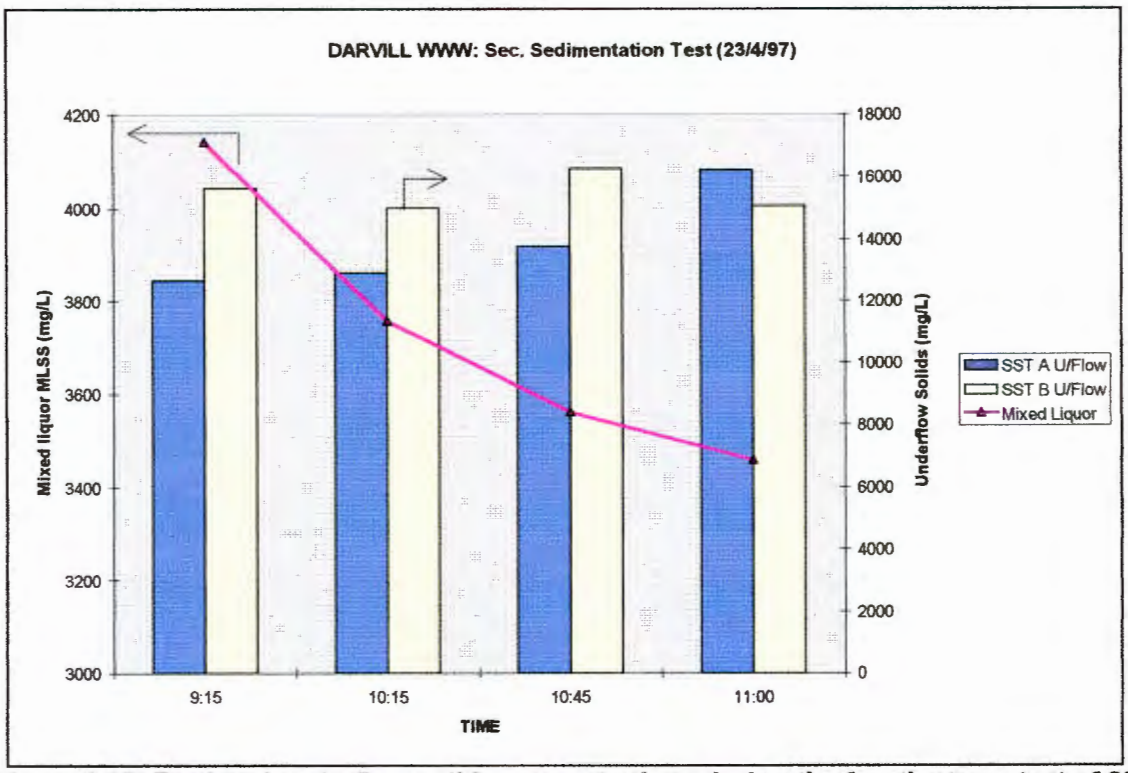


Figure 6.35: Feed and underflow solids concentrations during the fourth stress test of 23 April 1997.

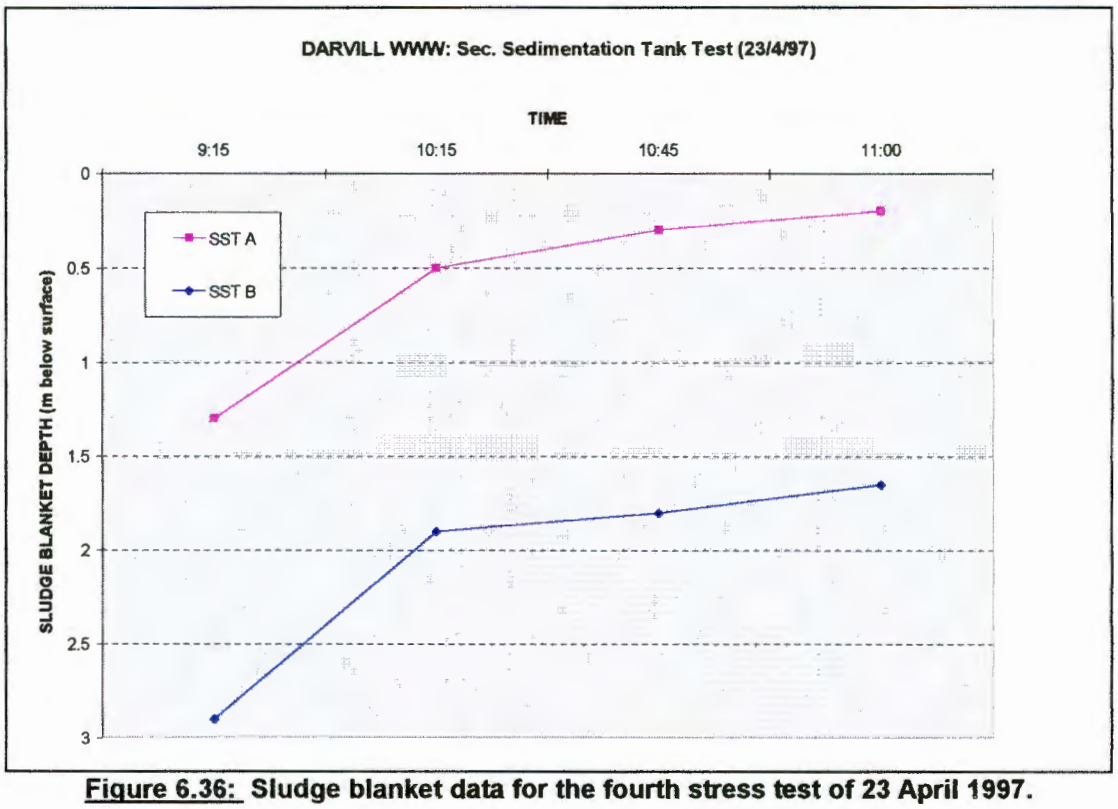


Figure 6.36: Sludge blanket data for the fourth stress test of 23 April 1997.

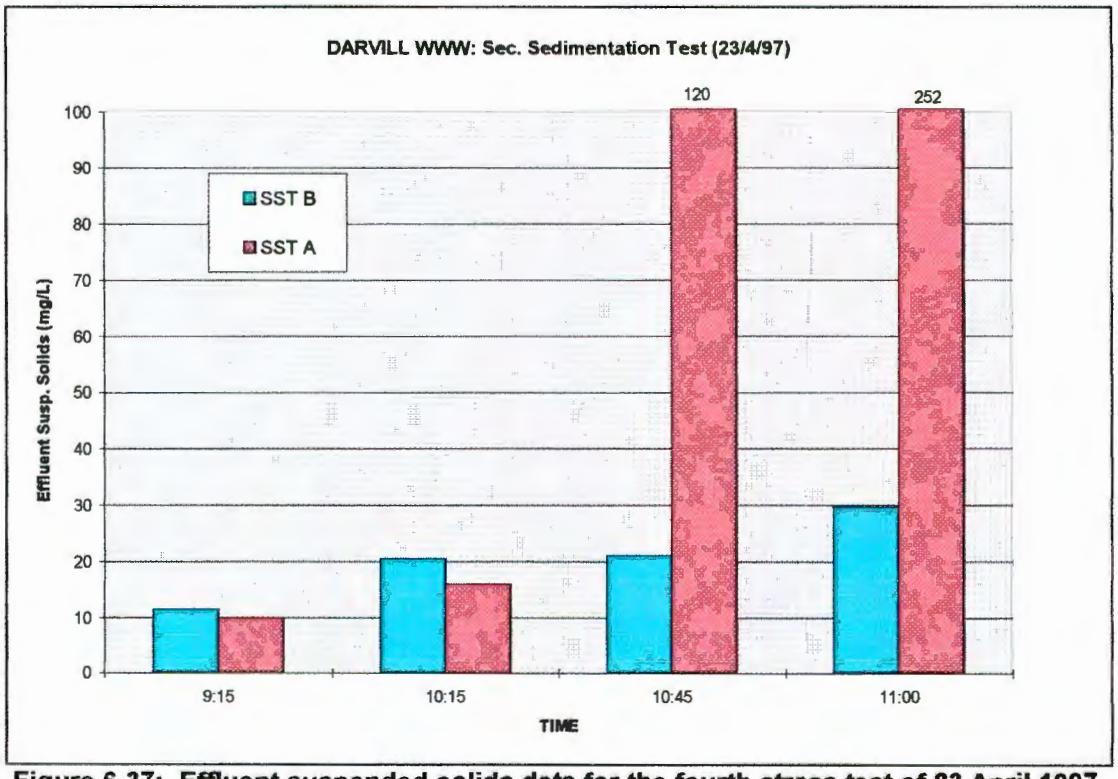


Figure 6.37: Effluent suspended solids data for the fourth stress test of 23 April 1997.

6.5.5 Summary of secondary clarifier stress tests in relation to flux theory

Using flux theory (WRC, 1984) it is possible to calculate the theoretical maximum solids loading rate (solids flux) at which an SST will be critically loaded. In terms of the modified flux theory, Ekama and Marais (1986) suggested that this maximum permissible solids flux be reduced to 0.8 (80%) of that predicted from standard flux theory. Hence, the data from the four SST stress tests in this study (sections 6.5.1 to 6.5.4 above) may be used to test whether the value of 0.8 proposed in the modified flux theory by Ekama and Marais (1986) has practical validity. The details of these calculations in this respect are given by de Haas and Ekama (1998) and the results are presented in Figs. 6.38a and 6.38b.

From Figs. 6.38a and b, it can be seen that the SST stress test data from this study appear to add validity to the *modified* flux theory:

- For the first three stress tests (Nos. 1 to 3), the applied solids flux (or solids loading rate) did not exceed 81% of the critical flux predicted from standard flux theory and the SSTs operated in a "safe" condition without gross solids overflow into the effluent;
- Conversely, in the fourth stress test (No. 4), the applied solids flux reached 86% of the critical flux predicted from standard flux theory and SST failure occurred, resulting in gross solids overflow into the effluent.

Figures 6.38a & b ...../

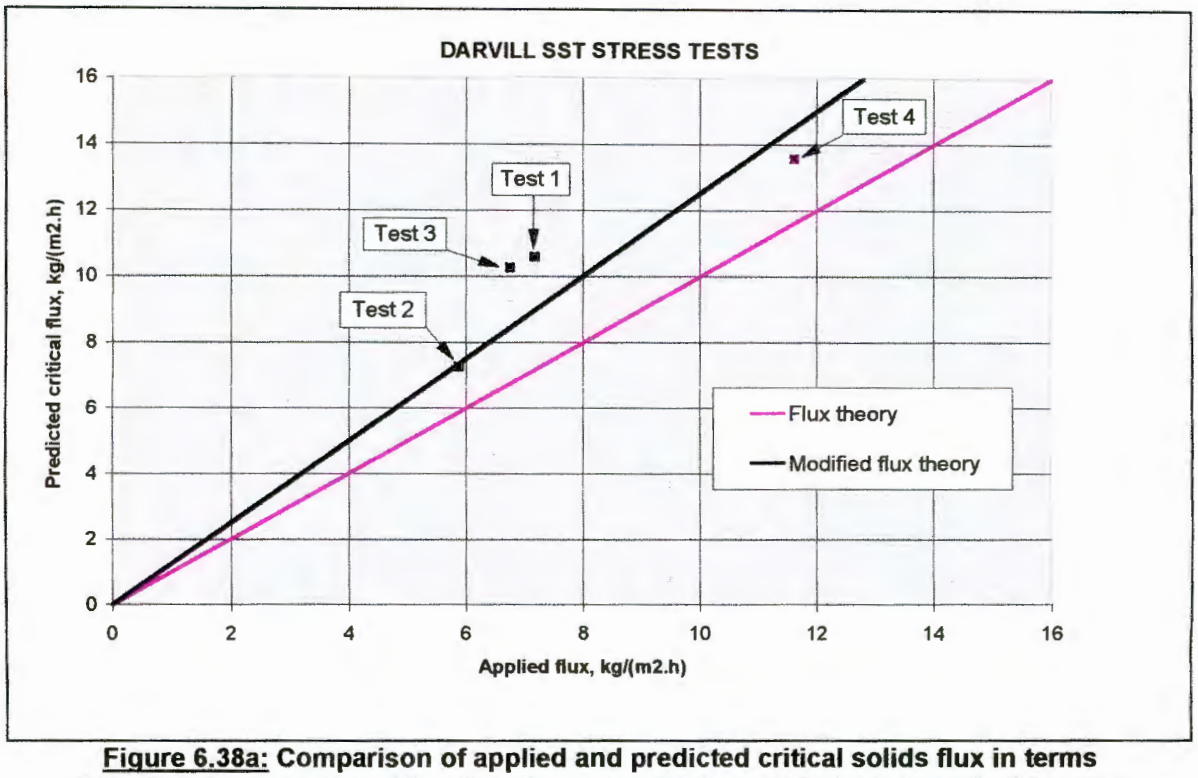


Figure 6.38a: Comparison of applied and predicted critical solids flux in terms of the flux theory and modified flux theory for the four SST stress tests in this study.

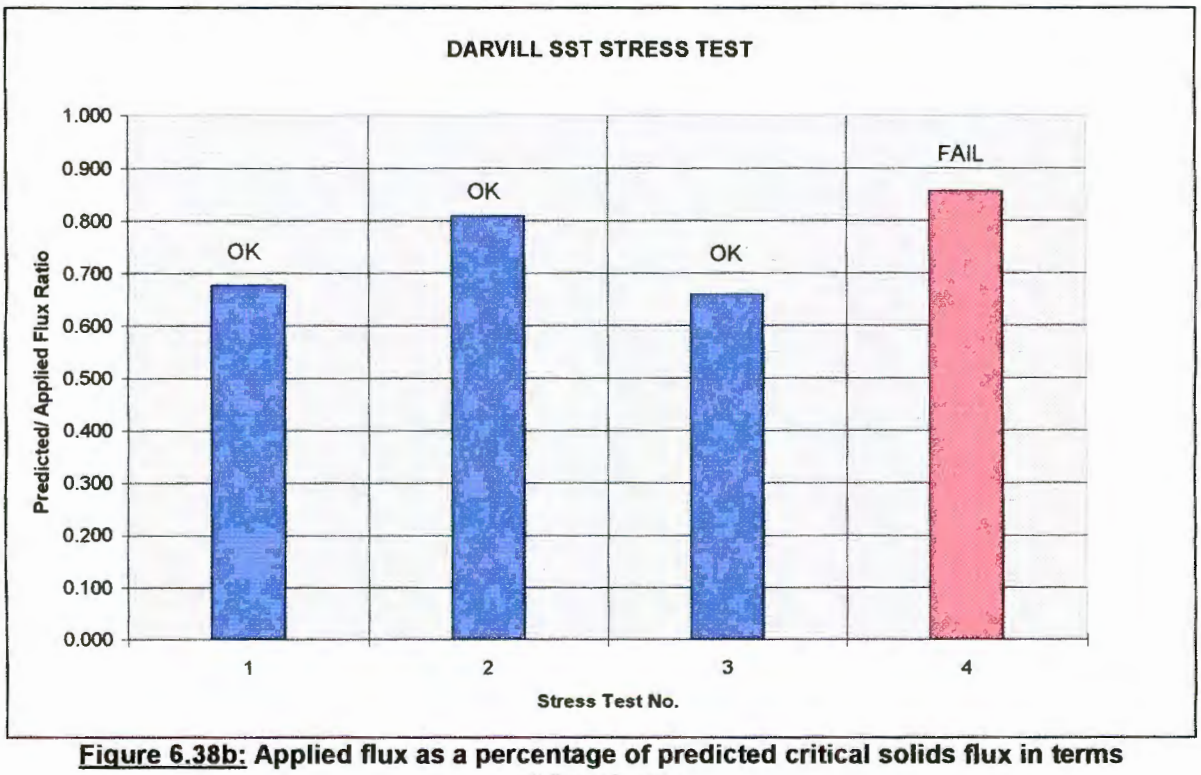


Figure 6.38b: Applied flux as a percentage of predicted critical solids flux in terms of flux theory.

6.6 COST IMPLICATIONS OF CHEMICAL DOSING

Chemical dosing costs constitute a significant component (approximately 18%) of the total operating costs at Darvill WWW. Since the upgrade of the Works was designed to enhance biological P removal and required considerable capital outlay, the aim was to minimise expenditure on supplementary chemicals without jeopardising compliance with the Special Phosphate Standard.

Initial indications were that ferrous-ferric chloride could prove cheaper than aluminium sulphate. Iron salts are widely used in the Gauteng (Johannesburg) area for simultaneous chemical-biological P removal in wastewater treatment. However, the major producers of iron salts are located in Gauteng, and road haulage over some 500 km to Darvill WWW in Pietermaritzburg would be required, whereas alum is transported by road from Richards Bay over a distance of some 250 km. The ferrous-ferric plant trial presented an opportunity to compare the costs of the two chemicals in more detail for Darvill WWW.

6.6.1 Assumptions

On the basis of the plant trial results (section 6.4.1), it was assumed that a dose of 0.101 mmol/ℓ metal (Fe or Al) would be the minimum required. This translates into 5.64 mg/ℓ as Fe in the case of the iron salt (ferrous-ferric chloride) and 2.73 mg/ℓ as Al (or 30 mg/ℓ as $Al_2(SO_4)_3.14H_2O$) in the case of alum.

It was further assumed that the daily dose would be based on a dry weather flow of 60 Mℓ/d.

6.6.2 Product costs and specifications

For 1995-7, Umgeni Water had a two year contract with *Minamet* to supply alum at a cost of R465/ ton product (wet), which is equivalent to R1010/ dry ton as $Al_2(SO_4)_3.14H_2O$ or R11110/ dry ton as Al. The alum is supplied as a 46% m/m solution with an specific gravity (S.G.) of 1.31.

A quotation was obtained from *NCP Ultrafloc* for ferrous-ferric chloride supplied to Darvill. The estimated cost was R632/ ton product (wet), which is equivalent to R4752/ dry ton as Fe. The ferrous-ferric chloride solution is a blend containing approximately 90% FeCl2 and 10% FeCl3. Based on the 10 batches delivered over a two month period during the plant trial, it contains approx. 13.1% m/m total Fe and has a specific gravity of 1.33.

The prices quoted above include VAT.

6.6.3 Cost comparison

From Table 6.10 it can be seen that the cost savings produced by the iron salt (compared to alum) are of the order of 12% for this Works. This is only a modest saving and needs to be weighed up against the potentially negative influence which the iron salt may have produced in terms of scum and foam or settling problems. The use of a polymer to counteract these settling problems would negate any savings accruing from the use of the cheaper metal salt.

The results of this study suggest that a further plant trial be conducted in future to determine whether the negative effects observed with the use of the iron salt can be repeated. Should no negative impact on overall plant performance materialise, potential savings of 12% in chemical costs could be realised.

Table 6.10: Results of cost comparison for chemical dosing at Darvill WWW for a dry weather flow of 60 Mℓ/d.

Chemical	Dose (mmol/ℓ)	Dose (mg/ℓ)	Annual cost 1996 Rands
Aluminium sulphate	0.101 as Al	2.73 as Al	R664 000
Ferrous-ferric chloride blend	0.101 as Fe	5.64 as Fe	R587 000
Difference			*R 77 000*

6.7 CONCLUSIONS

1. A review of historical plant performance using simultaneous alum at Darvill WWW suggested that good compliance (in excess of 90%) with the Special P Standard (<1 mgP/ℓ dissolved ortho P) is attainable over several months, provided that trade effluent effects can be minimised.

2. A three month full-scale plant trial using ferrous-ferric chloride instead of alum as simultaneous precipitant at Darvill WWW showed excellent P removal (96% compliance with the Special P Standard) for the first two months, followed by a marked deterioration in P removal. During the third month of the trial, compliance with the Special P Standard fell to <20%. The absence of a control reactor at full scale made it impossible to determine conclusively to what extent the deterioration in P removal performance was directly attributable to iron dosing. Several grab samples of influent (settled sewage) showed high total P and/or ortho P concentrations (up to approximately twice the average concentrations). Given a history of trade effluent-related treatment problems at this Works, the possibility could not be ruled out that the deterioration in P removal observed during the latter part of the ferrous-ferric chloride plant trial may have been largely related to changes in influent composition.

3. Following the conclusion of the ferrous-ferric chloride plant, when the plant was switched back to alum dosing, there was an apparent (temporary) improvement in effluent P compliance. However, this coincided with the December 1996- January 1997 period during which influent total and ortho P concentrations were relatively low (due to dilution with rain/ groundwater ingress) and relatively few trade effluent-related problems were observed (probably due to the Christmas recess). Moreover, effluent P compliance deteriorated markedly in February 1997 when flows approached those for dry weather conditions and an increase in the incidence of abnormally high influent P concentrations or other trade-related problems occurred. This supports the view that factors other than the nature of the chemical precipitant (alum vs. ferrous-ferric chloride) were the primary cause of poor effluent P compliance at this Works.

4. Circumstantial evidence suggested that iron (ferrous-ferric) dosing played a role in stabilising biological scum/ foam formation in the full-scale plant, to a greater extent than alum. The dominant nuisance organism in the scum was identified as the filamentous organism *Nocardia*. *Nocardia* may also have played a role in the deterioration on sludge settleability noted for the activated sludge plant during the plant trial. However, the absence of a Control reactor precluded a definite conclusion in respect of the impact of iron dosing on sludge settleability. Moreover, a seasonal trend in DSVI appeared to be discernible from four years of data for this plant (increasing DSVI in the colder dry season i.e. winter-spring; and decreasing DSVI in the hotter summer season when ingress of stormwater/ groundwater to the sewer system is an regular feature). The record high DSVI observed during the ferrous-ferric plant trial may have been part of this seasonal trend, coupled with the selective effect of high influent oil and grease concentrations (of known trade effluent origin for this Works) on the proliferation of *Nocardia*. Attempts by operational staff to physically trap and remove the scum and oil/grease layer from the surface of the activated sludge reactors may have worsened the problem.

5. Secondary clarifier stress tests conducted before, during and after the ferrous-ferric chloride plant trial confirmed the deterioration in sludge settleability observed from DSVI data during the trial. Immediately before the trial (with alum dosing), the DSVI was 78 mℓ/g and the estimated maximum "safe" overflow rate for the secondary clarifiers was 25 m/d (120 Mℓ/d for five clarifiers, or ca. 75% of design capacity) at an MLSS of 4500 mg/ℓ with a minimum recycle ratio of 0.75. During the ferrous-ferric plant trial, when the DSVI was 104 mℓ/g, the estimated maximum "safe" overflow rate was 15 m/d (72 Mℓ/d for five clarifiers, or ca. 45% of design capacity) at an MLSS of 4500 mg/ℓ with a minimum recycle ratio of 1.1). Four months after the trial, with alum dosing resumed, the estimated maximum "safe" overflow rate for the secondary clarifiers was 47 m/d (theoretically 225 Mℓ/d for five clarifiers, or ca. 139% of design capacity) at an MLSS of 4500 mg/ℓ with a (theoretical) minimum recycle ratio of 0.46. These results illustrated the strong dependence of clarifier performance on sludge settling characteristics. Observations of clarifier performance (sludge blanket depth and effluent suspended solids) were in general support of modified flux theory (Ekama and Marais, 1986) as a predictor of safe solids loading limits in order to achieve an effluent suspended solids concentration of <25 mg/ℓ. However, the specific settling characteristics observed in the context of this plant trial may not have been representative of the effects of chemical dosing alone since no Control system was available and other factors (including trade effluent and seasonal variations related to influent composition) may have impacted on sludge settleability.

6. For Darvill WWW, ferrous-ferric chloride dosing could offer a modest 12% (or R77 000 p.a.) saving in chemical costs relative to alum. However, it is recommended that prior to opting for ferrous-ferric chloride to replace alum, a further plant trail should be conducted in order to ascertain whether the apparent negative effect on sludge settleability observed at this Works during this study could be repeated using the iron salt.

REFERENCES

Bagg, W, Burke, R, Wentzel, MC, Dold, PL, Loewenthal, RE, Ekama, GA and Marais, GvR. (1985). Annual report to the Water Research Commission on the research contract: Biological excess phosphorus removal in the activated sludge process, Dept. of Civil Eng., University of Cape Town, Rondebosch, 7700, Cape Town.

Barnard, JL. (1992) Personal communication. Wates Meiring & Barnard, Kings Highway, Lynnwood, Pretoria, South Africa.

D'Elia, M and Isolati, A. (1992) Observed synergistic effects of aluminium and iron salts in nutrients removal. *Chemical water and wastewater treatment II: proceedings of the 5th Gothenburg Symposium, September 28-30, 1992, Nice, France.*, Klute, R and Hahn, HH (eds.), Springer-Verlag, New York, 389-400.

De Haas, DW and Adam N. (1995) Use of a simple titration procedure to determine $H_2CO_3^*$ alkalinity and volatile fatty acids for process control in waste-water treatment. *Water SA* 21 (4), 307-318.

De Haas, DW and Borain, GP. (1995) Pilot-scale investigation of biological phosphorus removal under conditions of low influent strength. Proceedings of the WEF Specialty Conference on New and Emerging Environmental Technologies and Products for Wastewater Treatment and Stormwater Collection, Toronto, Canada, 4-7 June, 1995.

De Haas, DW and Ekama., GA (1998) Evaluation of the flux theory for predicting secondary settling tank solids loading rate at the Darvill Wastewater Treatment Plant. Paper to be presented at the WISA Biennial Conference, Cape Town, South Africa, May 1998.

Dold, PL, Wentzel, MC, Billing, AE, Ekama, GA and Marais, GvR. (1991) *Activated sludge system simulation programs*. Water Research Commission, PO Box 824, Pretoria, South Africa.

Ekama, GA. (1994) A selection of impressions and statements from papers and posters presented at the 1st IAWQ Activated Sludge Population Dynamics (ASPD) conference on micro-organisms in activated sludge and biofilm processes, Paris, 1993. IAWQ ASPD Newsletter, 7(1), 16-19.

Ekama, GA, Barnard, JL, Gunthert, FW, Krebs, P, McCorqodale, JA, Parker, DS, and Wahlberg, EJ. (1996). Secondary settling tanks: Theory, design, modelling and operation. IAWQ STR No. 6, IAWQ, London (In Press).

Ekama, GA, Dold, PL and Marais, GvR. (1986) Procedures for determining influent COD fractions and the maximum specific growth rate of heterotrophs in activated sludge systems. Water Sci. Technol. 18, 91-114.

Ekama , GA and Marais GvR. (1986) Sludge settleability and secondary settling tank design procedures. *Water Pollut. Control* 1986, 101-113.

Forster , CF. (1996) Aspects of the behaviour of filamentous microbes in activated sludge. *J. CIWEM* 10, 290 - 294.

Howard, JR. (1996) Personal communication. Water Quality Dept., Umgeni Water, PO Box 9, Pietermaritzburg 3200, August 1996.

Jenkins, D, Richard, MG and Daigger, GT. (1984) *Manual on the causes and control of activated sludge bulking and foaming.* Report prepared for Water Research Commission, PO Box 824, Pretoria, South Africa.

Kerley, S and Forster, CF. (1995) Extracellular polymers in activated sludge and stable foams. *J. Chem. Tech. Biotechnol.* 62, 401-404.

Lemmer, H and Baumann, M. (1988) Scum actinomycetes in sewage treatment plants - Part 2: The effect of hydrophobic substances. *Water Res.* 22 (6), 761-763.

Mamais, D, Jenkins, D and Pitt, P. (1993) A rapid physico-chemical method for the determination of readily biodegradable COD in municipal waste-water. *Water Res.* 27 (1), 195-197.

Meiring & Barnard. (1990) *First Interim Report on Upgrading of Darvill Wastewater Treatment Plant*. Report to City Engineers Dept., Pietermaritzburg by Wates Meiring Barnard (formerly Meiring & Barnard), Midrand, Johannesburg, South Africa.

Pillay, M. (1994) *Detergent phosphorus in South Africa: Impact on eutrophication with specific reference to the Umgeni catchment*. MSc Thesis, Dept. of Chemical Engineering, University of Natal, Durban, December, 1994.

Umgeni Water. (1993) Engineering plans for extensions to Darvill Wastewater Works. Produced by Wates Meiring Barnard/ Watermeyer Legge Piesold Uhlmann (Knight Piesold). Umgeni Water Design Centre, PO Box 9, Pietermaritzburg, South Africa.

Wentzel, MC, Ekama, GA, Dold, PL and Marais, GvR. (1990) Biological excess phosphorus removal - Steady state process design. *Water SA* 16 (1), 29 -48.

WRC. (1984) *Theory, design and operation of nutrient removal activated sludge processes.* Water Research Commission, PO Box 824, Pretoria, South Africa.

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting biological enhanced phosphate removal.

Chapter 7

Modelling of simultaneous chemical-biological P removal

DW de Haas

CHAPTER SEVEN

MODELLING OF SIMULTANEOUS CHEMICAL-BIOLOGICAL P REMOVAL

7.1 INTRODUCTION

Mathematical models of modified activated sludge systems incorporating biological nutrient removal (BNR) are well established (*inter alia* Dold et al., 1991; Wentzel et al., 1992, IAWQ, 1995). These models serve a useful function as research and design tools, and are also emerging as operator aids in the form of real-time simulation of full-scale activated sludge plants (Thornberg, 1995). Until very recently, simultaneous chemical precipitation reactions have not been incorporated into models of biological phosphate removal in activated sludge systems. However, with the prevalence of simultaneous chemical addition to biological P removal systems, the need for a more comprehensive combined chemical-biological model has been recognised. The purpose of this chapter is to review the manner in which the chemical processes have been incorporated into the biological model and to test at least one of the available combined models against the pilot plant data presented in Chapters 3, 4 and 5.

At present, there are three main mathematical (or mechanistic) models of the biological processes which are commonly used: the UCT model (or UCTPHO, in computer program format) (Wentzel *et al.*, 1992); the IAWQ ASM 2 model (IAWQ, 1995; Wentzel and Ekama, 1995); and the Dold model (or "BIOWIN" in computer program format) (Barker and Dold, 1997). These models differ in detail on certain key processes, but do not differ in concept and will produce closely similar results for many applications. At a biochemical level, these models all have the same origin, namely, the work of Wentzel *et al.* (1986) and Comeau *et al.* (1986). Mino *et al.* (1987) also proposed a biochemical model which differed from the Wentzel and Comeau models to the extent that stored glycogen was proposed as an additional stored ("internal") substrate in the poly P accumulating organisms. For the anaerobic sequestration of substrate (e.g. acetate) to form poly-hydroxyalkanoate (PHA), Mino et al. (1987) proposed that glycogen[1] served as the source of reducing power (and partly as energy source), an alternative to the tricarboxylic acid cycle (and poly P) in the Wentzel/ Comeau model. In terms of the mechanistic models, the effect of this proposal is to change the stoichiometry of P release/ uptake. Smolders *et al.* (1994) have subsequently shown that the stoichiometry of anaerobic P release is also dependent on the prevailing reactor pH. To the extent that the mechanistic models allow the stoichiometry to be calibrated, the exact biochemical processes are not important. However, considerable effort is being directed world-wide toward developing more detailed (and hopefully better) models which are based more closely on the relevant biochemical processes.

In this study, the objective was not to compare or evaluate in detail the merits of the respective models in respect of their treatment of the biological processes. The objective here was merely to use the UCTPHO model as reference for setting up the biological processes in the IAWQ model in such a way as to predict the behaviour of the experimental systems as closely as possible. This allowed the chemical precipitation processes proposed in the IAWQ ASM2 model (IAWQ, 1995) to be tested against the results obtained from the experimental systems dosed simultaneously with metal precipitant.

7.1.1 The chemical model of Luedecke *et al.* (1989)

Luedecke *et al.* (1989) developed a chemical model of phosphate precipitation with ferric (iron III) salts in aqueous systems and applied it to a conventional activated sludge system. Their model represents an important contribution toward developing a combined chemical-biological model for P removal in activated sludge systems and is worthy of detailed examination.

[1] This work was based on the observation that continuous cultures systems of activated sludge exhibiting BEPR show a variable tendency to store glycogen. The biological P removal capacity of these systems appears to be inversely related to the size of glycogen reserves. This has led to the hypothesis that so-called G-bacteria may dominate the anaerobic sequestration of substrate in such systems without enhanced P uptake under aerobic conditions. The microbiological identity of such "G bacteria" is still the subject of research.

Luedecke *et al.* (1989) pointed out that the chemistry of phosphate in aqueous solutions is not fully understood even though there have been a number of studies on this subject. Since inorganic phosphates are known to combine with a number of metal ions to form chelates, complexes or insoluble salts, determination of the composition of precipitates becomes problematic. A general formula for ferric hydroxy-orthophosphate $Fe_rPO_4(OH)_{3r-3}$ was reported by Stumm and Morgan (1970) (cited by Luedecke *et al.*, 1989) as one of the solid phases that may occur in natural aqueous environments. Luedecke *et al.* (1989) accepted this formula and that for amorphous ferric hydroxide (FeOOH) as the two principal forms of iron precipitate which could exist in activated sludge. Since their model involved two precipitates, they postulated that four possible precipitation "regions" could exist, namely (Figure 7.1):

- FeOOH (s) precipitation;
- co-precipitation of $Fe_rPO_4(OH)_{3r-3}$ (s) [2] and FeOOH (s);
- $Fe_rPO_4(OH)_{3r-3}$ (s) precipitation;
- no precipitation.

The conditions applying to each of these four regions may be summarised as follows (Luedecke *et al.*, 1989):

7.1.1.1 Co-precipitation of $Fe_rPO_4(OH)_{3r-3}$ (s) and FeOOH (s)

If the dose of Fe is sufficiently high and the initial ortho P concentration is not limiting, both ferric hydroxy-phosphate and ferric hydroxide will precipitate:

$$r\,Fe^{3+} + PO_4^{3-} + (3r-3)\,OH^- \leftrightarrow Fe_rPO_4(OH)_{3r-3}\,(s) \qquad pK_s = ?? \qquad \text{..... Eqn 7.1}$$

$$Fe^{3+} + 2H_2O \leftrightarrow FeOOH\,(s)\,(amorphous) + 3H^+ \qquad pK_s = -0.5 \qquad \text{..... Eqn 7.2}$$

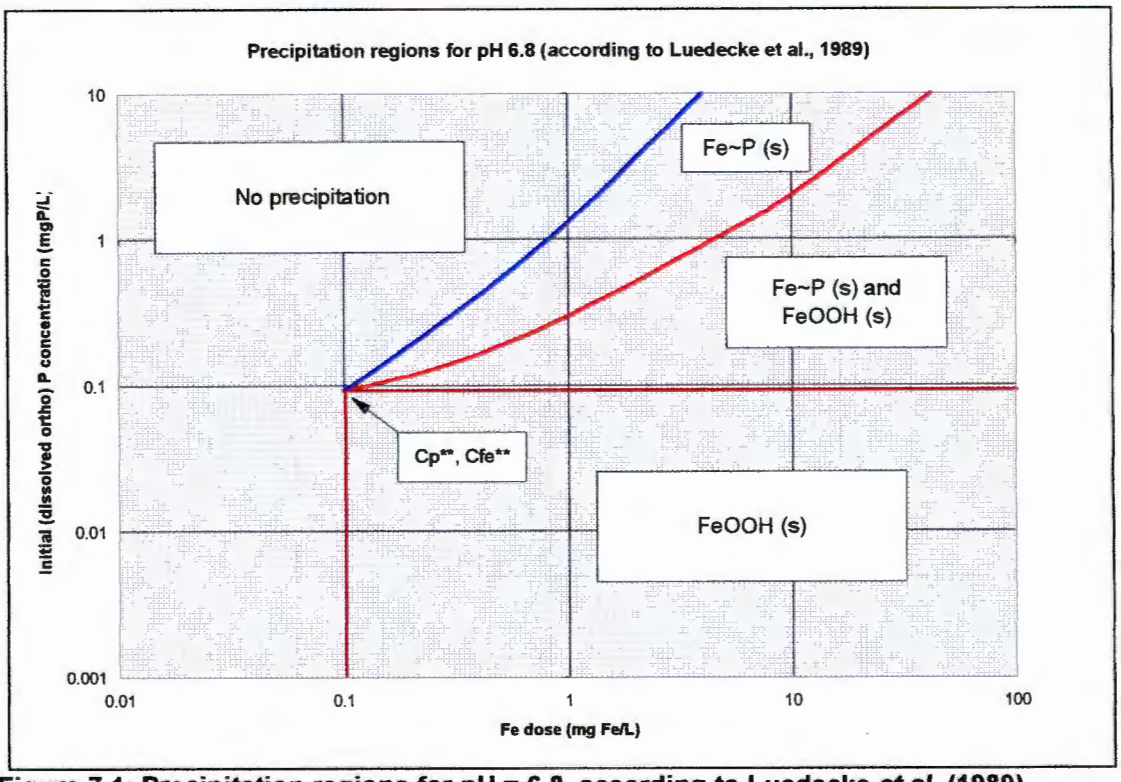


Figure 7.1: Precipitation regions for pH = 6.8, according to Luedecke *et al.* (1989). Refer to text for definition of C_p^{**} and C_{fe}^{**}. See footnote[1] for definition of Fe~P.

[2] $Fe_rPO_4(OH)_{3r-3}$ is abbreviated as Fe~P in Fig. 7.1.

Based on Equations 7.1 and 7.2, expressions were developed from equilibrium chemistry for the maximum concentrations of dissolved orthophosphate (c_p^{**}) [3] and dissolved iron (c_{Fe}^{**}) which can *co-exist* with $Fe_rPO_4(OH)_{3r-3}$ and FeOOH at a particular pH under conditions of co-precipitation. In these expressions ion-pairing effects were taken into account: dissolved orthophosphate species included iron complexes (viz. $FeH_2PO_4^{2+}$ and $FeHPO_4^{+}$) and dissolved iron species included complexes with phosphate or hydroxide (viz. $FeOH^{2+}$; $Fe(OH)_2^{+}$; $Fe(OH)_3^{0}$; $Fe(OH)_4^{-}$; $FeH_2PO_4^{2+}$ and $FeHPO_4^{+}$).

Ferric phosphate and ferric hydroxy-phosphate ($Fe_rPO_4(OH)_{3r-3}$) have low solubility products: pK_s = 23 for amorphous $FePO_4$; pK_s = 28.7 for $FePO_4$ as strengite; and Luedecke *et al.* (1989) assumed pK_s = 96.7 for $Fe_rPO_4(OH)_{3r-3}$). Hence, it was assumed that ferric hydroxy-phosphate precipitation essentially will be complete. This could be conceptualised as ferric hydroxy-phosphate forming in preference to ferric hydroxide (i.e. being thermodynamically more stable), although this should not be interpreted in kinetic terms here. Hence, for co-precipitation, the concentration of ferric hydroxy-phosphate precipitate formed ($c_{p,\ prec}$) could be determined by the difference between the initial (or "influent") dissolved orthophosphate concentration ($c_{p,in}$) and c_p^{**}:

$$c_{p,\ prec} = c_{p,in} - c_p^{**} \quad \text{..... Eqn 7.3}$$

Similarly, the amount of ferric hydroxide precipitate formed was found from the Fe(III) mass balance (i.e. Fe(III) dose - c_{Fe}^{**} - Fe(III) removed stoichiometrically as $Fe_rPO_4(OH)_{3r-3}$):

$$c_{Fe,\ prec} = c_{Fe,\ dose} - c_{Fe}^{**} - r\,(c_{p,in} - c_p^{**}) \quad \text{..... Eqn 7.4}$$

Since co-precipitation ceases when no ferric hydroxide precipitate forms, the boundary between the co-precipitation region and the ferric hydroxy-phosphate region was defined by the condition:

$$c_{Fe,\ dose} - c_{Fe}^{**} > r\,(c_{p,in} - c_p^{**}) \quad \text{..... Eqn 7.5}$$

Typically at near-neutral pH, co-precipitation was expected in the region of low residual dissolved orthophosphate concentrations (0.1 to 2 mgP/ℓ) with an iron dose of approximately 1 to 10 mg/l as Fe (refer to Fig. 7.1).

7.1.1.2 Precipitation of FeOOH (s) only

If the initial orthophosphate concentration ($c_{p,in}$) is less than c_p^{**}, then ferric hydroxy-phosphate precipitate will not form; only ferric hydroxide will form, provided the Fe(III) dose exceeds c_{Fe}^{**}. Hence a boundary between co-precipitation and ferric hydroxide precipitation could be defined.

At near-neutral pH, using the solubility product and dissociation constant values assumed by Luedecke *et al.* (1989), ferric hydroxide precipitation only may be expected in the region of low residual dissolved ortho P concentrations (<0.1 mgP/ℓ) and iron doses of >0.1 mg Fe/ℓ (refer to Fig 7.1).

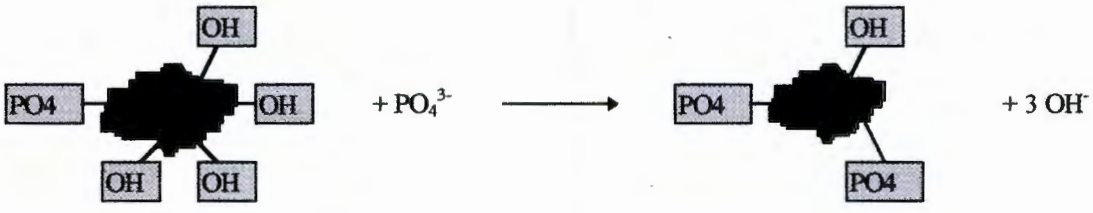
7.1.1.3 Precipitation of $Fe_rPO_4(OH)_{3r-3}$ (s) only

Since ferric hydroxide-phosphate is very insoluble and considered to form "preferentially" to ferric hydroxide, a boundary could be defined between the condition of no precipitation (i.e. neither precipitate but only soluble iron-phosphate complexes present) and the onset of precipitation (i.e. the limiting case of only a minuscule amount of ferric hydroxy-phosphate precipitate forming). Since the equation describing this limiting case could not be expressed explicitly, an implicit form had to be derived by tedious algebraic manipulations based on assumed solubility and dissociation constant values and the equilibrium equations for the respective species over a range of the two variables, iron dose ($c_{Fe,\ dose}$) and initial (or influent) dissolved ortho P concentration ($c_{p,in}$).

[3] The double asterisk is used to indicate equilibrium concentrations of P or Fe under conditions of *co- precipitation*.

7.1.1.4 Adsorption

Using the precipitation model described above, Luedecke *et al.* (1989) calculated equilibrium (residual) ortho P concentrations ($c_{p,eq}$) for a range of Fe(III) doses likely to be encountered in activated sludge systems. Batch tests were carried out with activated sludge samples dosed with ortho P and ferric (iron III) chloride in the same range. Comparing calculated and experimentally observed data, they found that the observed $Fe_{dose}/P_{removed}$ (Fe/P) ratios were consistently *lower* than the calculated ratios in the range where $c_{p,eq}$ was low (ca. < 0.5 mgP/ℓ). This discrepancy was postulated to be due to adsorption of phosphate on the formed precipitate. Luedecke *et al.* (1989) further postulated that adsorption of phosphate ions occurs onto *both* ferric hydroxy-phosphate and ferric hydroxide (if present in the system). The concentration of adsorbed phosphate is proportional to the amount of adsorbing precipitate and remains in equilibrium with the residual phosphate and hydroxide concentrations. By lumping the two types of precipitate, Luedecke *et al.* (1989) proposed a simple mass transfer model to describe the adsorption reaction, in which the key unknown is the adsorption coefficient (k_a):



$$c_{p,\,ads} = K_a \,.\, X_a \,.\, [PO_4^{3-}]_{res} / [OH^-] \qquad \text{..... Eqn 7.6}$$

where : $c_{p,\,ads}$ is the concentration of ortho P adsorbed on the precipitate

K_a is the adsorption coefficient

X_a is the concentration of precipitate in the system, calculated from the sum of the concentration of iron precipitated (in the case of ferric hydroxide) and P precipitated (in the case of ferric hydroxy-phosphate), adjusted for the number of hydroxyl groups available (i.e. 1 per Fe for ferric hydroxide; (3r-3) per Fe for ferric hydroxy phosphate); and

$PO_4^{3-}{}_{res}$ (or $c_{p,res}$) is the residual ortho P concentration determined analytically as "dissolved".

In summary, the complete model of Luedecke *et al.* (1989) consists of equilibrium equations describing the reactions of orthophosphate species dissociation and iron complexation with phosphate or hydroxide, mass balance equations for phosphate and iron, equations defining the split between the type of precipitate formed at a given pH and an associated adsorption equilibrium. After solving these equations, it is possible to obtain the value of dissolved orthophosphate ($c_{P,eq}$) in equilibrium with the precipitate(s) for a given pH, initial phosphate concentration and Fe(III) dose. $c_{P,eq}$ is then further partitioned between an adsorbed fraction ($c_{P,ads}$) and residual fraction ($c_{P,res}$) measured in the dissolved phase:

$$c_{P,eq} = c_{P,ads} + c_{P,res} \qquad \text{..... Eqn 7.7}$$

7.1.1.5 Experimental vs. model results of Luedecke *et al.* (1989) and estimation of unknowns

The model of Luedecke *et al.* (1989) contains four parameters with unknown values:

- the stoichiometric coefficient, r, in $Fe_rPO_4(OH)_{3r-3}$
- the solubility product, K_{sp}, for $Fe_rPO_4(OH)_{3r-3}$
- the equilibrium (stability) constant (K_{fp}) for the iron-phosphate complex $FeH_2PO_4^{2+}$ (see footnote[4]) and
- the adsorption coefficient (K_a).

Luedecke *et al.* (1989) evaluated these unknowns from the experimental results of batch and continuous tests for simultaneous dosing of ferric chloride to activated sludge under aerobic conditions with strict pH control (pH 7.2 for continuous tests and either pH 6.8, 7.2 or 8.0 for batch tests). The experiments took into account the observation that during the first hour of aeration, hydrolysis of complex forms of phosphate (mainly of particulate origin) to dissolved orthophosphate occurred.

Luedecke *et al.* (1989) found good agreement between the observed and calculated (model) results. All the observed $Fe_{dosed}/P_{removed}$ curves (Figs. 7.2a through c) exhibited the following common features:

- moving from high (ca. 6 mgP/ℓ) to lower (ca. 0.5 to 2 mgP/ℓ) residual ortho P concentrations, there was a slow increase in the Fe/P ratio during the period when only ferric hydroxy-phosphate precipitation was predicted. The fact that the Fe/P ratio was not constant in this region prior to ferric hydroxide formation implied that the composition of the precipitate was not constant under these conditions. It was interpreted by Luedecke *et al.* (1989) as being consistent with the predictions of their adsorption model. However, they did note that P adsorption onto the biological mixed liquor suspended solids could not be ruled out.;

- a sharp increase in the Fe/P ratio occurred at low P concentrations when ferric hydroxide precipitation commenced.

By means of fitting calculated (model) data (Figs. 7.2a to 7.2c) to the observed values, Luedecke *et al.* (1989) concluded that the composition of ferric hydroxy-phosphate formed in their experimental systems was essentially the same for all pH values. All estimates were distributed around a mean value of r = 2.5 mol Fe/mol P, which gives the empirical formula of $Fe_{2.5}$ PO_4 $(OH)_{4.5}$. The estimated pK_s value for this precipitate was 96.7. This value is much lower than the literature value for $FePO_4$ as strengite (pK_s = 28.7) or amorphous $FePO_4$ (pK_s = 23). From their results, supported by similar data from an independent source, Luedecke *et al.* (1989) concluded that the solubility of ferric (hydroxy) phosphate precipitating in activated systems is much lower than in pure chemical systems.

The mean estimated value for pK_{fp} (see above) was -21.5, although some uncertainty in the range -20.7 to -22.7 was noted for the pH range 6.8 to 8.0 (Luedecke *et al.*, 1989).

Considerable uncertainty arose in estimating the value of K_a at low (6.5) or high (8.0) pH. Less uncertainty in the data was evident in the pH range 6.8 to 7.2, and K_a appeared to be at a minimum at pH ca. 7.0. The combined data gave a mean K_a = 1.68 x 10^{-12} mol^2/ℓ^2 ; in the pH range 6.8 to 7.2, the mean K_a was 0.99 to 1.90 x 10^{-12} mol^2/ℓ^2; and at pH 8.0, the mean K_a was 4.1 x 10^{-12} mol^2/ℓ^2. Luedecke *et al.* (1989) noted that the variation in the value of K_a is probably a reflection that their hypothetical adsorption mechanism is over-simplistic and does not fully describe the actual phenomenon.

[4] The value of the equilibrium constant for the reaction $Fe^{3+} + H_2PO_4^- = FeH_2PO_4^{2+}$ was reported to vary over a wide range in the literature. Since the formation of this complex could control residual ortho P solubility at low pH, the value of this constant was estimated by Luedecke *et al.* (1989) from experimental results. The estimated pK value for this complex was -21.5).

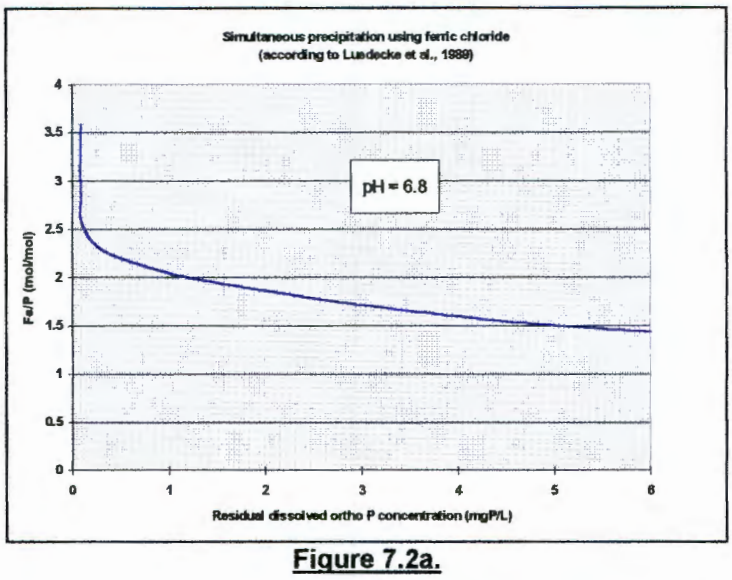


Figure 7.2a.

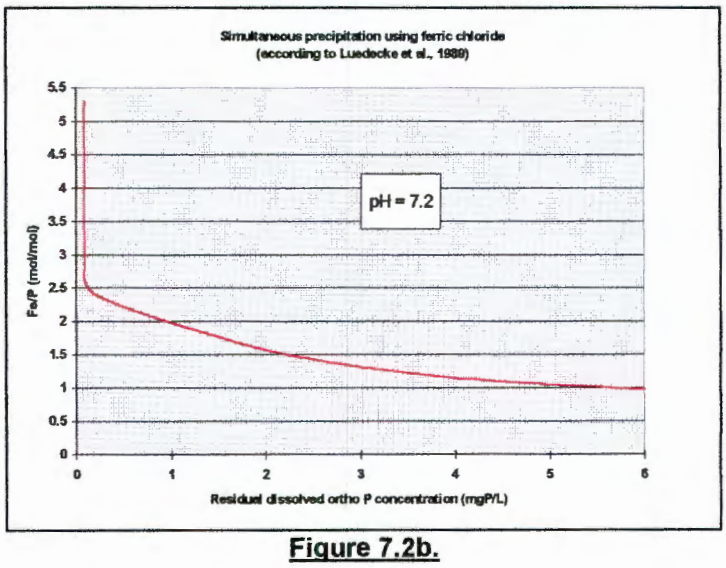


Figure 7.2b.

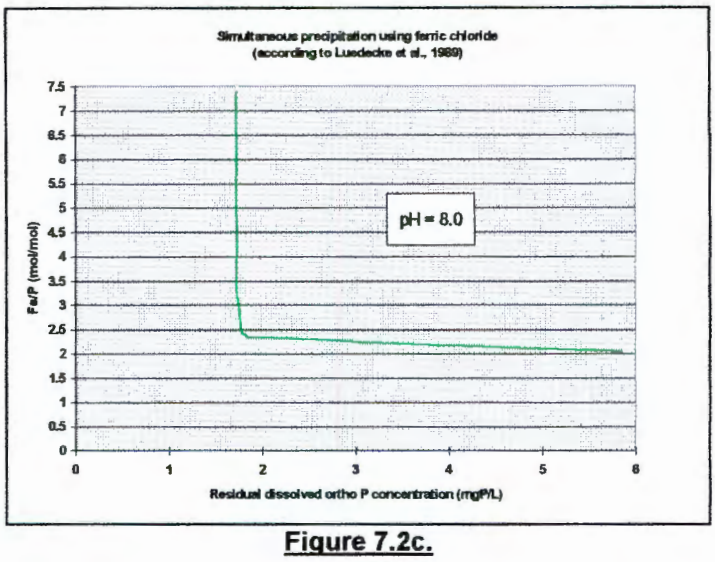


Figure 7.2c.

Figures 7.2a to 7.2c: Fe(dosed)/ P(removed) ratios as a function of residual ortho P concentrations. See Luedecke *et al.*, 1989, for full data sets (observed and calculated).

7.1.2 The chemical model of Briggs (1996)

Using the steady-state model of Luedecke *et al.* (1989) as a starting point, Briggs (1996) developed a model describing simultaneous P removal in activated sludge systems. Following its development, Briggs (1996) incorporated this precipitation model into a dynamic activated sludge simulation program and tested its effectiveness. As will be seen by comparison in section 7.2 below, the modelling approach used by Briggs (1996) for the chemical P removal processes was more fundamental than the chemical precipitation processes incorporated in the IAWQ ASM Model No. 2 (IAWQ, 1995). Therefore, the model of Briggs (1996) warrants detailed examination in order to draw comparisons later in this chapter[5].

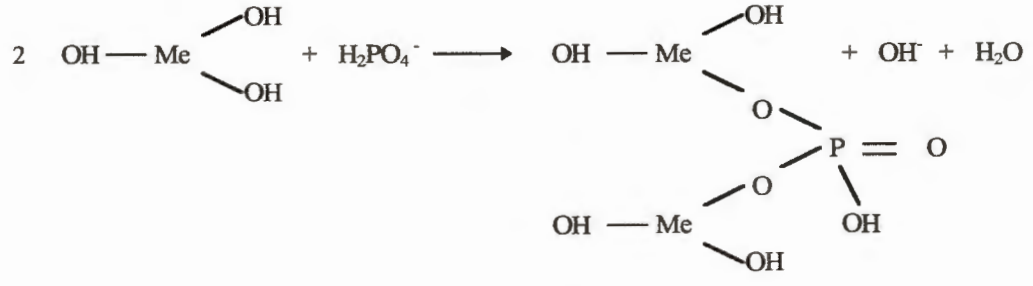
7.1.2.1 Basis of the Briggs chemical model

Certain fundamental assumptions in the Briggs (1996) model of chemical P removal were based on the work of Luedecke *et al.* (1989), namely:

- Chemical reactions at the point of metal salt addition are assumed to be instantaneous;
- Phosphate is removed through the ("preferential") formation of metal hydroxy-phosphate precipitate;
- Once a critical (low) residual phosphate concentration is reached, metal ions which are surplus to the precipitation of metal hydroxy-phosphate will precipitate as metal hydroxide. This has the apparent effect of significantly increasing the ratio of metal (dosed): P (removed) ;
- The degree of phosphorus removal is dependent on two main factors: the metal:P ratio at the point of addition and the final pH after metal salt addition;
- At high dosages, when both hydroxy-phosphate and hydroxide precipitates are present, the residual phosphate concentration is strongly influenced by pH; and
- Adsorption of phosphate onto metal hydroxide (or metal hydroxy-phosphate) precipitate can be used to "make up the difference" between precipitation predictions and experimental results.

As further evidence that adsorption is an important chemical P removal mechanism, Briggs (1996) cited the work of Rabinowitz and Marais (1980) and Siebritz *et al.* (1983) which showed that simultaneously dosed activated sludge systems showed a "persistence effect" in that low effluent P concentrations could be maintained for a number of days after metal salt addition was discontinued. However, Briggs (1996) also pointed out that no studies appear to have isolated and reviewed adsorption as a chemical removal mechanism *per se* in activated sludge systems. On the other hand, many studies have been reported for phosphate removal in soil, including adsorption to ferric hydroxide (or goethite, FeOOH) and aluminium hydroxide (gibbsite, $AlOH_3$). From review of the soil science literature, Briggs (1996) drew the following conclusions:

- Phosphorus adsorption involves replacement of hydroxyl groups with orthophosphate ions, and phosphate groups tend to form bonds which bridge between two adjacent metal oxide molecules. The general mechanism can be represented as :



[5] A summary of the Briggs model is also given by Dold and Briggs (1995).

- Adsorption capacity for phosphate on metal hydroxide appears to reduce with time. For example, for ferric hydroxide, one study showed a reduction from 1.5 mol $P_{adsorbed}$ /mol Fe to 0.2 mol $P_{adsorbed}$ /mol Fe after ageing the precipitate for 1 day.
- There is evidence that the kinetics of adsorption on metal hydroxides shows an initial rapid adsorption (e.g. over the first day), followed by a slower adsorption period. Some studies have attempted to describe the kinetics as two first order reactions. Others have recommended use of an Elovich-type equation for this purpose. According to Briggs (1996), the general form of the Elovich equation is:

$$\frac{dq}{dt} = a \exp(bq) \quad \text{..... Eqn. 7.8}$$

where:
q = mass of adsorbate (i.e. P) taken up per unit solid mass (i.e. metal hydroxide)
a = a constant relating to the initial rate of the adsorption reaction
b = a constant relating to the activation energy for adsorption

The development the Elovich-type equation in this context assumes that the activation energy increases linearly as a function of q (i.e. giving a relatively high rate of adsorption when q is small, tapering off as q increases).

7.1.2.2 Influent phosphorus fractions

In order to integrate the chemical, precipitation model into the biological model, Briggs (1996) proposed fractions for the influent phosphorus along similar lines to that for nitrogen in the IAWQ ASM Models (Nos. 1 and 2). Five influent phosphorus fractions were proposed, collectively comprising the influent total P, namely: soluble ortho P (P_{Pi}); soluble unbiodegradable organic P (P_{ui}), particulate unbiodegradable organic P (P_{xi}); particulate biodegradable organic P (P_{ei}); and soluble biodegradable organic P (P_{oi}). Ortho P (P_{pi}) is readily determined colorimetrically after filtration (e.g. Standard Methods, 1985). Phosphorus other than ortho P is considered to be organic P, in four sub-fractions (P_{ui}, P_{xi}, P_{ei}, P_{oi}). P_{ui} is considered to be negligible (Briggs, 1996). P_{xi} is modelled as a fraction of the inert particulate influent COD (X_{ii}), based on the total P/VSS ratio (converted to total P/COD) for biomass not exhibiting excess biological P removal capacity (e.g. 0.025 mgP/mg VSS). P_{ei} is modelled as a fraction of the slowly biodegradable (particulate) COD fraction. P_{oi} is found from the difference:

$$P_{oi} = P_{ti} - P_{Pi} - P_{ei} - P_{ui} - P_{xi}$$

7.1.2.3 Precipitation processes

In view of the lack of consensus on the types of precipitate formed during phosphorus precipitation using metal salts in wastewater systems, Briggs (1996) followed the approach of Luedecke *et al.* (1989) and adopted the general formula for a fictitious precipitate as the basis for an equilibrium model. The equilibrium expression for the fictitious precipitate may be written as (c.f. Eqn 7.1):

$$r\,Me^{3+} + PO_4^{3-} + (3r-3)\,H_2O \leftrightarrow Me_rPO_4(OH)_{3r-3} + (3r-3)\,H^+ \quad \text{..... Eqn. 7.9}$$

In Eqn. 7.9, Me^{3+} is the trivalent metal ion. The value of r can be adjusted to represent the stoichiometry of precipitation, typically determined at high initial P: low metal dose ratios (e.g. in jar tests).

At high metal dose: P ratios, metal hydroxide co-precipitation is expected, thereby reducing the stoichiometry of overall P removal:

$$Me^{3+} + H_2O \leftrightarrow Me(OH)_3 + H^+ \quad \text{..... Eqn. 7.10}$$

7.1.2.4 Point of addition of metal salt

For the sake of simplicity, the precipitation model of Briggs (1996) was only developed for a metal salt addition point immediately following the aeration basin. This should be analogous to addition in the aeration tank itself under ideal completely mixed conditions. The aeration basin or the line from the aeration basin to the secondary clarifiers are the most common dosing points. For modelling purposes, these points also have the advantage that the concentration of complexing organics is low and most of the soluble phosphorus is in the ortho P form (i.e. biological hydrolysis of organic P and biological P uptake are essentially complete).

7.1.2.5 Precipitation processes and equilibrium considerations

Briggs (1996) applied a first order expression which relates P removal through precipitation to the initial metal: P ratio. This expression was used by Narasiah *et al.* (1991) to model simultaneous precipitation with ferric chloride or alum as an empirical exponential decline expression. It relates the residual phosphorus concentration after precipitation to the initial metal:P ratio at the point of chemical dosing:

$$\frac{P_r}{P_{P0}} = e^{-\alpha(Me_0:P_{P0})} \quad \text{..... Eqn. 7.11}$$

where P_r = residual (ortho) P concentration (mgP/ℓ)
P_{P0} = initial (ortho) P concentration (before precipitation) (mgP/ℓ)
$Me_0:P_{P0}$ = ratio of metal (dosed) to initial (ortho P) concentration (mgMe/mgP)
α = constant relating to stoichiometry of removal (mg P/mg Me)

Equation 7.11 was re-written in linear form and a second constant introduced:

$$\ln (P_r/P_{P0}) = \ln\alpha_1 - \alpha_2.(Me_0:P_{P0}) \quad \text{..... Eqn. 7.12}$$

where α in Eqn. 7.11 becomes α_2, and α_1 (mgP/mgP) relates to the minimum metal dose required to initiate precipitation. At low dosage, where $\alpha_2.(Me_0:P_{P0}) < \ln \alpha_1$, Eqn 7.12 will predict $P_r > P_{P0}$ (impossible), implying that no P is precipitated. The value of α_1 is expected to vary, depending on wastewater characteristics, with numerous authors indicating that increased metal dosages are required to initiate precipitation in pre-precipitation systems. In such applications, the value of α_1 is expected to be greater than unity. However, for simultaneous (or post) precipitation applications, where the concentration of metal-complexing organics in the soluble phase is expected to be negligible, Briggs (1996) assumed the value of α_1 to be unity.

Under certain conditions (typically at high dose ratios of metal: P and/or low pH), the residual ortho P concentration may be controlled by equilibrium (i.e. solubility of the precipitate becomes significant). Under these conditions it is necessary to replace the residual ortho P concentration (P_r) in Eqn. 7.11 with the equilibrium residual predicted from the solubility products. In order to cater for this, Briggs used the term P_P^* for the residual ortho P concentration. Taking this into account, and rewriting Eqn. 7.12 in exponential form, Eqn. 7.13 is obtained:

$$P_P^* = \alpha_1 . P_{P0} . e^{-\alpha 2.(Me_0/P_{P0})} \quad \text{..... Eqn. 7.13}$$

The minimum (pH dependent) residual ortho P and metal concentrations derived by the solubility products of the precipitates were calculated by Briggs (1996) from Eqns 7.14 and 7.15:

$$K_{MeP} = [Me^{3+}]^r [PO_4^{3-}] [OH^-]^{3r-3}$$

$$K_{MeH} = [Me^{3+}] [OH^-]$$

Substituting:

$$[Me^{3+}] = K_{MeH} / [OH]^3 \quad \text{..... Eqn. 7.14}$$

$$[PO_4^{3-}] = K_{MeP} / (K_{MeH}{}^r). [OH]^3 \quad \text{..... Eqn. 7.15}$$

By means of equilibrium relationships, total (soluble) metal and ortho P concentrations can be derived from $[Me^{3+}]$ and $[PO_4^{3-}]$ in Eqns. 7.14 and 7.15. Briggs (1996) defined this ortho P concentration as the *minimum equilibrium concentration of ortho P with both solids present* ($P_{P\,res}$) and represents the *absolute minimum phosphorus residual which can be achieved at any given pH*. Hence, the ortho P residual concentration (P_P*) predicted by Eqn. 7.13 *must never be less than* $P_{P\,res}$. Mathematically this condition can be satisfied by the expression:

$$P_P^* = \max \{\alpha_1 . P_{P0} . e^{-\alpha 2 . (Me/P_{P0})} , P_{P\,res}\} \quad \text{..... Eqn. 7.16}$$

The equilibrium expressions for $P_{P\,res}$ (as mgP/ℓ) and equilibrium soluble metal concentration Me_T (as mg Me/ℓ) are given in Eqns. 7.17 and 7.18 (see footnote [6]).

$$P_{P\,res} = 1000.AM_P .[PO_4^{3-}]\{1+ [H^+]/k_{p,3} + [H^+]^2/(k_{p,2}. k_{p,3}). (1+ k_{MHP}[Me^{3+}]) + [H^+]^3/(k_{p,1}.k_{p,2}.k_{p,3})\} \quad \text{..... Eqn. 7.17}$$

$$Me_T = 1000.AM_{Me} .[Me^{3+}]. \{1+ k_{Me,1}/[H^+] + k_{Me,2}/[H^+]^2 + k_{Me,3}/[H^+]^3 + k_{Me,4}/[H^+]^4 + k_{MHP}. [PO_4^{3-}].[H^+]^2/(k_{p,2}. k_{p,3})\} \quad \text{..... Eqn. 7.18}$$

where AM_P and AM_{Me} are the atomic masses of phosphorus and the metal (in g/mol)
and $k_{p,1}$, $k_{p,2}$,..... k_{MHP} etc. are defined in Table 7.1.

Table 7.1: Equilibrium relationships and constants used by Briggs (1996).

Reaction	Equilibrium constant	pK Al^{3+} salts	pK Fe^{3+} salts
$H_3PO_4 \leftrightarrow H_2PO_4^- + H^+$	$k_{p,1}$	2.1	2.1
$H_2PO4^- \leftrightarrow HPO4^{2-} + H^+$	$k_{p,2}$	7.2	7.2
$HPO4^{2-} \leftrightarrow PO_4^{3-} + H^+$	$k_{p,3}$	12.3	12.3
$Me^{3+} + H_2PO_4^- \leftrightarrow MeH_2PO_4^{2+}$	k_{MHP}	-6.0	-21.5 [7]
$Me^{3+} + H_2O \leftrightarrow Me(OH)^{2+} + H^+$	$k_{Me,1}$	5.0	3.0
$Me^{3+} + 2H_2O \leftrightarrow Me(OH)_2^+ + 2H^+$	$k_{Me,2}$	8.7	6.4
$Me^{3+} + 3H_2O \leftrightarrow Me(OH)_3^0 + 3H^+$	$k_{Me,3}$	15.2	13.5
$Me^{3+} + 4H_2O \leftrightarrow Me(OH)_4^- + 4H^+$	$k_{Me,4}$	23.3	23.5

Having solved for P_P* and Me_T (= Me *) using Eqns. 7.14 through 7.18, it is possible to calculate the amounts of metal hydroxy-phosphate (X_{MeP}) and metal hydroxide (X_{MeH}) precipitate formed though mass balances (Briggs, 1996):

$$X_{MeP} = MW_{MeP}/MW_P . (P_{P0} - P_P^*) \quad \text{..... Eqn. 7.19}$$

$$X_{MeH} = MW_{MeH}/MW_{Me} (Me_0 - r.MW_{Me}/MW_P.(P_{P0} - P_P^*) - Me^*) \quad \text{..... Eqn 7.20}$$

where P_{P0} and P_P* (in mgP/ℓ) are defined above
MW implies molecular weight (g/mol)
Me_0 = initial metal concentration (dosed) (in mg Me/ℓ)
X_{MeP} = concentration of metal hydroxy-phosphate formed (mg/ℓ)
X_{MeH} = concentration of metal hydroxide formed (mg/ℓ)

[6] Briggs appeared to have used both terms (Me* and Me_T) to describe the same residual equilibrium metal concentration.
[7] During model testing Briggs (1996) found that this constant required adjustment to pK = -17.5. The reason for this was the use of the solubility product of $Fe(OH)_3$ by Briggs (1996) rather than that for FeOOH used by Luedecke *et al.* (1989).

- As an alternative, the solubility product for aluminium hydroxide could have been decreased, thereby "freeing" more aluminium which would precipitate phosphate and decrease the equilibrium ortho P residual concentration. However, this adjustment was not made since the equilibrium aluminium residuals were considered to be in the correct range (ca. 0.1 mg/ℓ as Al);
- Good prediction of VSS and TSS (or MLSS) concentrations was obtained over the range of sludge ages tested, noting that the masses of chemical sludges (metal phosphate and metal hydroxide precipitates) were included in the TSS predictions[16];
- The waters of hydration of the chemical precipitates could affect TSS predictions to a significant extent. Briggs used the formula $AlPO_4.2H_2O$ for aluminium phosphate and $Al(OH)_3$ for aluminium hydroxide. The aluminium hydroxide precipitate shows more impact on the TSS predictions than aluminium phosphate, for two reasons: Firstly, the relative proportion of metal phosphate to TSS in the system is small (limited by influent available P); and secondly, the relative contribution of each water of hydration to the molecular weight of the precipitate is greater for $AlOH_3$ (MW= 78 g/mol) than for $AlPO_4$ (MW = 122 g/mol).
- Changing the phosphate precipitation efficiency parameter (α_2 in Eqn. 7.16) only affects the ortho P residual concentration when the latter is not equilibrium-controlled (i.e. when $P_P^* > P_{P\,res}$). Increasing α_2 can result in lower ortho P residuals and can result in the system becoming equilibrium-controlled. Decreasing α_2 has the opposite effect. Briggs (1996) found the default value of $\alpha_2 = 1.41$ for alum (see 7.1.3.1 above) gave satisfactory agreement with observed effluent TP data.
- Results indicated that neither the adsorption nor the dissociation kinetics had any effect on model predictions. This was ascribed by Briggs to the low adsorption maximum for phosphorus onto the $Al(OH)_3$ precipitate, q_{mM}. (Presumably the mass of metal phosphate precipitate in the system was too small to be significant in phosphorus adsorption). Doubling or halving the value of q_{mM} had no impact on the effluent ortho P (or TP) predictions since a very small default adsorptive capacity for the $Al(OH)_3$ precipitate had been assumed ($q_{mM} = 2 * 10^{-4}$, see Table 7.5). This implies that adsorption plays a minor role in the chemical model as proposed by Briggs (1996).

7.1.4 Conclusions from the Briggs (1996) model

The model proposed by Briggs (1996) is useful in that it originates from first principles of phosphate equilibrium chemistry, with kinetic expressions introduced for certain processes (notably, organic phosphate hydrolysis; metal hydroxide precipitation and dissociation; metal hydroxy-phosphate dissociation; and adsorption). Although little attention has been paid in this review to the aspect of pH, the equilibrium approach makes it possible to model the link between pH and phosphate precipitation directly - a link which is important and well established. However, the equilibrium approach introduces considerable complexity to the chemical model. It is necessary to examine whether this complexity can be justified in terms of the certainty over predicted results and the potential for an equilibrium chemical precipitation model of this type to be integrated into the larger (and already complex) kinetic model for biological excess P removal in modified activated sludge systems.

[16] It appears that Briggs (1996) did not take into account that the measured ISS (i.e. by ashing) and calculated ISS are expected to differ for ferric hydroxide. Assuming the formula of $Al(OH)_3$ for residual aluminium hydroxide accumulating in the mixed liquor solids, upon ashing the hydroxide form may be expected to convert to the oxide form, Al_2O_3 :

$$2\,Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O$$

Based on the change in molecular weight a conversion factor (102/156 = 0.65) should be applied for the calculated aluminium hydroxide contribution to ISS in the model. Since good agreement between the model calculations and measured TSS were reported by Briggs (1996) assuming a default molecular weight of 78 for $Al(OH)_3$ contribution to the TSS, it appears that the magnitude of aluminium hydroxide contribution to the TSS was relatively small (ca. 6%) for the test case of Mid-Halton Works.

7.1.3.2 Adsorption kinetics and stoichiometry

The Elovich-type equations used by Briggs (1996) for describing phosphate adsorption to metal hydroxy-phosphate and metal hydroxide were given respectively in Eqns. 7.23 and 7.24. In these equations, two main constants control the rate of adsorption: a_m and b_m. According to Briggs (1996), b_m affects mainly the *slope* of the rate curve (i.e. phosphate residual or phosphate adsorbed versus time) during the initial phase of rapid adsorption when the ratio of adsorbed P to mass of precipitate is relatively small. a_m affects the overall magnitude of the rate and is mainly relevant to the latter phase of slower adsorption. Data from the literature examined by Briggs (1996) suggested that the initial phase of rapid adsorption takes place in a matter of minutes, followed by a slower rate over several days. The equation proposed by Briggs (1996) (Eqn. 7.23) was not able to model the first very rapid phase of adsorption over a time frame as brief as in the experimental data, but a rapid phase over the first day, followed by a declining rate over several days was predicted. The default values of a_m and b_m accepted by Briggs (1996) are given in Table 7.5, along with adsorption maxima (q_{mM}) derived from literature data.

Table 7.5: Default parameters for adsorption, according to Briggs (1996).

Precipitate	a_m mgP/mg $Me(OH)_3$	b_m mg $Me(OH)_3$/ mgP	q_{mM} mgP/mg $Me(OH)_3$
Aluminium hydroxide	0.15	169	$2.0 * 10^{-4}$
Ferric hydroxide	0.10	300	$3.1 * 10^{-2}$

7.1.3.3 Calibration to the Mid-Halton plant (by Briggs, 1996)

Mid-Halton Wastewater Treatment Facility was reported by Briggs (1996) to consist of primary sedimentation followed by a fully aerobic step-feed activated sludge process in four stages with simultaneous alum addition in the last aeration tank. On the basis of average monthly data, the sludge age was calculated to vary from 2.1 to 6.6 days. Nitrification was not reported by Briggs (1996).

Briggs (1996) used an earlier version of the IAWQ (IAWPRC) model for COD, VSS and MLSS predictions (Henze, 1987). Phosphorus removal was based on largely the chemical model described above, *without consideration of BEPR mechanisms*. The only biological components affecting the model are:

- incorporation of so-called "inert particulate P" fraction expressed on the basis of the influent (P_{xi}) and modelled as a fixed 2.5% of the biomass VSS;
- hydrolysis of particulate biodegradable organic P (P_e) to soluble biodegradable ortho P (P_o) at the same rate as the hydrolysis of particulate (slowly) biodegradable COD in the same manner as in the IAWQ (IAWPRC) model;
- followed by hydrolysis of soluble biodegradable ortho P (P_o) to ortho P (P_p), modelled as a simple first order decay reaction with a rate constant of k_{rp}.

For Mid-Halton works, this approach was satisfactory in that BEPR would not be expected in a completely aerobic activated sludge process.

The modelling results for Mid-Halton were satisfactory. The following observations were made by Briggs (1996) from calibration to experimental data and sensitivity analysis:

- The hydrolysis rate constant (k_{rp}) for conversion of P_o to ortho P (P_P) needed to be increased in order to reduce the proportion of P_o in the effluent. The effect of k_{rp} on the effluent total P was small in absolute terms but it did affect the relative proportions of P_o and P_P predicted in the effluent, especially since the observed ortho P residual was low (<0.5 mgP/ℓ).
- The solubility product for $AlPO_4$ had to be increased to 22.2 (see footnote 13) in order to reduce the equilibrium ortho P residual concentration predicted in relation to the actual plant data;

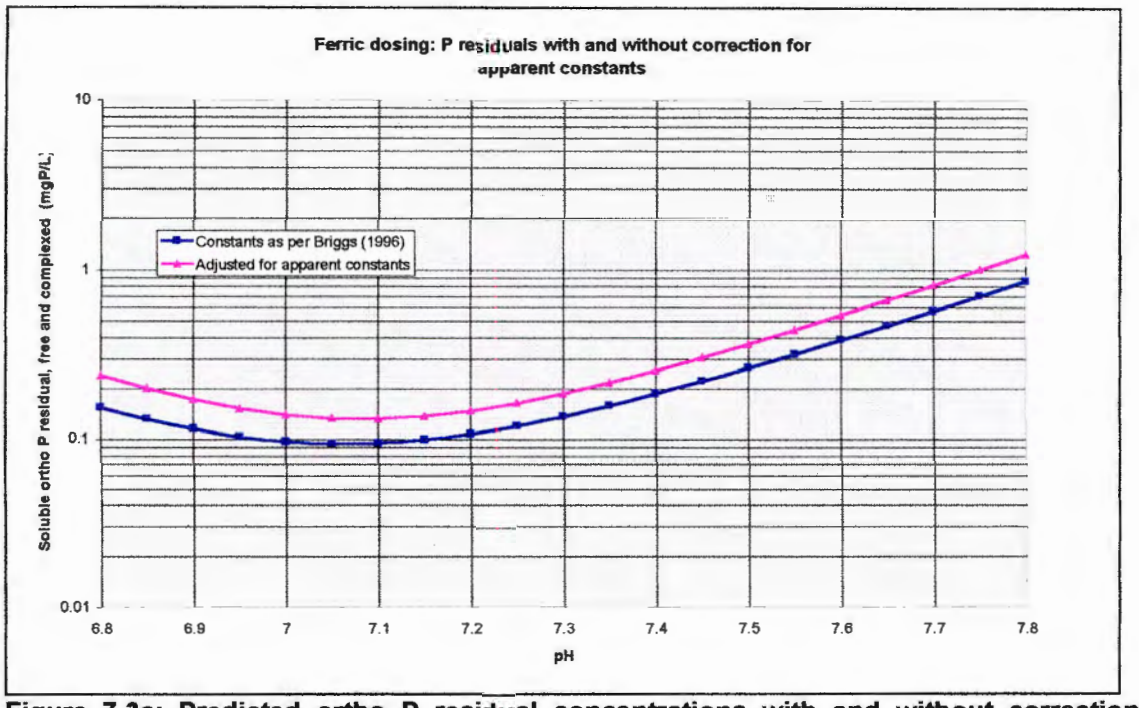


Figure 7.3c: Predicted ortho P residual concentrations with and without correction to apparent solubility product and equilibrium constant data using the Briggs (1996) chemical equilibrium precipitation model for ferric chloride (without adsorption).

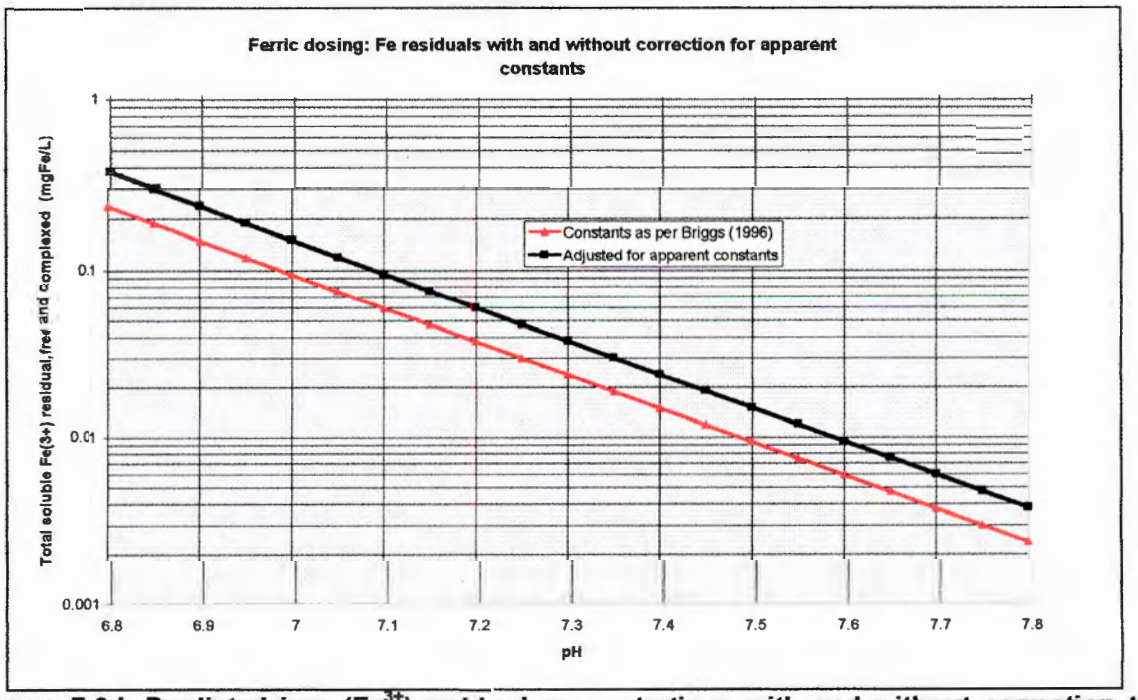


Figure 7.3d: Predicted iron (Fe^{3+}) residual concentrations with and without correction to apparent solubility product and equilibrium constant data using the Briggs (1996) chemical equilibrium precipitation model (without adsorption) for ferric chloride.

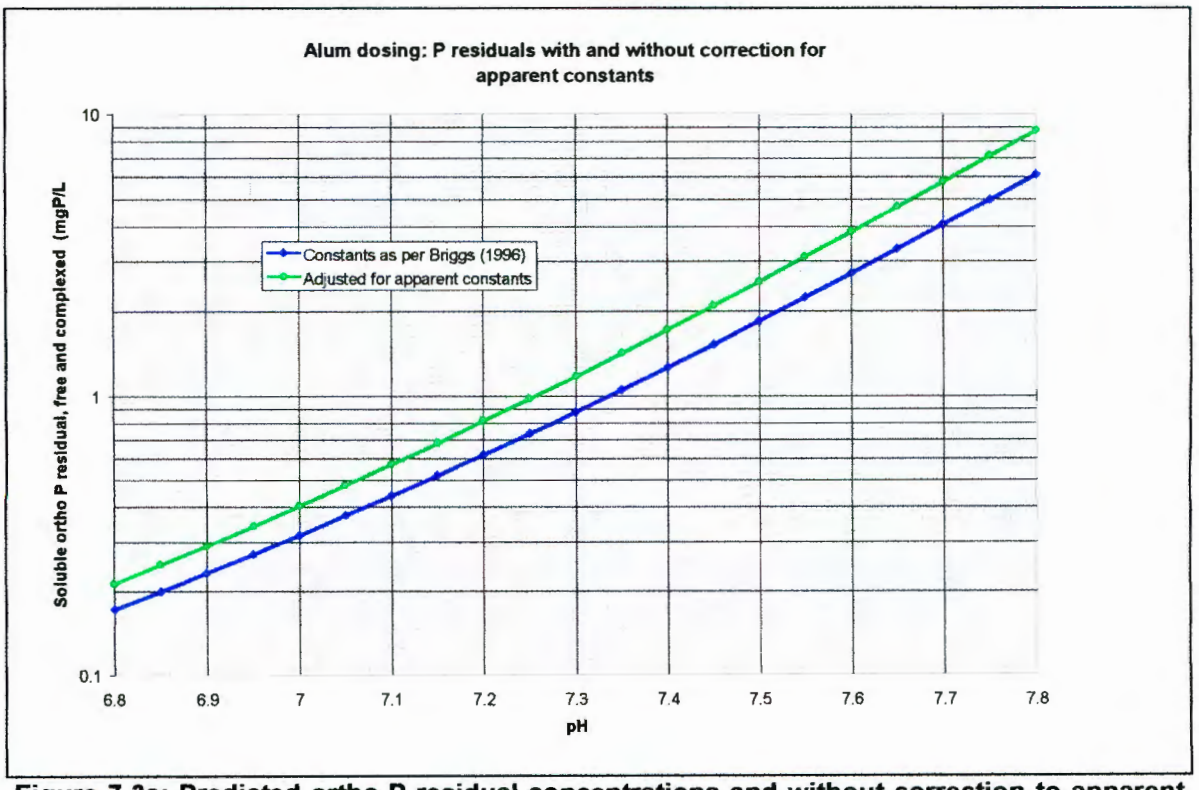


Figure 7.3a: Predicted ortho P residual concentrations and without correction to apparent solubility product and equilibrium constant data using the Briggs (1996) chemical equilibrium precipitation model for alum (without adsorption).

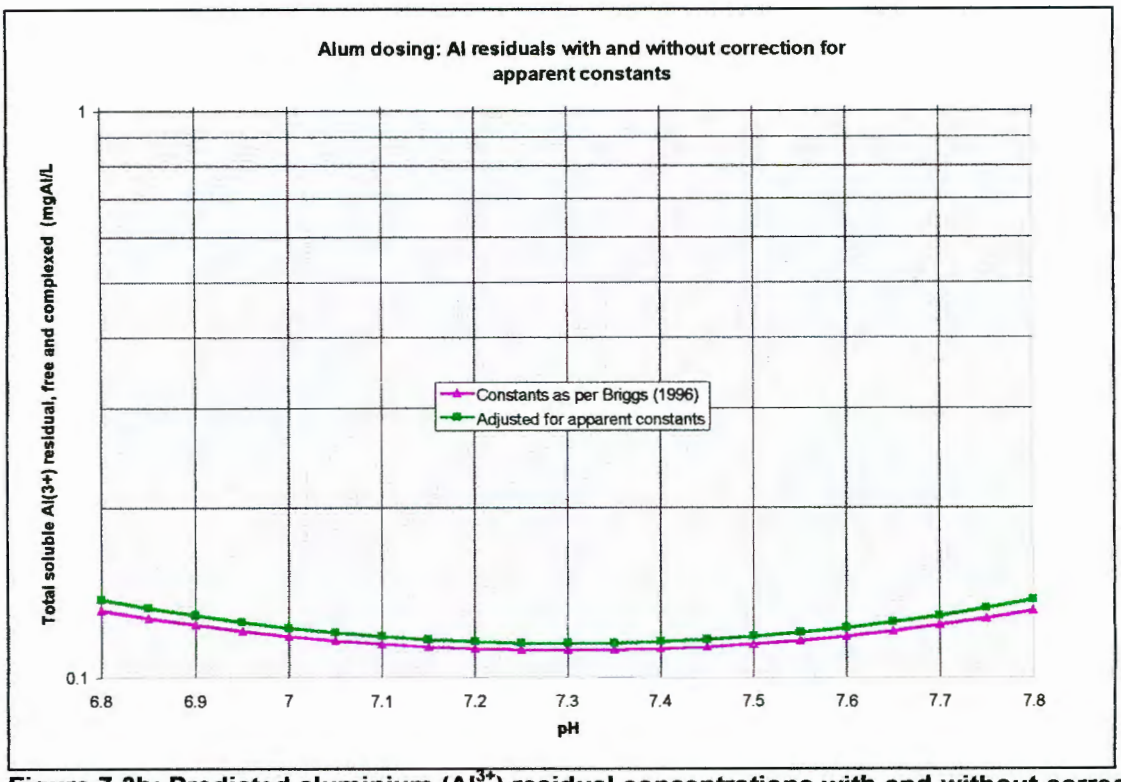


Figure 7.3b: Predicted aluminium (Al^{3+}) residual concentrations with and without correction to apparent solubility product and equilibrium constant data using the Briggs (1996) equilibrium precipitation model for alum (without adsorption).

The effect of using the apparent constants is shown in Figs. 7.3 (a&b) for alum and in Figs. 7.3 (c&d) for ferric salts.

From Figs. 7.3 (a to d) it can be seen that the effect of correcting for apparent solubility products and equilibrium constants is to increase the residual ortho P and metal concentrations. However, the changes are relatively small. The biggest difference found (Fig. 7.3a) was for alum at pH 7.8, giving a change in $P_{p\,res}$ = 2.7 mgP/ℓ; at pH 6.8 the change was only 0.04 mgP/ℓ. For ferric salt the corresponding changes ranged from approx. 0.1 mgP/ℓ (pH 6.8) to 0.4 mgP/ℓ (pH 7.8). The changes in soluble metal residual were negligible for alum (0.01 mg/ℓ as Al) and minor for ferric salt (<0.14 mg/ℓ as Fe). Accordingly, on the basis of Figs. 7.3 (a to d), the need to correct from theoretical to apparent solubility product and equilibrium constant data appears to be insignificant at an ionic strength of 0.01 (TDS approx. 400 mg/ℓ).

Figs. 7.3a to 7.3d...../

In his model, for both alum and ferric salt addition, Briggs (1996) opted for using the simple $MePO_4$ solubility products rather than those of the more complex metal hydroxy-phosphate, on the basis that similar (low) phosphate residuals are predicted using Eqns 7.14 and 7.15 as a function of pH. Following determination of $[PO_4^{3-}]$ from solubility products and pH, the total equilibrium phosphate residuals can be estimated as a function of pH using the complexes and equilibrium constants given in Table 7.1. According to Briggs (1996), the $MePO_4$ solubility product was "adjusted slightly" to provide residual phosphate predictions similar to those published in the literature [12]. Similarly, the $Me(OH)_3$ solubility product was "manipulated about the average value" (presented in Table 7.2) to provide metal equilibrium residuals of approximately 0.1 mg/ℓ in the range 6.5 to 7.5 to mimic residuals reported in the literature. The need for manipulations of this kind by Briggs (1996) illustrates that literature values for the various constants in the chemical model cannot be applied directly in all cases; a degree of calibration is required, based on actual experimental results for the particular system under study.

Briggs (1996) did not report the use of apparent solubility products or apparent equilibrium constants in his work. Apparent constants can be derived from the literature data in 7.1 and 7.2 using Debye-Hückel theory (Loewenthal and Marais, 1976). The resultant values are given in Tables 7.3 and 7.4 [13].

Table 7.3: Apparent equilibrium constants derived from values reported by Briggs (1996) for ionic strength (μ) = 0.01. ***Compare with Table 7.1***

Reaction	Apparent equilibrium constant	pK' Al^{3+} salts	pK' Fe^{3+} salts
$H_3PO_4 \leftrightarrow H_2PO_4^- + H^+$	$k'_{p,1}$	2.05	2.05
$H_2PO4^- \leftrightarrow HPO4^{2-} + H^+$	$k'_{p,2}$	7.07	7.07
$HPO4^{2-} \leftrightarrow PO_4^{3-} + H^+$	$k'_{p,3}$	12.07	12.07
$Me^{3+} + H_2PO_4^- \leftrightarrow MeH_2PO_4^{2+}$	k'_{MHP}	-5.72	-21.22 [14]
$Me^{3+} + H_2O \leftrightarrow Me(OH)^{2+} + H^+$	$k'_{Me,1}$	5.23	3.23
$Me^{3+} + 2H_2O \leftrightarrow Me(OH)_2^+ + 2H^+$	$k'_{Me,2}$	9.06	6.76
$Me^{3+} + 3H_2O \leftrightarrow Me(OH)_3^0 + 3H^+$	$k'_{Me,3}$	15.61	13.91
$Me^{3+} + 4H_2O \leftrightarrow Me(OH)_4^- + 4H^+$	$k'_{Me,4}$	23.66	23.86

Table 7.4: Solubility product data for metal phosphate and metal hydroxide precipitates from literature sources quoted by Briggs (1996). ***Compare with Table 7.2***

Precipitate	Average pK'sp
$AlPO_4$	21.18 [15]
$Al(OH)_3$	32.75
$FePO_4$	27.18
$Fe(OH)_3$	37.79

[12] Although Briggs (1996) did not state the final values accepted for K_{MeP}, a value of for K_{MeP} (FePO4) = 28.75 was derived by trial-and-error in the formulation of Fig. 7.3c in order to match the model data presented by Briggs (1996).

[13] In these derivations, the ionic strength of real solutions corresponding to the experimental system, must be assumed. For the purposes of deriving the apparent constants in Tables 1.3 and 1.4, an ionic strength (μ) of 0.01 was assumed. This corresponds to a real solution with a TDS of approximately 400 mg/l, which was representative of the effluent TDS for Darvill Wastewater Works in this study.

[14] Using the amended value of -17.5 (Briggs, 1996 - see footnote 5), the apparent constant (k'_{MHP}) becomes -17.22.

[15] Several values for the solubility product of $AlPO_4$ were reported by Briggs (1996). The value of 20.3 (Table 7.2) gives unrealistic results for P_{pres} of 8 to 300 mgP/ℓ in the pH range 6.8 to 7.8. The value of 22.2 accepted by Briggs (1996) (see footnote 7) may correspond to an apparent constant since it was based on calibration against actual experimental results for Mid-Halton Works. For the sake of consistency in Figs. 7.3 (a to d), the value of 22.0 was accepted from Briggs (1996, p88) and was adjusted on the same theoretical basis as the other constants in Tables 7.3 and 7.4 to derive an apparent solubility product of 21.18.

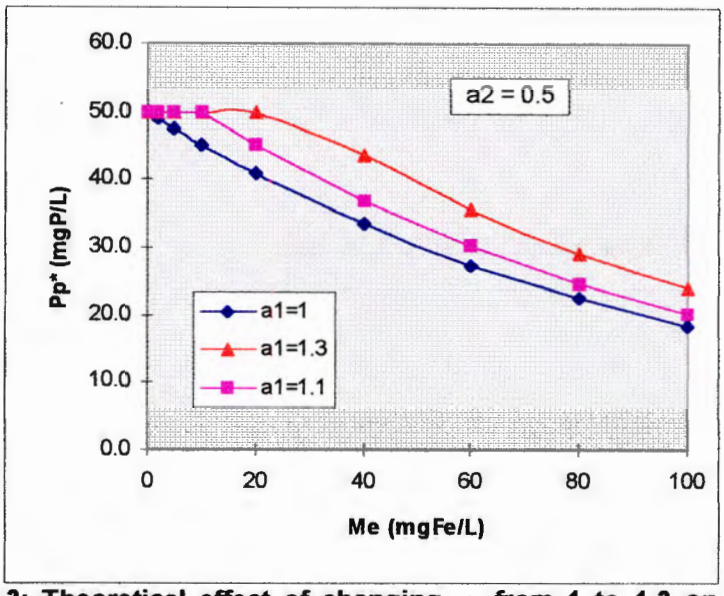


Figure 7.3: Theoretical effect of changing α_1 from 1 to 1.3 on ortho P residual predicted from Eqn. 7.13 for conditions in which P_{p0} = 50 mgP/ℓ and α_2 = 0.5 for ferric chloride dosing, according to Briggs (1996).
***Note:* a1 and a2 represent α_1 and α_2 in Fig. 7.3.**

7.1.3.2 Equilibrium residuals

The (total) soluble ortho P residual is the sum of a number of phosphate species: PO_4^{3-}/ HPO_4^{2-}/ $H_2PO_4^-$/ H_3PO_4 and any soluble metal phosphate complexes which may be present. The relative amount of each complex present in solution is dependent on the solubility products for the chemical precipitates (which control PO_4^{3-} and Me^{3+} as a function of pH) and the equilibrium constants for the soluble phosphate species (which are dependent on pH, and concentrations of PO_4^{3-} and Me^{3+} determined by the solubility products) (Briggs, 1996).

Prediction of equilibrium ortho P residuals is highly dependent on the choice of solubility products and equilibrium constants. Table 7.2 summarises the solubility data obtained from literature sources by Briggs (1996).

Table 7.2: Solubility product data for metal phosphate and metal hydroxide precipitates from literature sources quoted by Briggs (1996).

Precipitate	pK_{sp} range in literature	Average pKsp
$AlPO_4$	20 to 21 [9]	20.3 [10]
$Al_{1.4}PO_4(OH)_{1.2}$	32.2 to 34	32.5
$Al(OH)_3$	33	33
$FePO_4$	28	28
$Fe_{2.5}PO4(OH)_{4.5}$	96.7	96.7
FeOOH	-0.5	-0.5
$Fe(OH)_3$	38 to 38.6	38.2 [11]

[9] Galarneu and Gehr (1997) reported a value of 18.24 for the K_{sp} of $AlPO_4$. However, this leads to the conclusion that the minimum equilibrium ortho P concentration would be 2244 mgP/ℓ for aluminium phosphate precipitation, which appears erroneous. In the light of this, a value of at least 20 for this constant seems more reasonable (see Footnote 9).
[10] After testing the chemical model against actual data from an activated sludge plant with simultaneous alum dosing, Briggs (1996) found that the a pK_{sp} value of 22.2 was required in order to decrease predicted equilibrium ortho P residuals.
[11] The Briggs (1996) model is based on $Fe(OH)_3$ as the form of ferric hydroxide, unlike the model of Luedecke *et al.* (1989) which was based on FeOOH.

$r_7 = r_3 \cdot q_M = P_{aM} / X_{MeH}$ ..... Eqn. 7.26

where P_{aP} and P_{aM} are the concentrations of phosphate adsorbed per unit mass metal hydroxy-phosphate and metal hydroxide, respectively.

7.1.3 Calibration and testing of the Briggs model

Briggs (1996) incorporated the chemical model outlined in section 7.1.2 into a dynamic biological model of activated sludge systems. In order to calibrate the chemical model, Briggs commenced with estimates of the key parameters based on literature results, followed by site-specific calibration to a full-scale wastewater works using simultaneous alum addition. In order to evaluate the suitability of the model for application to the results of this study, it is instructive to examine the calibration steps reported by Briggs (1996).

7.1.3.1 Stoichiometry for metal (hydroxy) phosphate precipitation

Equation 7.13 contains two constants, namely α_1 and α_2. α_1 is essentially a correction factor to account for the minimum dosage required to initiate precipitation (Briggs, 1996). The point has already been made (section 7.1.2.5) that the value of α_1 may be assumed to be unity for simultaneous precipitation processes since the concentration of soluble organics which may complex the added metal ions would be expected to be low, particularly in (or after) the aeration basin.

α_2 relates to the stoichiometry of precipitation. Briggs (1996) derived values for α_2 by fitting Eqn. 7.13 to actual reported precipitation data and model results (e.g. that of Luedecke *et al.*, 1989) and obtained values of 1.40 to 1.42 for dosing with aluminium ions and 0.43 to 0.59 for ferric ions. Furthermore, the data of Luedecke *et al.* (1989) suggested that ferric chloride shows a "lag" at low metal:P ratios, with α_1 = 1.3 giving the best fit (Briggs, 1996). Fig. 7.3 shows the effect that this theoretically could have on Pp*.

This investigation has found that iron doses in the range ca. 5 to 20 mgFe/ℓ as ferric (or ferrous) chloride are likely to be realistic for simultaneous dosing to biological excess phosphorus removal (BEPR) plants. From Fig. 7.3 it is apparent that the uncertainty over α_1 is likely to be particularly significant for modelling chemical precipitation under these conditions since it falls into the range where the "lag" effect may be present. Briggs (1996) assumed α_1 = 1 for alum and only reported model testing for actual plant data with alum dosing, with the result that the α_1 value for ferric ions was not further investigated.

Analysis of Eqns. 7.22 and 7.23 shows that precipitation (r_2) will be turned on when Me > Me* and off when Me < Me*, whereas the converse will be true for dissociation (r_3). Dissociation will also be turned off when no metal hydroxide precipitate (X_{MeH}) is left in the system.

Due to the rapid kinetics of phosphate precipitation/ dissociation, Briggs (1996) assumed that the reactions would be virtually complete after approx. 30 seconds. Phosphate precipitation/ dissociation was modelled in the concentration range ca. 0.5 to 5 mgP/ℓ (a reasonable estimate for most domestic wastewaters), and a default value of k_p = 0.1 sec^{-1} (or 8640 d^{-1}) was accepted. Furthermore, Briggs (1996) assumed that the kinetics of metal hydroxide precipitation would be similar to that for metal phosphate. Hence, the default value for k_m was also set to 8640 d^{-1}. Overall, the precise calibration of these rate constants was considered to be unimportant since the chemical precipitation/ dissociation reactions are much faster than most of the biological processes activated sludge.

7.1.2.8 Rate equations for adsorption/ desorption

Briggs (1996) pointed out that in terms of the Elovich equation (Eqn 7.8) there is no limit to adsorption since no maximum adsorption capacity is defined. That is, even if a maximum adsorption capacity (q_m) is defined, the rate of change of q with time will still be positive, implying that q will continue to increase. Similarly, as ortho P residuals reach zero, phosphate adsorption can still occur in terms of Eqn. 7.8, which is impossible. As one possible solution to this problem, Briggs (1996) incorporated switching functions for adsorption capacity and phosphate residual into Eqn. 7.8, and produced generalised forms of the equation for adsorption onto each of the precipitates, namely metal hydroxy-phosphate and metal hydroxide (Eqns. 7.24 and 7.25 respectively):

$$r_4 = a_P . X_{MeP} . \exp\{-b_P . q_P\} . [P_P/(K_{SP}+P_P)] . [(q_{mP}-q_P)/(K_{sq}+(q_{mP}-q_P)] \quad \text{..... Eqn. 7.23}$$

$$r_5 = a_M . X_{MeH} . \exp\{-b_M . q_M\} . [P_P/(K_{sP}+P_P)] . [(q_{mM}-q_M)/(K_{sq}+(q_{mM}-q_M)] \quad \text{..... Eqn. 7.24}$$

where a_P and a_M = adsorption rate constants (mgP/[mgX.d])
b_P and b_M = constants related to activation energy for adsorption (mgX/mgP)
q_P = mass of phosphate adsorbed per unit mass metal hydroxy-phosphate precipitate (mgP/mgX_{MeP})
q_M = mass of phosphate adsorbed per unit mass metal hydroxide precipitate (mgP/mgX_{MeH})
q_{mP} = maximum adsorption capacity for metal hydroxy-phosphate (mgP/mgX_{MeP})
q_{mM} = maximum adsorption capacity for metal hydroxide (mgP/mgX_{MeH})
K_{sq} = adsorptive capacity switching function constant (mgP/mgX)
K_{sP} = phosphorus switching function constant (mgP/ℓ)

Since the composition of the chemical solids present in the system may vary, the adsorptive capacity of the solids may vary. The adsorptive capacity would be expected to be directly correlated to the number of hydroxyl groups available for exchange - see 7.1.2.1). Uncertainty over the composition of the solids present in the system therefore makes it difficult to quantify the constants q_{mP} and q_{mM}, implying that they will need to be empirically determined or based on an hypothetical precipitate composition. In the case of adsorption onto metal hydroxy-phosphate, it is possible to state that no adsorption will occur when r = 1 (refer to Eqn. 7.9) since no hydroxyl groups will be available on the precipitate. The variables a_P and q_{mP} should be set to zero when r = 1 (Briggs, 1996).

During dissociation of precipitate, any adsorbed phosphate would be desorbed. Therefore, Briggs (1996) modelled the desorption rate as a simple proportion of the rate of dissociation, based on the mass of phosphate adsorbed per unit precipitate:

$$r_6 = r_1 . q_P = P_{aP}/ X_{MeP} \quad \text{..... Eqn. 7.25}$$

7.1.2.6 pH, alkalinity and equilibrium considerations

Briggs (1996) derived equilibrium relationships for pH and alkalinity in order to predict the effect of chemical addition on these parameters and to link the equilibrium pH to the residual ortho P and metal concentrations (using equations 7.14 though 7.18).

For simplicity, the model considerations in this chapter will be confined to those under conditions of *constant pH*. Examination of the pilot plant pH data in Chapters 3, 4 and 5 (Tables 3.11; 4.7; & 5.8) shows that pH generally fluctuated in relatively small range close to neutral (ca. 7.2 to 7.6) in most cases. The reasons for this were that the influent alkalinity was usually supplemented with bicarbonate alkalinity (except in cases where the effect of withdrawal of this supplement was tested), and the metal dosages used were relatively small (see footnote[8]).

7.1.2.7 Rate equations for precipitation/ dissociation

The chemical solids produced in simultaneous precipitation systems will accumulate in the system as inert solids. However, if soluble concentrations of ortho P or metal ion are reduced below the minimum equilibrium concentrations at the prevailing pH, then metal hydroxy-phosphate and/or metal hydroxide will dissociate to maintain equilibrium residuals. Accordingly, Briggs (1996) proposed rate equations for dissociation of the precipitates. Although a (reverse) rate equation was proposed for metal hydroxide formation, *no rate equation for metal hydroxy-phosphate formation was proposed* (Briggs, 1996). This appears to be somewhat paradoxical. It implies that in the chemical model of Briggs, metal hydroxy-phosphate formation is assumed to be instantaneous and complete (i.e. at equilibrium) throughout the system. No allowance is made for dynamic formation of metal hydroxy-phosphate in response to metal ion potentially becoming available through the dissociation of metal hydroxide, for example. The possible implications of this may need to be investigated.

The rate equation for metal hydroxy-phosphate dissociation (Briggs, 1996) is given in Eqn. 7.21. It should be noted that two switching functions are included in Eqn 7.21: one to switch off dissociation when there is no precipitate ($X_{MeP}/\{K_{s,diss} + X_{MeP}\}$) and the other to switch dissociation on when the actual residual ortho P concentration (P_P) drops below the minimum equilibrium ortho P concentration ($P_{P\,res}$) at a given pH:

$$r_1 = 0.5.\, k_p.\, [(P_{P\,res} - P_P) + |P_{P\,res} - P_P|].\, (X_{MeP}/\{K_{s,diss} + X_{MeP}\}) \quad \text{..... Eqn. 7.21}$$

where $K_{s,diss}$ = switching function constant (mg/ℓ MeP)
k_p = metal hydroxy-phosphate dissociation rate constant (d^{-1})

When $P_P < P_{Pres}$, dissociation is turned on and Eqn 7.21 reduces to :

$$r_1 = k_p.\, (P_{P\,res} - P_P)\, .(X_{MeP}/\{K_{s,diss} + X_{MeP}\})$$

However, Briggs (1996) pointed out that this will rarely occur and may be expected only at high metal: P dosage ratios, or in the presence of high organic loading when biological (excess) P removal can result in influent P concentrations becoming limiting.

In similar fashion to Eqn. 7.21, rate equations for metal hydroxide dissociation and precipitation were proposed by Briggs (1995):

For precipitation: $r_2 = 0.5\, k_m\, [(Me - Me^*) + |Me - Me^*|]$ ..... Eqn. 7.22
For dissociation: $r_3 = 0.5\, k_m\, [(Me^* - Me) + |Me^* - Me|].\, (X_{MeH}/\{K_{s,diss} + X_{MeH}\})$ ..... Eqn. 7.23

where k_m is the metal hydroxide precipitation/dissociation rate constant (d^{-1})
Me is the actual metal ion concentration (mg Me/ℓ)
Me* is the minimum equilibrium metal ion concentration at a given pH (mg Me/ℓ).

[8] The highest metal dose was ca. 60 mg/l as $FeCl_3$ which would have given a theoretical alkalinity loss of 55 mg/l as $CaCO_3$, compared to the alkalinity supplement of 100 mg/ℓ as $CaCO_3$.

7.1.4.1 Calibration and uncertainty of constants

It was seen from section 7.1.3 above that uncertainty of some of the constants required in the chemical model of Briggs (1996) presented a degree of difficulty and required calibration from actual plant data. In this respect, an equilibrium model is no different from a kinetic model.

The key constants identified by Briggs (1996) which greatly influence the effluent ortho P (or TP) residual concentration were:

- The solubility product (K_{sp}) for metal (hydroxy) phosphate;
- The solubility product (K_{sp}) for metal hydroxide (only tested for the case of aluminium); and
- The equilibrium constant (k_{MHP}) for the metal phosphate complex ($MeH_2PO_4^{2+}$) - footnote[17].

To this may be added that the equilibrium constants ($k_{Me,1}$ to $k_{Me,4}$) for aluminium hydroxide ion pairs had a certain inconsistency:

Briggs (1996) identified the following aluminium hydroxide ion pairs (refer to Table 7.1):

$Me^{3+} + H_2O \leftrightarrow Me(OH)^{2+} + H^+$ $\quad k_{Me,1} = 5.0$

$Me^{3+} + 2H_2O \leftrightarrow Me(OH)_2^{+} + 2H^+$ $\quad k_{Me,2} = 8.7$

$Me^{3+} + 3H_2O \leftrightarrow Me(OH)_3^{0} + 3H^+$ $\quad k_{Me,3} = 15.2$

$Me^{3+} + 4H_2O \leftrightarrow Me(OH)_4^{-} + 4H^+$ $\quad k_{Me,4} = 23.3$

Alternatively, the ion pairs can be written as acid-base reactions in the following manner:

$Me^{3+} + H_2O \leftrightarrow Me(OH)^{2+} + H^+$ $\quad k_{a,1}$

$Me(OH)^{2+} + H_20 \leftrightarrow Me(OH)_2^{+} + H^+$ $\quad k_{a,2}$

$Me(OH)_2^{+} + H_20 \leftrightarrow Me(OH)_3^{0} + H^+$ $\quad k_{a,3}$

$Me(OH)_3^{0} + H_20 \leftrightarrow Me(OH)_4^{-} + H^+$ $\quad k_{a,4}$

The values of the equilibrium constants $k_{a,1}$ through $k_{a,4}$ can be derived from $k_{Me,1}$ through $k_{Me,4}$. For example, using the above data for the aluminium ion pairs:

$k_{a,1} = k_{Me,1} = 10^{-5.0}$

$$k_{Me,1} = \frac{[Me(OH)^{2+}] \cdot [H^+]}{[Me^{3+}]} \quad \text{therefore} \quad [Me^{3+}] = \frac{[Me(OH)^{2+}] \cdot [H^+]}{k_{Me,1}}$$

$$k_{Me,2} = \frac{[Me(OH)_2^{+}] \cdot [H^+]^2}{[Me^{3+}]} \quad \text{therefore} \quad \frac{k_{Me,2}}{k_{Me,1}} = \frac{[Me(OH)_2^{+}] \cdot [H^+]}{[Me(OH)^{2+}]} = k_{a,2} = 10^{-8.7+5.0} = 10^{-3.7}$$

Similarly, it can be shown that :

$$\frac{k_{Me,3}}{k_{Me,2}} = \frac{[Me(OH)_3^{0}] \cdot [H^+]}{[Me(OH)_2^{+}]} = k_{a,3} = 10^{-15.2+8.7} = 10^{-6.5}$$

and :

$$\frac{k_{Me,4}}{k_{Me,3}} = \frac{[Me(OH)_4^{-}] \cdot [H^+]}{[Me(OH)_3^{0}]} = k_{a,4} = 10^{-23.3+15.2} = 10^{-8.1}$$

It can be expected that the series $pK_{a,1} < pK_{a,2} < pK_{a,3} < pK_{a,4}$ will emerge with the increasing substitution of Me^{3+} ions with OH^-. However, from the above, it can be seen that the data of Briggs (1996) for the aluminium ion pairs produces an inconsistency in that $pK_{a,2} = 3.7 < pK_{a,1} = 5.0$. The data for the iron ion pairs (Table 7.1) does not show the same problem. The inconsistency in the aluminium ion pair equilibrium constant data may explain why Briggs (1996) found it necessary to manipulate the aluminium hydroxide solubility product in order to provide metal equilibrium residuals which were in agreement with experimental data reported in the literature.

Accepting that inconsistency in the metal-hydroxide ion pair equilibrium constant data may have been the cause of uncertainty over the aluminium hydroxide solubility product, the two constants which bear further examination are the metal hydroxy-phosphate solubility product (K_{MeP}) and the metal-phosphate complex equilibrium constant (k_{MHP}).

In order to illustrate the effect of uncertainty over k_{MHP}, the case mentioned by Briggs (1996) for dosing with ferric ions is shown in Fig. 7.4. The range of uncertainty in the source data for k_{MHP}

[17] Uncertainty over this constant was also identified by Luedecke *et al.* (1989) - see 7.1.1.5

was -20.5 to -22.7 (Luedecke *et al.*, 1989). Briggs (1996) took the average (-21.5) and corrected this to -17.5 to take into account the use of $Fe(OH)_3$ instead of FeOOH as ferric hydroxide precipitate in the model. If the same approximation is applied to the range in data from Luedecke *et al.* (1989), k_{MHP} values in the range -16.5 to -18.5 are obtained. The family of P_{pres} curves shown in Fig. 7.4 may then be generated. From Fig. 7.4 it can be seen that the change in k_{MHP} affects both the magnitude of both P_{pres} in the range 0.05 to 1.1 mgP/ℓ (for the pH range 6.8 to 7.8) as well as the "optimum" pH at which lowest P_{pres} is predicted. These changes will be significant for systems in which the Me_{dosed}: $P_{initial}$ ratio is relatively high such that the effluent residual ortho P concentration becomes equilibrium controlled. Typically this could occur for many real situations in which the effluent ortho P (or total P) discharge standard is <1 mgP/ℓ. The need for calibration of k_{MHP} will therefore be most important if model accuracy of this order is required for such applications.

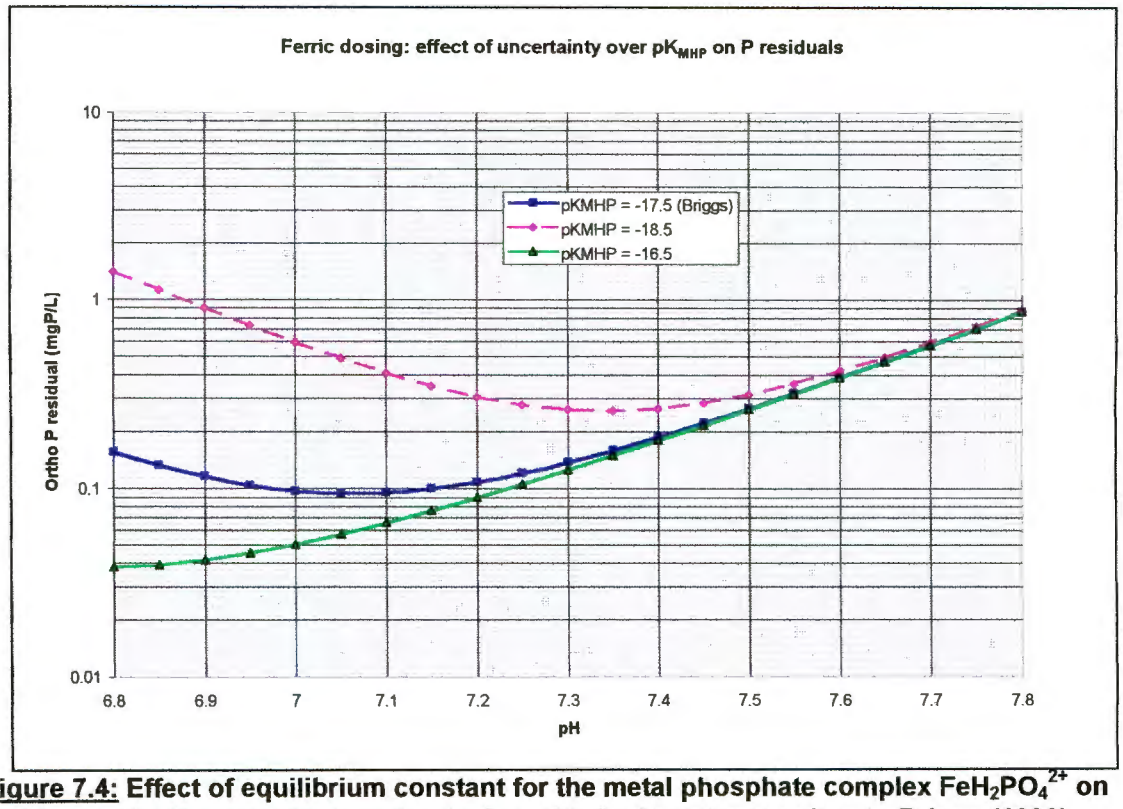


Figure 7.4: Effect of equilibrium constant for the metal phosphate complex $FeH_2PO_4^{2+}$ on residual ortho P concentrations for dosing with ferric salt, according to Briggs (1996) chemical equilibrium precipitation model.

In order to illustrate the effect of uncertainty over the metal phosphate solubility product (K_{sp}), the example of $AlPO_4$ mentioned earlier (see footnote[13]) may be examined in more detail. Two sources of data for K_{sp} ($AlPO_4$) were quoted by Briggs (1996), namely:

- K_{sp} = 20 (CRC, 1988)
- K_{sp} = 21 (Snoeyink and Jenkins, 1980)

Briggs (1996) first accepted an intermediate value of K_{sp} = 20.3 but later changed this to K_{sp} = 22.2 in order to obtain ortho P residuals of the right order, according to published precipitation data. From calibration to Mid-Halton Works results, a revised value of K_{sp} = 22.0 was accepted by Briggs (1996). Figure 7.5 depicts the effect of these changes on P_{pres}.

It can be seen from Fig. 7.5 that the precipitation model is extremely sensitive to the K_{sp} parameter, with predicted P_{pres} values spanning three orders of magnitude over the pH range 6.8 to 7.8, which would be applicable to simultaneous precipitation in biological systems. To some degree this weakens confidence in the chemical model and emphasises the importance of calibration of the model to experimental data in as many applications as possible.

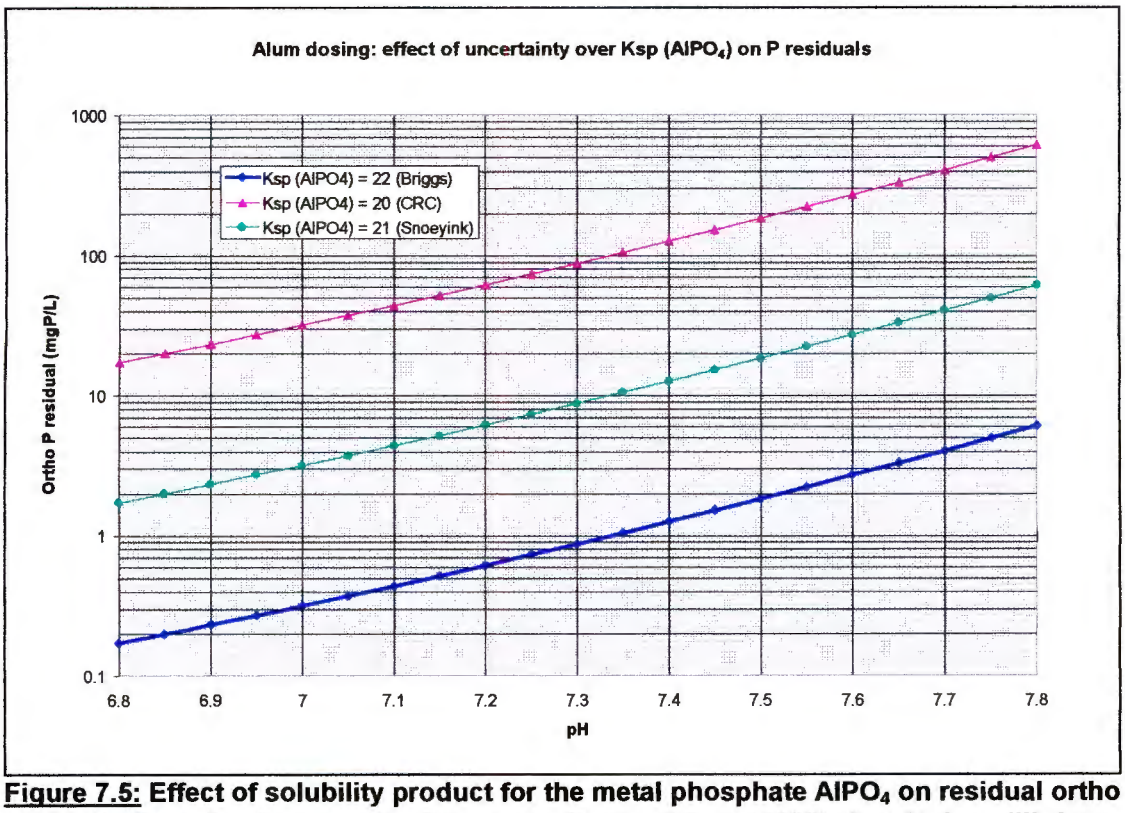


Figure 7.5: Effect of solubility product for the metal phosphate $AlPO_4$ on residual ortho P concentrations for dosing with alum, according to Briggs (1996) chemical equilibrium precipitation model.

7.1.4.2 Metal hydroxy-phosphate precipitation

In section 7.1.2.7, attention was drawn to the fact that the Briggs (1996) model contains kinetic expressions for the *dissociation* of metal (hydroxy) phosphate *but not for its precipitation*. The reason for this is that the precipitation calculations are based on equilibrium chemistry, which is fundamental to Briggs' model. The assumption is made that the precipitation processes take place (virtually) instantaneously at the point (in time and space) of metal salt addition. The kinetic processes are subsequently solved for the steady-state condition.

Interestingly, metal hydroxide precipitation is modelled as a kinetic process, with a rapid precipitation/ dissociation rate set equal to that for phosphate dissociation. In fact, the approach followed by Briggs (1996), as described in section 7.1.2.7 above, was an attempt to model precipitation kinetics with a rate equation and to assume that the same rate constant ($k_p = k_m$) would be applicable to the dissociation of metal (hydroxy) phosphate as well as the precipitation and dissociation of metal hydroxide. Briggs (1996) did not report any sensitivity analysis for k_p or k_m.

Briggs (1996) confined the application of his chemical model to incorporation with IAWQ (or IAWPRC) ASM Model No. 1, which includes nitrification-denitrification processes, but not BEPR processes. As stated before, the incorporation of both equilibrium and kinetic expressions resulted in a paradox in the model of Briggs (1996): precipitation of metal (hydroxy) phosphate is not modelled as a kinetic process, whereas its dissociation is. It has the implication that metal hydroxy phosphate cannot form dynamically during the solution procedure for predicting the steady-state. This could lead to problems with reaching the correct steady-state result, particularly in model BEPR systems where several additional dynamic processes involve phosphate release or uptake.

Using the approach of Briggs (1996), calculation of the initial state would have set the mass of phosphate precipitated as metal (hydroxy) phosphate prior to commencement of the dynamic

mathematical solution procedure. No further formation of this precipitate will be possible since no kinetic process for its formation was included. An initial metal hydroxide precipitate mass would also have been calculated. If the soluble metal concentration drops below the minimum permissible equilibrium concentration at any stage during the dynamic calculation (as it may if the initial Me: initial P dose was relatively low, which would be true for many simultaneous dosing situations where a significant degree of biological P removal is expected), then metal hydroxide dissociation will be "switched on" and metal ions will be solubilised. *However, it will be impossible for the dynamic solution to predict more metal (hydroxy) phosphate formation as a result.* This could lead to the incorrect steady-state prediction for soluble ortho P concentration.

7.1.4.3 The question of P_{P0}

Related to the question of the absence of a kinetic expression for metal (hydroxy) phosphate precipitation (7.1.4.2), is the question surrounding the definition of P_{p0} (Eqns. 7.13 or 7.16). Since the Briggs (1996) model is based on a conventional aerobic activated sludge system, apart from the chemical processes, the only dynamic biological phosphate process which needed to be considered was that for the hydrolysis of organic (complex) phosphate forms to ortho P. Furthermore, since the only point of metal salt addition considered by Briggs was to the last aerobic zone (or the line between this zone and the secondary clarifier), the initial ortho P concentration at the point of metal addition (P_{P0}) could be easily calculated. Briggs (1996) did not detail the mathematical solution procedure followed, but presumably a steady-state concentration of P_{P0} was first calculated (i.e. in the absence of metal salt addition) and then used as an initial condition for the algebraic expression in Eqn. 7.16. Again, since Eqn. 7.16 is not a kinetic expression, it would not form part of the dynamic procedure for calculating the steady-state.

If the Briggs model is to be extended to BEPR processes, the problem of setting a value for P_{P0} becomes more significant. By definition, BEPR processes are characterised by relatively high steady-state concentrations of phosphate stored in the biomass, with release typically occurring in the anaerobic zone and uptake in the aerobic zones. In such processes, it cannot be assumed that metal salt dosing will necessarily take place in the aerobic zone; the higher soluble ortho P concentrations in the anaerobic zone could increase the efficiency of precipitation (as Eqn. 7.13 predicts). However, it is also more difficult to predict a steady-state concentration for the anaerobic zone with simultaneous precipitation and BEPR processes both taking place in the system.

To examine the possible effect of uncertainty of P_{P0} at the point of dosing on precipitation, Eqn 7.13 may be tested, on the assumption that the systems are not equilibrium-limited. The concentration of ortho P removed through precipitation ($P_{precipitated}$) can be calculated from the difference between P_{p0} and P_P*. Figs. 7.6 (a &b) show the results of applying Eqn. 7.13 with the following assumptions, based on operating data for the pilot plants in this study (Chapters 3 and 4):

- Low alum dose = 4.65 mg/ℓ as Al (equivalent to 6.2 mmol/d as Al in 36 ℓ/d flow)
- High alum dose = 9.30 mg/ℓ as Al (equivalent to 12.4 mmol/d as Al in 36 ℓ/d flow)
- Low ferric dose = 9.63 mg/ℓ as Fe (equivalent to 6.2 mmol/d as Fe in 36 ℓ/d flow)
- High ferric dose = 19.25 mg/ℓ as Fe (equivalent to 12.4 mmol/d as Fe in 36 ℓ/d flow)

Fig. 7.6b shows the effect of using α_1 = 1.3 instead of unity in Eqn. 7.13 for ferric ions: above a certain value of P_{p0} the ferric dose is too small to initiate precipitation (refer also to Fig. 7.3 and discussion under 7.1.3.1 above).

Assuming α_1 = 1 for comparative purposes, it is clear from Fig. 7.6a that for larger P_{p0} values, uncertainty in P_{p0} exerts a relatively small effect on the concentration of $P_{precipitated}$ (i.e. P_{p0} - P_P*) through Eqn. 7.13. For P_{p0} approx. 25 to 50 mgP/ℓ and constant metal doses examined, the uncertainty in $P_{precipitated}$ will be of the order of $\leq$ 1 mgP/ℓ (lines almost horizontal) . However, uncertainty in $P_{precipitated}$ increases greatly as P_{p0} becomes smaller in relation to a constant metal dose (Fig. 7.6a). In the range 2 to 10 mgP/ℓ uncertainty over $P_{precipitated}$ lies in the range 2 to 5 mgP/ℓ for the metal doses examined.

It can be concluded from Fig. 7.6a that the Briggs (1996) precipitation model may fail to accurately predict effluent ortho P concentrations where the initial ortho P concentration (at the point of chemical dosing) is unknown, and particularly if it falls into the range <10 mgP/ℓ. The latter will apply to most real applications where an activated sludge plant receiving domestic waste-water is dosed with chemicals in the aerobic zone. In BEPR plants, if dosing takes place to the anaerobic zone where ortho P concentrations are likely to be >10mgP/ℓ, the uncertainty in P_{P0} will have a smaller impact on the predicted effluent ortho P, but could nevertheless be significant where the objective is to accurately predict removal in relation to low effluent phosphate standard (e.g. 1 mgP/ℓ).

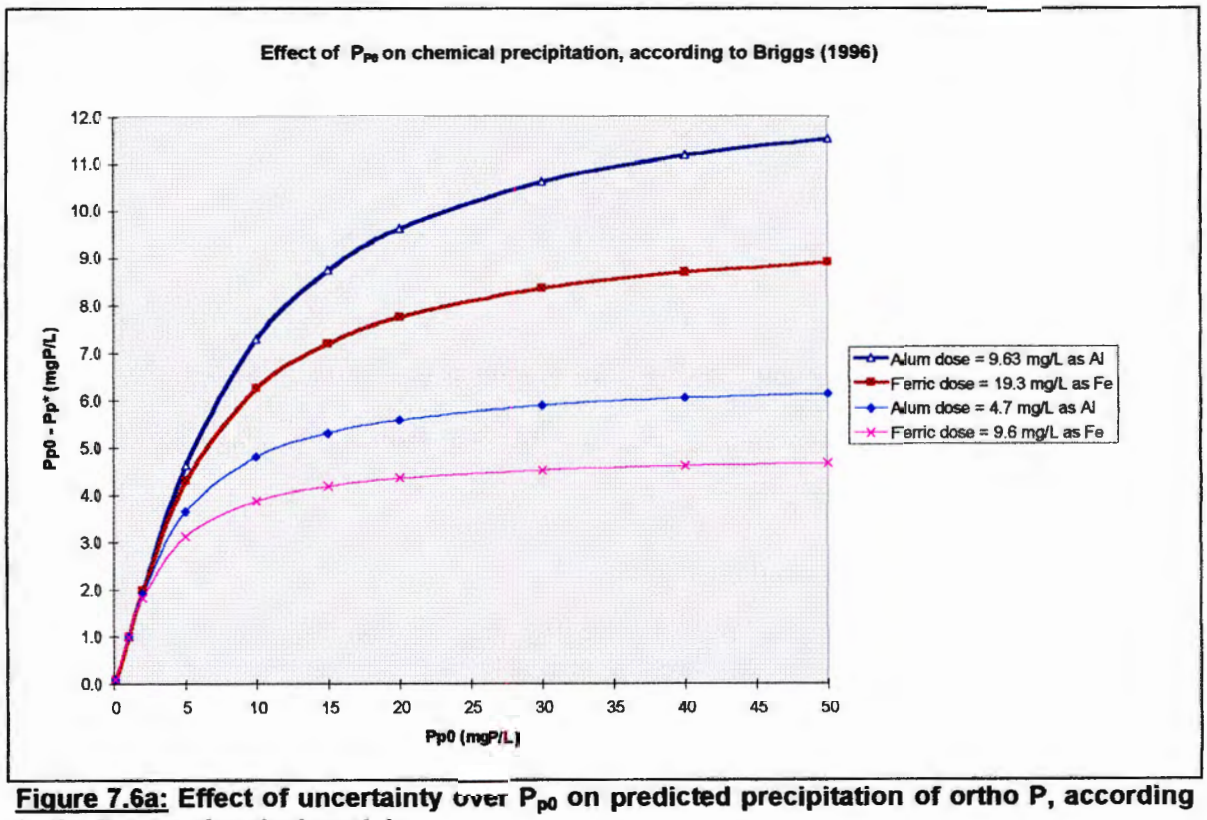


Figure 7.6a: Effect of uncertainty over P_{p0} on predicted precipitation of ortho P, according to the Briggs chemical model.
Refer to Eqn. 7.13 above: For alum, $\alpha_1 = 1$; $\alpha_2 = 1.41$; For ferric $\alpha_1 = 1$; $\alpha_2 = 0.51$.

Fig. 7.6b ..... /

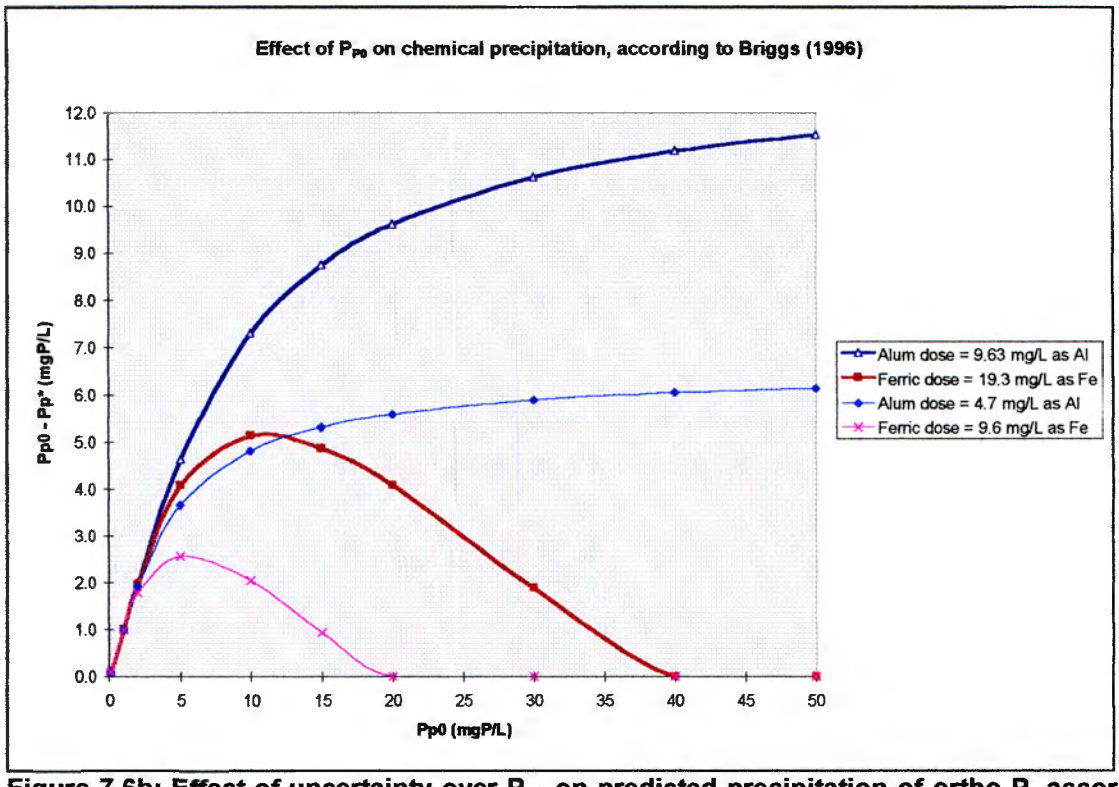


Figure 7.6b: Effect of uncertainty over P_{p0} on predicted precipitation of ortho P, according to the Briggs chemical model.
Refer to Eqn. 7.13 above: For alum, $\alpha_1 = 1$; $\alpha_2 = 1.41$; For ferric $\alpha_1 = 1.3$; $\alpha_2 = 0.51$.

7.1.4.4 Adsorption and metal complexation

For the systems against which the model was tested, Briggs (1996) concluded that the adsorption component of the chemical model played a negligible part in the predicted P removal of the system. This suggests that the added complexity introduced as a result of the adsorption processes cannot be justified.

Two further reasons may be given for ignoring the adsorption component of the model proposed by Briggs. Firstly, phosphate adsorption to the biomass has not been taken into account. Secondly, there may be little point in attempting to model phosphate adsorption to metal colloids separately from precipitation as metal phosphate when the two mechanisms are likely to be very closely related through ion-exchange or complexation mechanisms. The literature suggests that there is currently insufficient experimental evidence to resolve the exact mechanism by which phosphate is incorporated into an iron hydroxide colloid. The mechanism may be one or more of the following(He *et al.*, 1996):

- adsorption to the colloid;
- co-precipitation with the colloid; or
- co-deposition as iron-phosphate precipitate with the iron hydroxide colloid.

According to He *et al.* (1996), phosphate adsorption cannot readily be distinguished from ion exchange or surface complexation between phosphate and the iron hydroxide colloid.

Furthermore, from recent work using electron microscopy by He *et al.* (1996), some iron-P agglomerates in activated sludge appear to be trapped by meshes of microbial extracellular structures such as fibrils. Most likely, this extracellular organic material includes polysaccharides which appear to contribute significantly to the large capacity for the biomass to complex/ bind/ adsorb metals (see Chapter 1, section 1.9). The structural associations between iron hydroxide

and microbial cells in activated sludge and secondary effluent are to be the subject of further investigation (He *et al.*, 1996).

In view of the lack of detailed understanding of the mechanisms of chemical phosphate removal in activated sludge systems, it seems that the adsorption components of the Briggs (1996) model can be safely ignored. Any adsorption effects which do occur would thus be lumped (for modelling purposes) with the precipitation processes.

7.1.4.5 Kinetic models of chemical precipitation

One alternative to the equilibrium approach to precipitation proposed by Briggs (1996) would be to use a kinetic approach to describe both precipitation and dissociation reactions for metal (hydroxy) phosphate and metal hydroxide. In this case, the rate constants would be lumped parameters incorporating effects due to *inter alia* the stoichiometry and solubility of the precipitate, ion-pairing/ complexation of phosphate and metal ions, metal: P ratio at the dosing point, and adsorption. The number of constants requiring calibration would be greatly reduced in this manner, which may make the model easier to use. The kinetic approach would simplify integration of the chemical model with the biological (including BEPR) processes. However, pH and alkalinity would also need to be modelled kinetically in order to yield equivalent results to the equilibrium approach. Furthermore, the kinetic model would need to be tested under a variety of conditions (e.g. different influent composition, limiting P concentrations, different dosing points in the BEPR process) in order to determine the extent to which calibration of the kinetic constants is dependent on operating conditions.

The IAWQ Model No. 2 (IAWQ, 1995) uses a simple kinetic approach for inclusion of processes for precipitation using iron (ferric) salts. This model is reviewed in section 7.1.5.

7.1.5 IAWQ Model No. 2

The IAWQ Activated Sludge Model No. 2 (ASM2) (IAWQ, 1995) is an extension of its predecessor (ASM1) which incorporates processes describing biological P removal. In addition to the biological processes, ASM2 includes two chemical processes which may be used to model chemical precipitation, namely: precipitation and redissolution. Two components (hypothetical chemical compounds) are added in order to model these processes: metal hydroxide (X_{MeOH}) and metal phosphate (X_{MeP}).

The precipitation model (IAWQ, 1995) is based on the assumption that precipitation and redissolution are reverse processes of each other, which at steady state would be in equilibrium according to:

$$X_{MeOH} + S_{PO4} \leftrightarrow X_{MeP}$$

Precipitation (PRE) and redissolution (RED) may be modelled as simple first order reactions, with the following process rates (r_{PRE} and r_{RED}) respectively for compound i:

$$r_{PRE}, i = V_{PRE} \cdot k_{PRE} \cdot S_{PO4} \cdot X_{MeOH}$$
$$r_{RED}, i = V_{RED} \cdot k_{RED} \cdot X_{MeP}$$

where V_{PRE} and V_{RED} are the respective stoichiometric coefficients for precipitation and redissolution, S_{PO4} is the concentration of soluble ortho P, k_{PRE} and k_{RED} are the respective kinetic constants for the precipitation and redissolution reactions[18], and X_{MeOH} and X_{MeP} are the respective concentrations of metal hydroxide and metal phosphate in the mixed liquor.

IAWQ (1995) presented the example of dosing ferric ions to an activated sludge system. In this case, MeOH is assumed to be $Fe(OH)_3$ and MeP is assumed to be $FePO_4$. Provision may be made

[18] According to Aspegren (1995) these expressions originated from Langmuir-type expressions for phosphorus precipitation in soil and a switching function for S_{PO4} may be included ($S_{PO4}/[K_{PO4} + S_{PO4}]$, where K_{PO4} is very small, e.g. 0.001 mgP/ℓ).

in the model for loss of hydroxide ions (decrease in alkalinity) from the bulk phase during formation of $Fe(OH)_3$ but pH is assumed to be near neutrality [19]. Effectively, Fe^{3+} dosing is modelled as the addition of $Fe(OH)_3$ in the form of an influent to the activated sludge plant, on the basis that 1 g Fe converts to 1.91 g $Fe(OH)_3$. If total suspended solids (TSS) is modelled, the $Fe(OH)_3$ is considered to contribute to the influent TSS. Absolute values for the stoichiometry of ortho P precipitation may be calculated as follows:

$$PO_4^{3-} + Fe(OH)_3 \leftrightarrow FePO_4 + 3OH^-$$

where 1 g P reacts with 3.45 g $Fe(OH)_3$ to form 4.87 g $FePO_4$. Hence, with the units of P concentration being g/m^3 (or mgP/ℓ), for dosing with ferric ions:

$$V_{PRE,\ MeOH} = -3.45$$
$$V_{RED,\ MeOH} = 3.45$$
$$V_{PRE,\ MeP} = 4.87$$
$$V_{RED,\ MeP} = -4.87$$

Similarly, for alum dosing:

$$PO_4^{3-} + Al(OH)_3 \leftrightarrow AlPO_4 + 3OH^-$$

where 1 g P reacts with 2.52 g $Al(OH)_3$ to form 3.94 g $AlPO_4$. Hence, with the units of P concentration being g/m^3 (or mgP/ℓ), for dosing with aluminium ions:

$$V_{PRE,\ MeOH} = -2.52$$
$$V_{RED,\ MeOH} = 2.52$$
$$V_{PRE,\ MeP} = 3.94$$
$$V_{RED,\ MeP} = -3.94$$

IAWQ (1995) proposed values for the kinetic constants on the basis that these values gave predictions of residual ortho P concentrations which are considered typical of simultaneous precipitation with $FeCl_3$ in activated sludge systems:

$$k_{PRE} = 1\ \ell.\ (mg\ Fe(OH)_3)^{-1}.\ d^{-1}$$
$$k_{RED} = 0.6\ d^{-1}$$

IAWQ (1995) did not indicate whether these kinetic constants would also be suitable for alum dosed systems.

7.1.6 Summary

A model based partly on equilibrium and partly on kinetic processes has been proposed for simultaneous precipitation of phosphate in activated sludge systems (Briggs, 1996). The equilibrium chemistry incorporated in this model gives it a fundamental basis for the incorporation of pH and alkalinity as model parameters. However, the integration of equilibrium and kinetic processes poses certain problems in deriving a solution for this model. Moreover, like any other model, it is highly dependent on calibration. The Briggs (1996) model proved to be sensitive to several key constants (notably the solubility products of the precipitates and one or more of the equilibrium constants for metal-phosphate ion pairs). Calibration of the model to particular applications will require manipulation of these constants. To some extent, this negates the value of the model and should be seen in the light of the considerable complexity introduced by the equilibrium chemistry expressions. It suggests that the approach taken by the IAWQ Task Team (IAWQ, 1995) is more practical, mainly in that it is much simpler and may require empirical calibration of only two rate constants.

In view of the above, for the purposes of this study, the results of pilot plant experiments presented in Chapters 3, 4 and 5 were tested against the IAWQ Model No. 2.

[19] The assumption of constant pH is currently a constraint of the ASM2 model. The charge balance calculation for alkalinity is based on a pH value of 6.86 at which all the alkalinity is (effectively) in the form of bicarbonate (HCO_3^-). In practical application, where uncertainty over pH exists, a low calculated alkalinity value should be considered as a warning of possible low pH conditions (IAWQ, 1995).

University of Cape Town

7.2 MODELLING METHOD

The IAWQ Activated Sludge Model No. 2 (ASM2) was available in matrix format (IAWQ, 1995). In order to apply this model as a computer program, it was formulated using the AQUASIM platform (Reichert, 1994). Details of the AQUASIM program are given by Reichert (1994), with further notes in section 7.2.2 below.

In order to verify that the ASM2-AQUASIM program had been correctly set up, the results of the Control reactor (R2) for all experimental periods were compared to those obtained using the UCTPHO model described by Wentzel *et al.* (1992) and made available as a computer program by Wentzel (1997).

7.2.1 Influent characterisation

In order to apply either the ASM2 or UCTPHO model, the influent needs to be characterised with respect to the various influent COD fractions. Furthermore, the UCTPHO model requires that the influent nitrogen fractions be defined, whereas in ASM2 the influent nitrogen fractions are calculated from factors of the COD fractions.

A shortcoming of the experimental procedure used for the operation of the pilot plants (Chapter 3, sections 3.2.1 and 3.2.5) was that the influent readily biodegradable COD (RBCOD) fraction was not specifically measured for most of the experimental periods. The initial intention was to develop fully "enhanced" cultures in the pilot plants such that the influent COD was composed of 100% sodium acetate (i.e. 100% RBCOD). However, the settling problems which emerged in both the Test (alum dosed) and later also in the Control reactor during the first alum dosing period with 250 mg/ℓ acetate COD (see Chapter 3, section 3.3.2) resulted in a revision of the *modus operandi*. Circumstantial evidence suggested that either the high acetate dose or the associated acid doses (Wentzel *et al.*, 1988) resulted in floc break-up (or pin floc sludge formation) and hence in deteriorated sludge settling which made the pilot plants became inoperable. Hence, a lower acetate dose (usually 150 mg/ℓ as acetate) was accepted as the norm for further experiments, with settled sewage contributing the balance of the influent COD.

For a limited number of experimental periods (Periods 3.6.1 and 3.6.2 with ferric chloride dosing - see section 4.3.11 of Chapter 4), RBCOD was measured using the method of Mamais *et al.* (1993). For these periods, the measured RBCOD values were used for characterisation of the influent. For the balance (i.e. the majority) of the experimental periods, the objective for modelling was mainly confined to testing the chemical precipitation processes used in the IAWQ ASM No. 2. The absence of RBCOD data necessitated a trial-and-error approach with respect to characterisation of the influent COD fractions. This was accomplished using the UCTPHO model of Wentzel *et al.* (1992) calibrated against the measured parameters for the Control (R2) unit, which was not dosed with chemical precipitants.

In terms of the UCTPHO model, the respective influent COD fractions are defined as follows (WRC, 1984; Wentzel *et al.*, 1992):

- total influent COD: S_{ti}
- unbiodegradable (influent) soluble COD: $S_{usi} = f_{us}.\ S_{ti}$
- unbiodegradable (influent) particulate COD: $S_{upi} = f_{up}.\ S_{ti}$
- readily biodegradable (influent) soluble COD: $S_{bsi} = f_{bs}.\ (1-f_{us}-f_{up}).\ S_{ti}$
- slowly biodegradable (influent) soluble COD: $S_{bpi} = S_{ti} - S_{bsi} - S_{usi} - S_{upi}$

The readily biodegradable COD is further sub-divided into :

- readily biodegradable (influent) soluble COD which is *acetate (or free short-chain fatty acid)*: $S_{bs,ai} = f_{ac}. S_{bsi}$, and
- readily biodegradable (influent) soluble COD which can be *converted (or fermented)* to short-chain fatty acid: $S_{bs,ci} = (1-f_{ac}). S_{bsi}$

In respect of the nitrogen fractions, the UCTPHO model requires input for three fractions:

- f_{na} : fraction of influent TKN which is ammonia
- $f_{nob,p}$: fraction of the influent organic nitrogen which is biodegradable particulate
- $f_{nou,s}$: fraction of the influent TKN which is unbiodegradable and soluble

In practice, it was found that f_{na} values in the expected range 0.65 to 0.75 had little effect on the steady-state effluent results predicted by UCTPHO. A default value of f_{na} = 0.65 was accepted, based on historical data for Darvill settled sewage. Similarly, the default value of $f_{nob,p}$ = 0.50 (Wentzel *et al.*, 1992) was accepted. The exact value for this fraction is of little consequence since the model makes provision in any case for hydrolysis/ solubilisation of the organic biodegradable nitrogen, followed by conversion to ammonia (ammonification). These processes normally proceed to virtual completion under realistic operating conditions for activated sludge systems, leaving little or no soluble organic biodegradable nitrogen in the effluent.

All other values for constants (including kinetic and stoichiometric constants) used in the UCTPHO model were the default values (Wentzel *et al.*, 1992), with the exception of $\mu_{nm,\ 20}$ (max. specific growth rate at 20 °C for the nitrifiers), which was determined by trial-and- error, based on the observed effluent ammonia concentrations .

In summary, using the trial-and-error, the approximate "best fit" values were obtained for the following input parameters using the UCTPHO model applied to results from the pilot plant Control unit (R2). The following steps were followed in this approach:

1. $\mu_{nm,\ 20}$: adjusted such that predicted effluent ammonia concentration matched observed ammonia (free and saline) values;
2. $f_{nou,s}$: varied such that predicted effluent TKN matched observed values;
3. f_{ac} : fixed by acetate dose in most cases[20];
4. f_{us} : adjusted such that predicted effluent COD matched measured effluent COD;
5. f_{bs} and f_{up}: adjusted in a series of iterations through which the magnitudes of $S_{bs,ci}$ and S_{upi} are varied to match the predicted P removal and VSS concentrations to the observed values.

The results are presented in Table 7.6.1.

For periods 3.6.1 and 3.6.2 (a & b), which spanned a period of approximately 5 months in 1997, moving from dry weather in winter into wet weather in early summer, the RBCOD of the influent was measured using a physico-chemical method (Mamais *et al.*, 1993). During these periods, the *added* acetate concentration was held constant at 100 mg/ℓ as COD. The measured RBCOD during these periods was 174 (± 67) mg/ℓ (mean, ± S.D.), while the total COD was 400 (± 96) on the same basis. Taking the measured RBCOD and subtracting the *added* acetate concentration (i.e. assuming zero acetate in the original settled sewage), an approximate range for $S_{bs,ci}$ of 7 to 141 mg/ℓ can be estimated for the Darvill settled sewage[21] . The $S_{bs,ci}$ values obtained by trial-and-error influent characterisation for periods without RBCOD determination (see above and Table 7.6.1) were 13 to 144 mg/ℓ. Hence, the trial-and-error method of sewage characterisation appeared to be acceptable.

[20] Refer to Table 7.6.1: the only exception was experimental periods 3.4.1 to 3.4.4 (inclusive) and period 3.5.1 where observed P removal in the Control unit (R2) was significantly less than that predicted by the UCTPHO model (or IAWQ ASM No. 2). This point is discussed in section 7.2.3 of this chapter.

[21] $S_{bs} = S_{bs,\ ci} + S_{bs,ai}$ (see Appendix 8 for definition of symbols).

Table 7.6.1: Influent sewage composition and parameters assumed for UCTPHO modelling of selected pilot plant experimental periods of this study.

Period	S_{ti} mgCOD/ℓ	$S_{bs,ai}$ mgCOD/ℓ	$S_{bs,ci}$ mgCOD/ℓ	N_{ti} mg N/ℓ	P_{ti} mgP/ℓ	f_{bs}	f_{ac}	f_{us}	f_{up}	$f_{nou,s}$	$\mu_{nm,20}$ /μ_{AUT}, d^{-1}
3.2.2	478	150	144	[40.3] 35.0	53.06	0.685	0.51	0.03	0.07	0.015	0.36
3.2.3	379	151	114	[38.3] 32.3	49.67	0.85	0.57	0.03	0.15	0.015	0.30
3.2.4	346	150	96	[38.3] 25.0	49.00	0.865	0.61	0.03	0.15	0.015	0.25
3.2.5	251	150	35	[31.9] 23.0	46.71	0.90	0.81	0.03	0.15	0.005	0.30
3.2.7	350	150	81	[31.0] 29.5	47.02	0.695	0.65	0.02	0.03	0.015	0.45
3.2.8a	317	150	100	27.0*	45.31	0.85	0.61	0.02	0.05	0.015	0.32
3.3.1(b)	442	152	101	[31.3] 34.0	49.85	0.60	0.60	0.02	0.025	0.015	0.45
3.3.2	407	151	85	31.3	48.80	0.65	0.64	0.02	0.09	0.015	0.23
3.3.3	456	151	112	[35.0] 38.0	52.64	0.60	0.575	0.018	0.02	0.015	0.23
3.3.4	461	150	81	[33.5] 38.9	50.61	0.65	0.65	0.03	0.20	0.015	0.32
3.3.5	398	151	50	[30.1] 35.1	50.33	0.65	0.75	0.035	0.185	0.015	0.32
3.3.6	354	149	50	[26.7] 28.6	46.02	0.67	0.75	0.04	0.12	0.015	0.38
3.4.1	237	120 **	13	[15.4] 18.5	43.57	0.85	0.90	0.05	0.29	0.015	0.38
3.4.2	284	109 **	47	[18.0] 25.0	44.22	0.60	0.70	0.04	0.05	0.015	0.38
3.4.3	264	102 **	44	[15.6] 26.0	42.90	0.60	0.70	0.04	0.04	0.015	0.42
3.4.4	323	125 **	53	[26.6] 31.5	16.58	0.60	0.70	0.04	0.04	0.015	0.48
3.5.1	278	20	37	[34.1] 39.0	9.91	0.25	0.40	0.07	0.22	0.015	0.48
3.5.2	341	20	60	[35.7] 36.7	10.77	0.27	0.25	0.06	0.07	0.015	0.48
3.6.1	403	100	73	[31.5] 33.5	10.45	0.55	0.58	0.13	0.09	0.005	0.45
3.6.2a	427	100	82	[31.8] 32.8	10.46	0.50	0.55	0.09	0.06	0.015	0.45

* Estimate (too few observed data).

[ ] : Observed N_{ti} shown in brackets - for cases where N_{ti} was adjusted to obtain improved agreement between predicted and observed filtered NO_3^- result for the anoxic zone (see text).

** Loss of acetate in influent assumed (e.g. in wet weather, settled sewage may have been aerobic, possibly due to heterotrophic biomass present).

Table 7.6.2: Influent sewage composition and parameters assumed for IAWQ modelling of selected pilot plant experimental periods of this study. IAWQ symbols are given in brackets.

Period	S_{ti} (S_{TCOD}) mgCOD/ℓ	$S_{bs,ai}$ (S_A) mgCOD/ℓ	$S_{bs,ci}$ (S_F) mgCOD/ℓ	S_{usi} (S_I) mgCOD/ℓ	S_{upi} (X_I) mgCOD/ℓ	S_{bpi} (X_S) mgCOD/ℓ	N_{ai} (S_{NH4}) mg N/ℓ #	N_{ti} (C_{TKN}) mg N/ℓ ##	P_{ti} (S_{PO4}) mgP/ℓ	f_{bs}	f_{ac}	f_{us}	f_{up}	(i_{NSI})	$\mu_{nm,20}$ (μ_{AUT}) d^{-1}
3.2.2	478	150	144	24	33	126	22.8	37.1	53.06	0.70	0.51	0.05	0.07	0.11	0.36
3.2.3	379	150	113	23	57	36	21.0	33.2	49.67	0.88	0.57	0.06	0.15	0.15	0.30
3.2.4	346	150	96	21	52	27	16.3	25.5	49.00	0.90	0.61	0.06	0.15	0.08	0.25
3.2.5	251	150	35	16	38	12	16.9	23.0	46.71	0.94	0.81	0.064	0.15	0.11	0.30
3.2.7	350	150	81	18	11	92	20.2	28.9	47.02	0.715	0.65	0.05	0.03	0.11	0.45
3.2.8a	317	151	100	16	16	34	17.6	25.1	45.31	0.88	0.60	0.05	0.05	0.13	0.32
3.3.1(b)	442	150	100	22	11	159	22.1	34.7	49.85	0.61	0.60	0.05	0.025	0.11	0.45
3.3.2	407	151	85	20	45	109	20.3	31.2	48.80	0.68	0.64	0.05	0.11	0.08	0.23
3.3.3	456	150	111	20	9	166	25.4	38.2	52.64	0.61	0.575	0.02	0.10	0.10	0.23
3.3.4	461	150	81	20	92	119	22.1	37.1	50.61	0.66	0.65	0.043	0.20	0.07	0.32
3.3.5	398	149	52	20	74	104	21.8	34.8	50.33	0.66	0.74	0.05	0.185	0.10	0.32
3.3.6	354	149	50	21	42	91	17.6	27.6	46.02	0.685	0.75	0.06	0.12	0.09	0.38
3.4.1	237	121 **	13	19	69	15	11.7	18.5	43.57	0.90	0.90	0.08	0.29	0.05	0.38
3.4.2	284	109 **	47	16	14	98	16.3	23.5	44.22	0.615	0.70	0.056	0.05	0.06	0.38
3.4.3	264	102 **	44	16	11	91	16.9	24.7	42.90	0.615	0.70	0.06	0.04	0.13	0.42
3.4.4	323	125 **	53	19	13	113	20.5	29.6	16.58	0.613	0.70	0.06	0.04	0.11	0.48
3.5.1	278	20	37	19	61	148	24.1	37.3	9.91	0.25	0.40	0.07	0.22	0.10	0.48
3.5.2	341	20	60	23	24	215	21.5	36.7	10.77	0.27	0.25	0.067	0.07	0.14	0.48
3.6.1	403	100	72	58	36	137	21.2	31.4	10.45	0.557	0.58	0.144	0.09	0.02	0.45
3.6.2	415	100	82	42	25	171	20.2	32.8	10.46	0.505	0.55	0.10	0.06	0.02	0.45

#: Estimate.

##: Calculated from: $C_{TKN} = S_{NH4} + (X_I \cdot i_{NXI}) + (X_S \cdot i_{NXS}) + (X_H \cdot i_{NBM}) + (S_F \cdot i_{NSF}) + (S_I \cdot i_{NSI})$ (IAWQ, 1995)
where $X_H = 0$ by assumption. Values for i_{NXI}, i_{NXS}, i_{NSF} as per Wentzel and Ekama (1995).

From Table 7.6.1, the following points may be highlighted:

1. Some periods required relatively high values for f_{up} in order to match observed VSS values for the Control unit (R2). These periods appeared to correspond to periods in which the catchment of Darvill WWW received significant rainfall, for example:
    - Period 3.2.3: October - November 1994 (summer)
    - Period 3.2.4: November - December 1994 (summer)
    - Period 3.3.4: October 1995 (spring-summer)
    - Period 3.3.5: November 1995 (summer)
    - Period 3.3.6: November - December 1995 (summer)
    - Period 3.4.1: December 1995 - January 1996 (summer, accompanied by floods)
    - Period 3.5.1: mid June - July 1996 (winter - unusual, with widespread heavy rain and snow).

    The data for these periods therefore appear to confirm observations made in Chapters 3, 4 and 5 that the Darvill settled sewage appeared to vary considerably in composition, and that this variation was partly due to the heavy ingress of rainwater, storm-water and/or groundwater during wet weather (usually summer). The increase in unbiodegradable particulate COD may be in the form of very fine particles of soil origin (possibly colloids comprised partly of humic acids) which do not settle in the primary sedimentation tanks, but do contribute COD and become trapped in the activated sludge flocculation. This particulate material also appeared to improve sludge settleability (refer to Chapter 5, section 5.3.1.1; and Chapter 6, sections 6.3.2 and 6.4.3)[22].

2. Satisfactory prediction of P removal (see below) was obtained for most periods using values for f_{ac} derived from the known acetate concentrations added to the influent (refer to Tables 3.1, 4.1 and 5.1 in Chapters 3, 4 and 5). However, in order to achieve satisfactory P removal predictions using UCTPHO (or IAWQ model, see below), for many periods it was necessary to assume a relatively high fraction of readily biodegradable COD *originating from the settled sewage*[23]. In such cases the f_{bs} fraction (WRC, 1984; Wentzel *et al.*, 1992) for the original settled sewage ranged from 0.34 to 0.78 (average 0.46), assuming that the VFA content of the sewage was zero. For periods 3.6.1 and 3.6.2, in which the RBCOD was measured (see above), the corresponding f_{bs} values for the original settled sewage were 0.34 and 0.44 respectively, again assuming that the sewage itself contributed no VFA. Again, these results show fairly good agreement with the assumed values for periods in which RBCOD was not measured. On the other hand, De Haas and Adam (1995) measured VFA in the Darvill settled sewage (ca. 36 mg/ℓ as acetic acid), which corresponds to 38 mg/ℓ as COD. Assuming these results are representative, an alternative approximation for sewage characterisation (Table 7.6.1) therefore may have been to increase the amount of acetate in the influent on the basis that ca. 40 mg/ℓ as COD originated from the Darvill settled sewage. As it stands, Table 7.6.1 assumes that the amount of acetate COD in the sewage never exceeded the amount *added* as sodium acetate.

3. For certain periods (notably Periods 3.4.1 to 3.4.4), it was necessary to model a reduced concentration of influent acetate ($S_{bs,ai}$) in order to improve agreement between predicted and observed P removal. It is unclear why this effect was observed. One possibility is that the very dilute sewage of these periods (due to high rainfall in the catchment) was slightly aerobic and may have contained significant concentrations of heterotrophic biomass which metabolised

---

[22] In Chapter 6 (section 6.3.2) the point was discussed that sludge settleability at Darvill WWW improves significantly during wet summer months when storm water/ groundwater ingress makes a major contribution to the inflow. An increase in the inorganic suspended solids (decrease in %VSS) content of the activated sludge mixed liquor accompanies the improved settleability (Fig. 6.7 of Chapter 6). It seems likely that fine material of soil origin will contribute both inorganic material as well as poorly degradable (or unbiodegradable) organic material (COD).

[23] The default value for fbs of raw sewage is usually approximately 0.25 (WRC, 1984). However, the value for settled sewage depends heavily on the performance of the primary settling tanks (PSTs). For example, for a raw sewage COD of 500 mg/l (typical for Darvill WWW), with raw sewage f_{up} = 0.13 (default) and f_{us} = 0.05 (25 mg/l final filtered effluent COD typical for this works), the influent biodegradable COD (S_{bi}) = 410 mg/l, and S_{bsi} = 0.25* 410 = 103 mg/l. This fraction is expected to pass through the PSTs into the settled sewage. However, the reduction in total COD across the PSTs for this works is typically ca. 40 to 45%. Accepting the latter, and assuming the settled sewage f_{up} is reduced to 0.04 (default), then the S_{bi} (settled sewage) = 239 mg/l and f_{bs} (settled sewage) = 103/239 = 0.43.

some of the acetate in the influent tank (at 4°C) over the two day period corresponding to each sewage batch.

4. Problems with the TKN determination were noted during examination of mass balances in Chapter 3, 4 and 5 (see 3.3.31; 4.3.2.1; 5.3.3.1(b)). It became obvious during initial modelling attempts that a degree of uncertainty over influent TKN could affect phosphate predictions in so far as it determines the mass of nitrate recycled to the anaerobic and anoxic zones. Since reactor and effluent phosphate predictions were related to the primary objective of this study, it was decided to adjust the influent TKN concentration input to the model in order to improve agreement between observed and predicted anoxic reactor nitrate concentrations. In this manner, overall agreement between observed and predicted nitrate concentrations in all the reactors was also improved. For all experimental periods, it was found that this approach allowed the predicted nitrate concentration of the anoxic and second aerobic reactors to fall within ≤1.5 mg N/ℓ of the observed value. Using the steady-state model of Wentzel *et al.* (1990) it can be shown that nitrate variation of this order would affect the biological P removal potential of the experimental system used here by approximately ≤1 mgP/ℓ, which is well within the standard deviation of effluent total P concentrations observed for most experimental periods (Appendix 5).

5. The maximum specific growth rate of the nitrifiers ($\mu_{nm,20}$) required to achieve good agreement between predicted and observed effluent ammonia concentrations was varied over the range 0.25 to 0.48 d^{-1} in order to get good agreement with the measured effluent ammonia concentrations. According to WRC (1984), μ_{nm} may be regarded as a variable and classified as a wastewater characteristic. However, for low concentrations of ammonia in nitrifying systems, a relatively large change in $\mu_{nm,20}$ is necessary to effect a small change in the effluent ammonia concentration. An alternative approach would be to change the value of the half-saturation coefficient for the nitrifiers (autotrophs, i.e. K_{SA}), for which the default value is 1 mg N/ℓ (Wentzel *et al.*, 1992).

Using the influent characterisation for UCTPHO as a reference (Table 7.6.1), a similar influent characterisation procedure (by trial-and-error) was attempted for the IAWQ model. The results are shown in Table 7.6.2. From this table, the following points may be highlighted:

1. In the UCTPHO model, unbiodegradable soluble COD is *generated* by the death of poly-P accumulating organisms (PAO), whereas in the IAWQ model, this is not the case. In order to match the observed effluent COD for a given experimental period, the f_{us} fraction of the influent needed to be slightly greater for the IAWQ model, compared with the UCTPHO model. This further implied that one of the other influent COD fractions needed to be slightly smaller for the IAWQ model. In order to minimise the impact on biological P removal predictions, the readily biodegradable fractions (S_F and S_{Al}) were kept constant between the two models, and the unbiodegradable particulate fraction was left unchanged so as not to affect VSS predictions. Hence, the slowly biodegradable (particulate) COD fraction (X_S) was slightly smaller for the IAWQ model than that implicit in Table 7.6.1 for the UCTPHO model.

2. Nitrogen is modelled in a different manner in the two models.

- In the UCTPHO model (WRC, 1984; Wentzel *et al.*, 1992), influent TKN (N_{ti}) is divided into five fractions: (i) free and saline ammonia (N_{ai}); (ii) organic biodegradable particulate N ($N_{ob,p}$); (iii) organic biodegradable soluble N ($N_{ob,s}$); (iv) unbiodegradable soluble N ($N_{ou,s}$); and (v) unbiodegradable particulate N ($N_{ou,p}$). Of these, only the unbiodegradable particulate fraction is modelled as a fraction of the corresponding (unbiodegradable particulate) influent COD fraction. The unbiodegradable soluble N is usually small, but set in such a manner as to suit observed effluent TKN values, bearing in mind that residual organic biodegradable soluble N and ammonia N also contribute to the effluent TKN. The organic biodegradable particulate fraction (i.e. $N_{obi} = N_{ti} - N_{ai} - N_{oupi} - N_{ousi}$) is arbitrarily sub-divided into fractions which are 50% particulate (N_{obpi}) and 50% soluble (N_{obsi}) . Hence $f_{nob,p} = 0.50$ in the UCTPHO model.

- In the IAWQ model, influent TKN is not an input parameter as such. Influent ammonia concentration is an input parameter (along with influent nitrate, if present), but all other influent nitrogen fractions are derived from their COD counterparts (IAWQ, 1995):
  - $C_{TKN} = X_{TKN} + S_{TKN}$
  - $X_{TKN} = (X_I \,.\, i_{NXI}) + (X_S \,.\, i_{NXS}) + (X_H \,.\, i_{NBM}) + (X_{PAO} \,.\, i_{NBM}) + (X_A \,.\, i_{NBM})$
  - $S_{TKN} = S_{NH4} + (S_F \,.\, i_{NSF}) + (S_I \,.\, i_{NSI})$

  Unless the influent sewage is considered to have been aerated at some point, influent heterotrophic biomass (X_H), autotrophic biomass (X_A) and PAO biomass (X_{PAO}) may be taken as zero (Wentzel and Ekama, 1995).

  For the purposes of this study, the values suggested by Wentzel and Ekama (1995) for i_{NXI}, i_{NXS}, and i_{NSF} were accepted. Values for i_{NSI} were estimated on the basis of effluent TKN concentrations, taking into account that residuals of ammonia and organic biodegradable N also contribute to the effluent TKN.

  Finally, this left the need for influent ammonia as an input parameter. Since influent ammonia had not been measured during the pilot plant experiments, estimates of this parameter were made such that the influent TKN (C_{TKN}), calculated according to the above equations (IAWQ, 1995), gave predicted anoxic reactor nitrate concentrations which were close to the observed values. This resulted in an analogous approach to that described above for the UCTPHO model to ensure that uncertainty over influent TKN had a minimal impact on effluent phosphate predictions. From a comparison of Tables 7.6.1 and 7.6.2, the influent TKN concentrations derived in this manner for the IAWQ model compared well (to within 7%) of those accepted for the UCTPHO model.

7.2.2 Model set-up, calibration and testing

The use of AQUASIM (version 1.0) as a modelling platform has been described in detail by Riechert (1994). In particular, Section 8.2 of Riechert (1994) describes the procedure for encoding the old IAWPRC activated sludge model into AQUASIM. This method was followed, except that the modified or additional processes for BEPR and chemical precipitation were added as defined in the IAWQ ASM2 model (IAWQ, 1995).

The reactor layout depicted in Fig. 3.1 (Chapter 3) was used for both the IAWQ ASM2 (AQUASIM) and UCTPHO models. Actual influent flow data were used and constant a-recycle (3:1) and s-recycle ratios (1:1) were assumed. In the AQUASIM program, the a-recycle is set up as a "bifurcation" of an "advective link" from the (second) aerobic reactor (Reichert, 1994). In order to set up the sludge wasting (in practice from the second aerobic reactor), it was necessary to insert a hypothetical third aerobic reactor (of negligible volume) with a bifurcation (to a hypothetical drain) of the advective link from this reactor. Similarly, in order to set up the s-recycle, it was necessary to set up a hypothetical fourth reactor (of negligible volume) with a bifurcation of the advective link between it and the clarifier. By means of correct programming of the mass fluxes for the particulate versus soluble compounds, a "perfect" clarifier can be modelled such that no particulate mass leaves via the effluent (see example of IAWPRC Model No. 1 given on p180 of Reichert, 1994). This is the analogous approach to that used for the clarifier in the UCTPHO model (Wentzel, 1997).

In order to model the dosing of chemical precipitants, a small (0.5 ℓ) reactor was set up with an advective link to either the anaerobic or aerobic compartment of the activated sludge reactor system. A flow rate of 0.5 ℓ/d was provided for mass flux through this link. This modelled exactly the actual pilot plant layout in which the diluted metal salt solution was dosed to the system as an additional "feed line" with a small daily flow (0.5 ℓ/d).

Since the UCTPHO model (Wentzel *et al.*, 1992) was available in computer format which had been extensively tested (Wentzel, 1997), it was used as a bench mark for testing the IAWQ model in the AQUASIM format applied here. Apart from influent characteristics described in Tables 7.6.2, calibration of the IAWQ model was performed using the constants suggested by

FOR ALUMINIUM SALTS:

- **Reaction: $PO_4^{3-} + Al(OH)_3 \rightarrow AlPO_4 + 3OH^-$ when r =1; P/Al = 1**
  (see IAWQ, 1995)

Stoichiometry	S_{PO4} mgP/ℓ	X_{MeOH} mg/ℓ as $Al(OH)_3$	X_{MeP} mg/ℓ as $AlPO_4$	X_{TSS} mg/ℓ as TSS
Precipitation	-1	-2.52	+3.94	+1.42
Redissolution	+1	+2.52	-3.94	-1.42
Stoichiometry	S_{PO4} mmol/ℓ as P	X_{MeOH} mmol/ℓ as $Al(OH)_3$	X_{MeP} mmol/ℓ as $AlPO_4$	
Precipitation	-0.032	-0.032	+0.032	
Redissolution	+0.032	+0.032	-0.032	

MW, $Al(OH)_3$ = 78 g/mol
MW, $AlPO_4$ = 122 g/mol

- **Reaction: $PO_4^{3-} + 1.33\ Al(OH)_3 \rightarrow Al_{1.33}\ PO_4\ OH + 3OH^-$ when r =1.33; P/Al = 0.75**

Stoichiometry	S_{PO4} mgP/ℓ	X_{MeOH} mg/ℓ as $Al(OH)_3$	X_{MeP} mg/ℓ as $Al_{1.33}\ PO_4\ OH$	X_{TSS} mg/ℓ as TSS
Precipitation	-0.75	-2.52	+3.58	+1.06
Redissolution	+0.75	+2.52	-3.58	-1.06
Stoichiometry	S_{PO4} mmol/ℓ as P	X_{MeOH} mmol/ℓ as $Al(OH)_3$	X_{MeP} mmol/ℓ as $Al_{1.33}\ PO_4\ OH$	
Precipitation	-0.024	-0.032	+0.024	
Redissolution	+0.024	+0.032	-0.024	

MW, $Al(OH)_3$ = 78 g/mol
MW, $Al_{1.33}\ PO_4\ OH$ =148 g/mol

- **Reaction: $PO_4^{3-} + 1.43\ Al(OH)_3 \rightarrow Al_{1.43}\ PO_4\ OH_{1.29} + 3OH^-$ when r =1.43; P/Al = 0.70**

Stoichiometry	S_{PO4} mgP/ℓ	X_{MeOH} mg/ℓ as $Al(OH)_3$	X_{MeP} mg/ℓ as $Al_{1.43}\ PO_4\ OH_{1.29}$	X_{TSS} mg/ℓ as TSS
Precipitation	-0.70	-2.52	+3.51	+0.99
Redissolution	+0.70	+2.52	-3.51	-0.99
Stoichiometry	S_{PO4} mmol/ℓ as P	X_{MeOH} mmol/ℓ as $Al(OH)_3$	X_{MeP} mmol/ℓ as $Al_{1.43}\ PO_4\ OH_{1.29}$	
Precipitation	-0.023	-0.032	+0.023	
Redissolution	+0.023	+0.032	-0.023	

MW, $Al(OH)_3$ = 78 g/mol
MW, $Al_{1.43}\ PO_4\ OH_{1.29}$ =155.5 g/mol

- **Reaction: $PO_4^{3-} + 1.66\ Al(OH)_3 \rightarrow Al_{1.66}\ PO_4\ OH_2 + 3OH^-$ when r= 1.66, P/Al = 0.60**

Stoichiometry	S_{PO4} mgP/ℓ	X_{MeOH} mg/ℓ as $Al(OH)_3$	X_{MeP} mg/ℓ as $Al_{1.66}\ PO_4\ OH_2$	X_{TSS} mg/ℓ as TSS
Precipitation	-0.60	-2.52	+3.30	+0.78
Redissolution	+0.60	+2.52	-3.30	-0.78
Stoichiometry	S_{PO4} mmol/ℓ as P	X_{MeOH} mmol/ℓ as $Al(OH)_3$	X_{MeP} mmol/ℓ as $Al_{1.66}\ PO_4\ OH_2$	
Precipitation	-0.019	-0.032	+0.019	
Redissolution	+0.019	+0.032	-0.019	

MW, $Al(OH)_3$ = 78 g/mol
MW, $Al_{1.66}\ PO_4\ OH_2$ = 174 g/mol

Similarly, in the case of precipitation from ferric ions, the general formula $Fe_r\ PO_4\ OH_{(3r-3)}$ may be written and stoichiometry calculated as follows:

FOR FERRIC (IRON[III]) SALTS:

- **Reaction: $PO_4^{3-} + Fe(OH)_3 \rightarrow FePO_4 + 3OH^-$ when r =1, P/Fe = 1 (see IAWQ, 1995)**

Stoichiometry	S_{PO4} mgP/ℓ	X_{MeOH} mg/ℓ as $Fe(OH)_3$	X_{MeP} mg/ℓ as $FePO_4$	X_{TSS} mg/ℓ as TSS
Precipitation	-1	-3.45	+4.87	+1.42
Redissolution	+1	+3.45	-4.87	-1.42
Stoichiometry	S_{PO4} mmol/ℓ as P	X_{MeOH} mmol/ℓ as $Fe(OH)_3$	X_{MeP} mmol/ℓ as $FePO_4$	
Precipitation	-0.032	-0.032	+0.032	
Redissolution	+0.032	+0.032	-0.032	

MW, $Fe(OH)_3$ = 107g/mol
MW, $FePO_4$ = 151 g/mol

- **Reaction: $PO_4^{3-} + 1.33\ Fe(OH)_3 \rightarrow Fe_{1.33}PO4\ OH + 3OH^-$ when r =1.33, P/Fe = 0.75**

Stoichiometry	S_{PO4} mgP/ℓ	X_{MeOH} mg/ℓ as $Fe(OH)_3$	X_{MeP} mg/ℓ as $Fe_{1.33}PO4\ OH$	X_{TSS} mg/ℓ as TSS
Precipitation	-0.75	-3.45	+4.46	+1.01
Redissolution	+0.75	+3.45	-4.46	-1.01
Stoichiometry	S_{PO4} mmol/ℓ as P	X_{MeOH} mmol/ℓ as $Fe(OH)_3$	X_{MeP} mmol/ℓ as $FePO_4$	
Precipitation	-0.024	-0.032	+0.024	
Redissolution	+0.024	+0.032	-0.024	

MW, $Fe(OH)_3$ = 107g/mol
MW, $Fe_{1.33}PO4\ OH$ = 186 g/mol

- **Reaction: $PO_4^{3-} + 1.66\ Fe(OH)_3 \rightarrow Fe_{1.66}PO4\ (OH)_2 + 3OH^-$ when r =1.66, P/Fe = 0.60**

Stoichiometry	S_{PO4} mgP/ℓ	X_{MeOH} mg/ℓ as $Fe(OH)_3$	X_{MeP} mg/ℓ as $Fe_{1.33}PO4\ OH$	X_{TSS} mg/ℓ as TSS
Precipitation	-0.60	-3.45	+4.28	+0.83
Redissolution	+0.60	+3.45	-4.28	-0.83
Stoichiometry	S_{PO4} mmol/ℓ as P	X_{MeOH} mmol/ℓ as $Fe(OH)_3$	X_{MeP} mmol/ℓ as $FePO_4$	
Precipitation	-0.0194	-0.032	+0.0194	
Redissolution	+0.0194	+0.032	-0.0194	

MW, $Fe(OH)_3$ = 107g/mol
MW, $Fe_{1.66}\ PO4(OH)_2$ = 221 g/mol

- **Reaction: $PO_4^{3-} + 2.5\ Fe(OH)_3 \rightarrow Fe_{2.5}PO4\ (OH)_{4.5} + 3OH^-$ when r =2, P/Fe = 0.40**

Stoichiometry	S_{PO4} mgP/ℓ	X_{MeOH} mg/ℓ as $Fe(OH)_3$	X_{MeP} mg/ℓ as $Fe_{1.33}PO4\ OH$	X_{TSS} mg/ℓ as TSS
Precipitation	-0.40	-3.45	+4.01	+0.56
Redissolution	+0.40	+3.45	-4.01	-0.56
Stoichiometry	S_{PO4} mmol/ℓ as P	X_{MeOH} mmol/ℓ as $Fe(OH)_3$	X_{MeP} mmol/ℓ as $FePO_4$	
Precipitation	-0.013	-0.032	+0.013	
Redissolution	+0.013	+0.032	-0.013	

MW, $Fe(OH)_3$ = 107g/mol
MW, $Fe_{1.66}\ PO4(OH)_2$ = 311 g/mol

7.2.2.3 pH and alkalinity in the models

The UCTPHO and IAWQ models assume that pH in the activated sludge system is maintained close to neutrality. This is an acceptable assumption given that most biological systems operate optimally at a pH close to neutral. In Chapters 3, 4 & 5 it was reported that the reactor pH in the pilot plant systems used here fluctuated in the range 6.9 to 7.8, with median values close to pH 7.4. On this basis, the inherent assumption in the models with respect to pH appeared to be acceptable.

The UCTPHO and IAWQ models make provision for predicting *changes* in system alkalinity. This is particularly useful where low alkalinity influent wastewaters could yield a deficit in alkalinity as a result of nitrification or chemical precipitation reactions. However, in its present form, the IAWQ ASM No. 2 precipitation model (IAWQ, 1995) assumes that the loss of alkalinity through formation of metal hydroxide from added metal salt occurs *outside* the reactors (i.e. in the feed tank) and the model does *not* predict the *effect* of pH or alkalinity on chemical precipitation reactions. The loss of alkalinity due to precipitation may be easily included on the basis of known (or assumed) hydroxide stoichiometry in the precipitate. However, since surplus bicarbonate alkalinity (approx. 70 to 300 mg/ℓ as $CaCO_3$) was always present in the effluent during the experimental periods considered in this chapter, alkalinity was not included as a model parameter for this study.

7.2.3 Modelling results

The complete set of modelling results for the Test unit (IAWQ vs. Observed) and Control unit (IAWQ vs. UCTPHO vs. Observed) is given in Tables 7.8a and 7.8b respectively.

7.2.3.1 General observations: UCTPHO vs. IAWQ

Figure 7.7a shows a comparison of the predicted effluent (i.e. second aerobic reactor, AE2) soluble ortho P results for the two models, plotted against the observed effluent total P values[26] for the Control unit (R2). Similar results are shown in Figure 7.7b for the predicted soluble ortho P and observed filtered total P concentration of the anaerobic zone of the Control unit.

It can be seen from Fig. 7.7a that the UCTPHO and IAWQ models gave very similar effluent (AE2) ortho P predictions, which implies that their relative calibration was equivalent and that the IAWQ model structure in the AQUASIM program was correct. Fig. 7.7a also shows that good agreement was obtained between observed and predicted effluent phosphate values[27]. In one experimental period (Period 3.4.4), UCTPHO predicted complete P removal (effluent ortho P = 0.2 mgP/ℓ) while the IAWQ model predicted a value (2.2 mgP/ℓ), with the latter being closer to the observed effluent total P concentration (2.3 mgP/ℓ). No explanation could be found for this anomaly.

In general, the single biggest factor preventing better correlation between observed and predicted values, was the variability of the influent composition which probably contributed greatly to the relatively large standard deviations in the biological P removal data (Appendix 5). This problem has been commented on in Chapters 3, 4 and 5 and represents a weakness of the experimental set-up of this study. Ideally, the influent settled sewage should have been of sufficiently high COD strength that it could have been diluted down to a constant COD before feeding to the pilot plants. For an annual cycle, the Darvill settled sewage would have allowed this possibility only if a low

[26] The effluent soluble (filtered) ortho P and total P results were found to be very similar for the pilot plants since solids carryover from the clarifier was minimal (refer to Appendix 5). The observed total P results for the clarifier (CLAR) in Tables 7.8 (a&b) are plotted in Figs. 7.7 (a&b) and Figs. 7.8 (a,b,c).

[27] A linear correlation of the observed vs. predicted data (see Fig. 7.7a) gave a slope 1.5% to 3% greater than the 1:1 line (plotted), with $R^2 = 0.96$.

sewage COD contribution (ca. 100 mg/ℓ) was accepted as the norm[28]. Alternatively, a larger fraction of acetate could have been added to the influent[29].

According to IAWQ (1995), influent total P of municipal wastewater (which actually consists of ortho P and poly P - the latter originating from laundry detergents) may be approximated by the influent soluble ortho P. Fig. 7.7b shows that the predicted anaerobic zone soluble ortho P was generally approximately 15% less than the observed (filtered total P) values, for both models. At lower P concentrations (<20 mgP/ℓ), the agreement seemed to be better (Fig. 7.7b). Moreover, in the upper range, the difference between observed filtered total P and predicted soluble ortho P concentrations for the anaerobic zone was 10 to 15 mg/ℓ. Such large differences cannot be adequately explained on the basis of influent poly P of laundry detergent origin: for Darvill settled sewage, the difference between total P and ortho P concentrations is of the order of 3 to 4 mgP/ℓ (Chapter 6, Table 6.2). Further research with enhanced cultures and recalibration of the models would need to be undertaken to confirm the validity of observations from Fig. 7.7b. Since the model results for the effluent phosphate concentrations were in agreement with those observed for the Control, the differences noted for the steady state anaerobic zone ortho P concentration were not expected to impact on the study of *system P removal* predictions with or without chemical dosing. In other words, although the reactor ortho P concentration theoretically influences the rate of metal phosphate precipitation in IAWQ precipitation model formulation, in practice the precipitation reaction rapidly proceeds to completion, within realistic reactor retention times. Hence, the chemical P removal component is controlled mainly by stoichiometry and lowers the steady-state ortho P concentration in all the reactors while the slower biological processes continue to establish the relative ortho P concentrations in the respective reactors.

7.2.3.2 Precipitation results

Figures 7.8a, 7.8b and 7.8c show the predicted versus observed effluent (second aerobic zone) phosphate results for the IAWQ model in the presence (unit R1) and absence (unit R2) of alum, ferric chloride and ferrous-ferric chloride, respectively.

The ASM2 model (IAWQ, 1995) does not recommend kinetic or stoichiometric constants for precipitation reactions with alum. In this study, the same kinetic constants recommended by IAWQ (1995) for precipitation with ferric salts was applied to the case studies with alum. Only the stoichiometry was changed for alum (see section 7.2.3.2.1 below). A detailed investigation into the kinetic constants for the precipitation and redissolution reactions was not carried out. A cursory examination revealed that, for example, a change in k_{RED} (rate constant for dissolution) from 0.6 d-1 to 0.1 d-1 (while leaving the corresponding rate constant for precipitation, k_{PRE}, unchanged) made no difference to the predicted effluent soluble ortho P concentration. This implies that in the model formulation, the precipitation/ redissolution reactions are not rate-limited and easily reach completion within the hydraulic retention time of the experimental system used here (ca. 21 h). Hence, stoichiometry played the major role in determining the magnitude of P removal through precipitation processes for the experimental systems used in this study. However, it should be borne in mind that the IAWQ model assumes that the metal is dosed as metal hydroxide (effectively as an additional form of solids in the influent stream), and that redissolution of the metal phosphate precipitate results in reformation of metal hydroxide. The ratio of the rate constants for these precipitation/ redissolution reactions will have an effect on the steady-state concentration of metal phosphate relative to metal hydroxide; for the particular set of experimental conditions in this study, the effluent P concentration was relatively insensitive to the rate constants.

---

[28] This option was rejected since it would have produced low steady state VSS and low biological P removal potentials in the units, which was contrary to the aim of testing for possible interfering effects of chemical dosing on the BEPR mechanism under conditions in which the BEPR mechanism was strongly exhibited.

[29] The early alum dosing periods (notably Period 3.1.6 - see Chapter 3) with 250 mg/l influent acetate COD had presented settling (pin floc) problems which were suspected to be related to the high acid dose required for pH control under these conditions. However, with sufficient influent bicarbonate feed supplementation, these problems may have been overcome. The other option (reduced influent acetate, and no acid dosing) was adopted instead, which resulted in greater system P removal sensitivity to the sewage COD contribution.

7.2.3.2.1 Alum

The scatter in the data for observed versus predicted P concentrations (Fig. 7.8a) tended to confound accurate calibration of the model. The wide variation in observed $P_{removed}$: Al_{dosed} stoichiometry was highlighted in Chapter 3 (section 3.3.3.3). However, examining the results in Fig. 7.8a more closely, sampling or analytical error may be suspected for one experimental period (Period 3.2.2), with six observed results for the filtered AE2 zones averaging significantly higher than the eighteen observed results for the clarifier (effluent). For Periods 3.2.3 and 3.2.4, the observed effluent phosphate concentrations (both AE2 and effluent results, for the Test and Control units) were lower than the predicted results. It is possible that the systems were not operating suitably close to steady state during these periods. A new enhanced culture had been developed during August 1994 (ending with Period 3.2.1), but a slow increase in the average P content of the mixed liquor was noted in the Control reactor over the ensuing five months (refer to data in Appendix 5):

- Period 3.2.2 (Sept. 1994), R2 : Mean = 155.9 mgP/gVSS (± 11.7)
- Period 3.2.3 (Oct. - Nov. 1994), R2 : Mean = 185.1 mgP/gVSS (± 21.8)
- Period 3.2.4 (Nov. - Dec. 1994), R2 : Mean = 223.5 mgP/gVSS (± 19.9)
- Period 3.2.5 (Jan. 1995), R2 : Mean = 245.6 mgP/gVSS (± 10.0)
- Period 3.2.6 (Jan. 1995), R2 : Mean = 245.1 mgP/gVSS (± 7.1)

These data suggest that it may take up to six months for a (semi-) enhanced culture to be developed and reach steady-state. The changes were slow and difficult to discern during experimentation, occurring against a background of variance produced by changes in influent composition. Moreover, the P mass balances for Periods 3.2.3 and 3.2.4 were acceptable (Table 3.13, Chapter 3). Nevertheless, Fig. 7.8a suggests the need for caution in the interpretation of the results for these periods. For this reason, the data for R1 in Periods 3.2.3 and 3.2.4 were not used in the estimation of alum precipitation stoichiometry (Fig. 7.8a). Unfortunately this prevented evaluation of the low observed molar ratios of $P_{removed}$: Al_{dosed} = 0.18 to 0.34 for these periods (Table 3.14, Chapter 3).

In contrast, Period 3.2.5 was included in Fig. 7.8a. The results for this period with a high alum dose to the anaerobic zone of R1, had shown a somewhat lower molar ratio of $P_{removed}$: Al_{dosed} (0.57 mol P/mol Al), compared to other periods (molar ratios of $P_{removed}$: Al_{dosed} = 0.62 to 0.70 mol P/mol Al; Table 3.14, Chapter 3). Using the IAWQ model, reasonable correlation between observed and predicted AE2 zone ortho P values was obtained for Period 3.2.5 for stoichiometry of 0.60 mg P per 2.52 mg $Al(OH)_3$, i.e. 0.60 mol $P_{removed}$ per mol Al_{dosed} (Table 7.7). The lower molar ratio for Period 3.2.5 compared to the other alum dosing periods may have resulted from inhibition of the biological P removal mechanism, associated with alum being dosed at relatively high concentrations (9.3 mg/ℓ as Al , based on influent flow) to the anaerobic zone[30].

Model stoichiometry in the range 0.6 to 0.75 mol P/ mol Al for chemical precipitation is in broad agreement with that observed by difference in observed system P removal performance between the Test and Control units (Table 3.14, Chapter 3 - ignoring Periods 3.2.3 and 3.2.4, see above), as well as that estimated from fractionation data (Table 3.18, Chapter 3).

The role of pH and system alkalinity in relation to simultaneous precipitation processes needs to be studied further and there could be scope for inclusion in the IAWQ model of a function relating precipitation efficiency to reactor pH at the point of dosing. Evidence was found in this study (see Chapter 3, section 3.3.3.3) that bicarbonate alkalinity stabilised combined chemical-biological P removal with simultaneous chemical dosing, and that a reactor pH of ≤ 7.2 at the point of dosing resulted in significant inhibition of the biological P removal process, compared to a reactor pH in the range 7.2 to 7.6. In terms of system P removal, the benefit of alum addition under such conditions may be lost and the *apparent* effect is a reduction of chemical P precipitation efficiency. The IAWQ model, in its present format, is not able to *predict* inhibition of the biological process

[30] This observation was also made in Chapter 3 (sections 3.3.3.2 and 3.3.3.3). The IAWQ model is not able to predict inhibition of the bio-P mechanism in the absence of P limitation (see section 7.2.4.1), thus requiring a downward adjustment of P:Al stoichiometry to compensate for loss of system P removal.

(nor precipitation efficiency) and future research should focus on this aspect, particularly in so far as it relates to pH.

7.2.3.2.2 Ferric chloride

Ferric chloride dosing periods (Fig. 7.8b) showed good general agreement between observed and predicted phosphate values using the molar P:Fe stoichiometry in the range 0.60 to 1.0 for periods without P limitation. The fact that the stoichiometry applied in the model tended to be less than the ideal 1:1 stoichiometry for $FePO_4$ may be due to partial inhibition of the biological P removal mechanism (even without P-limitation), in a manner which the model is not able to predict[31]. The lowest stoichiometry observed for ferric chloride dosing periods was in Period 3.3.6, with a high ferric dose to the aerobic zone. It is probably significant that inexplicably low biological P release was noted for R1 compared to the Control (R2) during this period (Chapter 4, section 4.3.2.2). This suggested that the BEPR mechanism was more markedly inhibited in some way during this period. This observation may be related to the apparent deflocculation and settling problems (reduced zone settling velocity) also noted during this period and preceding periods (Chapter 4, section 4.3.10). As a result of weakened BEPR, the interpretation that chemical precipitation efficiency decreased during this period would be incorrect.

In general terms, P:Fe stoichiometry in the range 0.9 to 1.0 is in agreement with that observed from differences in system P release between the Test and Control units for ferric chloride dosing periods without P limitation for a 20d sludge age (Table 4.6, Chapter 4). These results are also in general agreement with those of Rabinowitz and Marais (1980) who reported 1:1 P:Fe stoichiometry for precipitation with ferric salts under similar conditions, also at a 20d sludge age. The modelled stoichiometry is somewhat higher than that observed from fractionation data; as discussed in Chapter 4 (section 4.3.6), this may be due to the failure of the fractionation method to account for all forms of chemical precipitate with iron.

Under P-limiting conditions (Periods 3.6.1 and 3.6.2a), the stoichiometry of precipitation was adjusted downwards to approximate that found by fractionation. This was somewhat arbitrary since both the Test and Control systems achieved similar low effluent ortho P concentrations (mean ca. 0.21 to 0.44 mgP/ℓ) during these periods. The IAWQ model predicted virtually complete P removal for the *Control* unit (predicted effluent ortho P = 0.1 to 0.16 mgP/ℓ); due to P limitation, iron addition to the Test unit produced virtually no further removal (0.01 to 0.03 mgP/ℓ). It is worth noting that equilibrium effects due to ion-pairing may produce a minimum limit for residual soluble ortho P (e.g. Fig. 7.4 above). A draw-back of the IAWQ model may be that it lacks the sophistication to take such effects into account. However, this is of minor consequence, since P removal may be regarded as essentially complete at effluent P concentrations of <0.5 mgP/ℓ, and uncertainty over certain key equilibrium constants would weaken confidence in a more complex equilibrium model (see section 7.1.4.1 above).

7.2.3.2.3 Ferrous-ferric chloride blend

The blend of ferrous-ferric chloride used (see Chapter 5) was a commercial product containing approximately 90% Fe (II) and 10% Fe (III). In order to model the addition of this chemical, it was assumed that oxidation of Fe (II) to Fe (III) was rapid (instantaneous) and complete after addition to the activated sludge reactor. Furthermore, it was assumed that precipitation took place from Fe (III) ions in the manner described above for the IAWQ model (section 7.1.5). These assumptions are consistent with the literature (see Chapter 1, section 1.2.1.1), and reasonable for the aerobic reactor, considering that the oxidation of Fe (II) to Fe (III) is likely to take <1 h (see 1.2.1.1) compared to the aerobic retention time of at least 2.7h in the pilot plant. In the case of dosing to the anaerobic reactor, the above-mentioned assumption leads to the apparent contradiction that

[31] This observation was also made in Chapter 4 (sections 4.3.2.2, 4.3.6 and 4.3.7) - refer also to section 7.2.4.1. However, as will be discussed in Chapter 8, it may also reflect the fact that the kinetics of "precipitation" (or more, likely, phosphate complexation by colloidal metal hydroxide) is substantially slower than assumed in the IAWQ ASM2 model (IAWQ, 1995). "Saturation" of the phosphate-binding capacity of the metal hydroxide may be incomplete at sludge ages <20d, hence, producing the observed stoichiometry of <1 mol P/ mol Fe.

oxidation of the Fe (II) ions dosed is considered to take place in the absence of oxygen (or nitrate). However, this contradiction may be academic since oxidation of Fe (II) ions, followed by precipitation of Fe(III) ions, will certainly take place once the mixed liquor moves in the aerobic zone. On the other hand, there is some evidence that ferrous phosphate (vivianite) may precipitate under anaerobic conditions (section 1.2.1.1). It is not clear whether the ferrous ions in this precipitate will oxidise with time under aerobic conditions.

The experimental periods in which ferrous-ferric chloride (≥ 90% Fe in ferrous form) was dosed (Fig. 7.8c) showed good general agreement between observed and predicted phosphate values for an assumed molar P:Fe stoichiometry of 0.75 in the absence of P limitation, using the IAWQ model. This is in agreement with the results of Rabinowitz and Marais (1980) who reported that chemical P removal from simultaneous dosing with ferrous sulphate was 80% of the stoichiometric amount (i.e. P:Fe stoichiometry = 0.8:1). The fact that the stoichiometry of P removal (in terms of the IAWQ model) appeared to be somewhat lower for ferrous-ferric chloride in comparison with ferric chloride, may reflect the fact that ferrous phosphate, $Fe_3(PO_4)_2$ does precipitate to some extent. However, the variance in the data prevented more accurate calibration of the model. Approximate agreement was obtained between the model stoichiometry used and that calculated from system P removal and fractionation data (Tables 5.6 and 5.12a, Chapter 5). This was more true for ferrous-ferric chloride dosing periods with (partial) P limitation, in which the model P:Fe stoichiometry applied was 0.4 to 0.6 mol P/mol Fe.

7.2.3.2.4 The question of bio-P mechanism inhibition vs. precipitation stoichiometry

In chapters 3, 4 and 5, experimental evidence was presented which suggested that the biological P (bio-P) removal mechanism is inhibited to a certain degree in the presence of simultaneous chemical addition. This evidence took the form of fractionation data and P release mass balance data for the anaerobic zone. These data are collated in Table 8.1 (Chapter 8) and may be summarised as follows:

- **Alum** (Chap. 3, section 3.4) produced 10 to 17% inhibition at doses of 5 mg/ℓ as Al (based on influent), and 20 to 24% inhibition at 9 mg/ℓ as Al. In all of these tests, P was added to the influent and was therefore never limiting.
- **Ferric chloride** (Chap. 4, section 4.4) produced 3 to 21% (average ca. 11%) inhibition for doses of 10 to 20 mg/ℓ as Fe (based on influent) under conditions when P was never limiting; the higher dose produced more inhibition in some, but not all, instances. Under P-limited conditions, inhibition of the biological mechanism was greater (approx. 35%), but the chemical precipitation efficiency was reduced to approximately the same extent.
- **Ferrous-ferric chloride blend (ca. 90% ferrous)** (Chap. 5, section 5.4) never gave more than 13% inhibition at doses of 10 to 19 mg/ℓ as Fe (based on influent), under conditions where P was never limiting. In one test period ca.10% stimulation of the bio-P mechanism was found. Under P-limited conditions, the bio-P mechanism was inhibited to a greater extent (23 to 39%).

The IAWQ precipitation model assumes that the chemical and biological P removal mechanisms operate independently of each other, except in so far as reactor soluble phosphate is concerned. From the above summary, it can be noted that a degree of inhibition of the bio-P mechanism in the presence of simultaneous chemical addition was found in most instances, even where P was not limiting. Where inhibition of the bio-P mechanism occurs, it may be expected that the stoichiometry of the metal (Me) phosphate precipitate (i.e. r = Me:P molar ratio) required in the IAWQ model to match the observed system P removal in the Test unit (R1), will be greater than the ideal stoichiometry (i.e. $r > 1$, for a trivalent metal ion). Again, the reason is that the model assumes that the biological and chemical mechanisms operate independently of one another: if P is not limiting, the model will predict that bio-P removal is essentially the same, irrespective of metal ion addition. If the observed system P removal in the presence of metal ion addition is less than that expected for ideal precipitate stoichiometry, then a lower stoichiometry will be required to match the predicted and observed system P removal.

Examining the modelling results in Figs. 7.8a to 7.8c and Table 7.7, and ignoring periods in which effluent P was potentially limiting (notably Periods 3.4.4, 3.5.2, 3.6.1 and 3.6.2) it can be seen that :

- For **alum** dosing periods, P:Al stoichiometry usually ranged 0.70 to 0.75 (r = 1.33 to 1.43), with adjustment to 0.6 (r = 1.67) for one experimental period where inhibition of the bio-P mechanism was pronounced (from fractionation and P release data). The fact that ideal stoichiometry (r = 1:1) did not materialise in the modelling results for any of the alum experimental periods, suggests that partial inhibition of the biological mechanism occurred. However, for a Control system typically producing bio-P removal of ca. 22 mgP/l during these experimental periods, inhibition by 10 to 20% (see above) would amount to ca. 2.2 to 3.7 mgP/l removal; adjustment of the stoichiometry from 1:1 to 0.75 P:Al amounts to 1.3 mgP/l for a dose of 5 mg/l as Al (based on influent). This suggests that inhibition of the bio-P mechanism does not fully account for the lower P:Al stoichiometry observed. The observed stoichiometry may also be attributable to the nature of the precipitate formed. For example, a theoretical aluminium hydroxy-phosphate formula such as $Al_{1.33}(X^{2+})PO_4$ $(OH)_3$ (where X^{2+} is some unknown cation, possibly Ca^{2+}) appears to be consistent with alkalinity data (Chapter 3, section 3.4) and fits the model stoichiometry adopted (P:Al = 0.75)[32]. At present, the IAWQ model assumes that the dosed metal enters the system as metal hydroxide, i.e. that alkalinity changes take place outside the model. The steady-state amounts of metal phosphate formed relative to metal hydroxide residual, are related to the stoichiometry of the precipitate specified in the IAWQ model, but alkalinity changes as a result of precipitation reactions are not related to the stoichiometry. Modelling of the alkalinity changes would help to provide a more direct link between the expected stoichiometry of the metal hydroxy-phosphate precipitate which is most likely formed. In addition, analysis of influent and effluent cation balances may allow the identity of other possible cations participating in the precipitation reactions to be determined, although allowance for biological uptake (e.g. for Mg ions) would also need to be made.

- For **ferric chloride** dosing periods at effluent P concentrations exceeding 10 mgP/ℓ, 1:1 P:Fe stoichiometry gave a good fit of predicted and observed P removal data for three experimental periods, while a further three experimental periods gave P:Fe stoichiometry in the range 0.60 to 0.90. Again, this suggests that inhibition of the biological mechanism could be significant for modelling purposes. No simple trend between the model stoichiometry and measured extent of inhibition of the bio-P mechanism could be found, although the period with lowest P release in the anaerobic reactor also required the lowest P:Fe model stoichiometry. However, it may not be possible to resolve low levels of inhibition (ca. 10%) within the constraints of model calibration and variance in the data (Fig. 7.8b). For example, with a typical Control system bio-P removal of ca. 23 mgP/ℓ, inhibition of the biological mechanism by 10% (see above) would amount to a margin of 2.3 mgP/ℓ, or 0.2 to 0.4 mol P/mol Fe for 10 to 20 mg Fe/ℓ, based on influent. On the one hand, a number of points in Fig. 7.8b lie within this margin of the line for perfect fit between predicted and observed effluent ortho P values. On the other hand, the nature of the precipitate also needs to be taken into account. If 1:1 P:Fe stoichiometry is accepted, then it is not clear how the observed alkalinity changes can be accommodated (ca. 2.2 mol consumed/ mol Fe dosed - see section 4.4 of Chapter 4). A stoichiometry of 0.6 mol P/mol Fe allows the alkalinity changes to be accounted for with the theoretical formula $Fe_{1.66}(X^{2+})$ PO_4 $(OH)_4$ where X^{2+} is an unknown divalent cation (e.g. Ca^{2+}). This aspect deserves further investigation, as will be discussed in Chapter 8.

- For **ferrous-ferric chloride**, 0.75:1 P:Fe stoichiometry gave a good fit for four experimental periods at effluent P concentrations of ca. 4 to 25 mgP/l. The reduced stoichiometry from 1:1 may be due to inhibition of the biological mechanism. For example, for a Control system bio-P removal typically of ca. 15 mgP/l during experimental periods 3.4.1 to 3.4.4, inhibition by 10% would amount to ca. 1.5 mgP/ℓ removal; adjustment of the stoichiometry from 1:1 to 0.75 P:Fe amounts to 1.3 mgP/l for a dose of 10 mg/l as Fe (based on influent). This suggests that inhibition of the bio-P mechanism could largely explain the lower P:Fe stoichiometry observed. Alternatively, if inhibition of the biological mechanism is neglected, the 0.75:1 P:Fe stoichiometry appears to be in keeping with observed alkalinity changes, assuming a

[32] It should be noted, though, that the apparent stoichiometry cannot be entirely attributed to *both* the inhibition of the bio-P mechanism and the formation of a "non ideal" metal hydroxy phosphate precipitate in which r > 1.

precipitate of ferric-hydroxy phosphate forms with an average formula of $Fe_{1.33}$ (X^{2+}) $PO_4(OH)_3$. In the same manner as discussed above for alum, this could indicate that ideal precipitation (1:1 Fe:P stoichiometry) may not occur in practice. Inclusion of kinetic processes for alkalinity in the IAWQ model may help to reconcile these differences from a modelling point of view.

Finally, it is worth noting that, under low (ca. <2 mgP/ℓ as effluent ortho P), the IAWQ model did, to some extent, predict partial "inhibition" of the bio-P mechanism by virtue of a lower poly P content (see Table 7.9 and discussion under section 7.2.4.1 below).

Figures 7.7a & b ...../
Figures 7.8a, b & c ...../
Tables 7.8a & b ...../

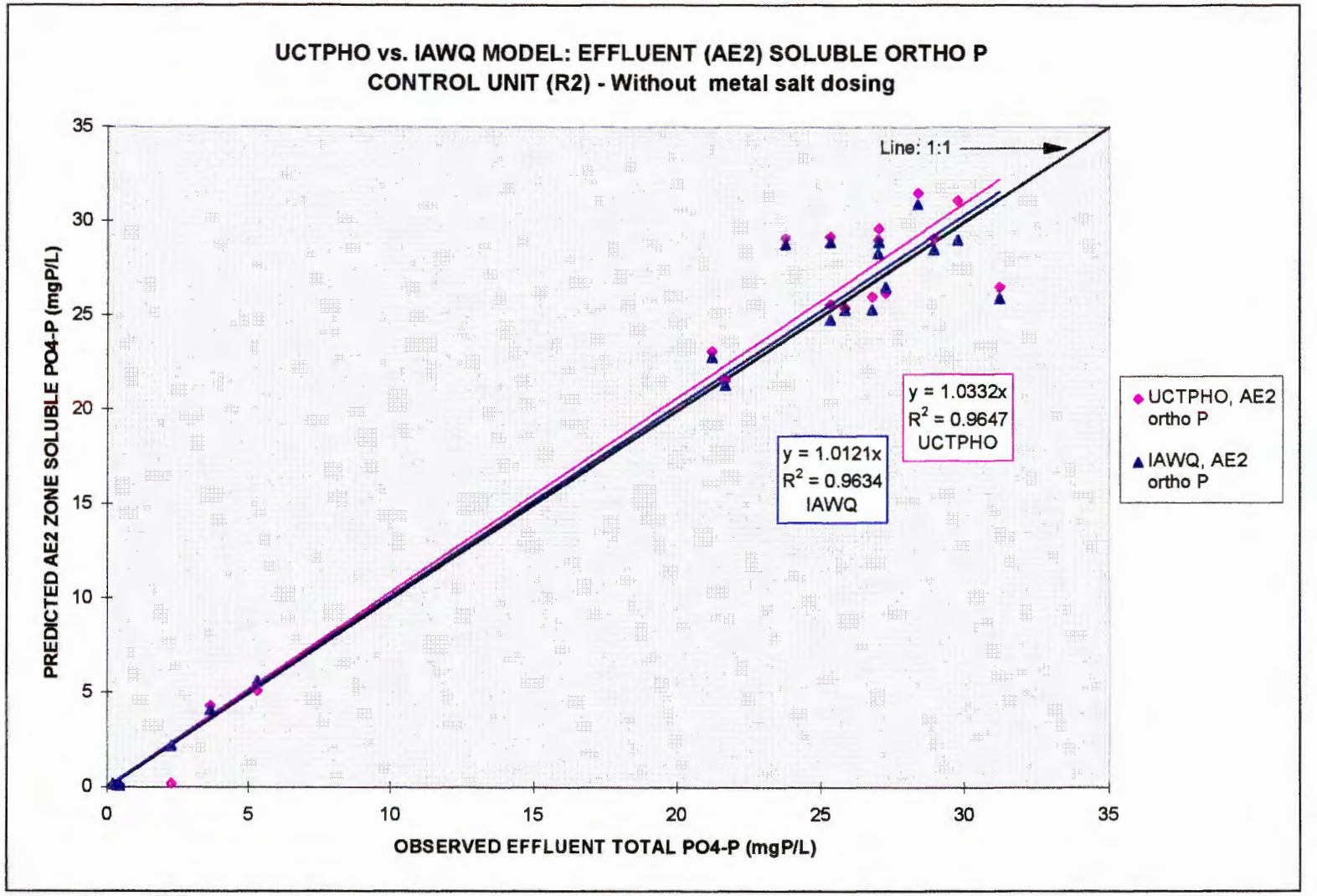


Figure 7.7a: Comparison of predicted second aerobic zone soluble ortho P and observed effluent total P .

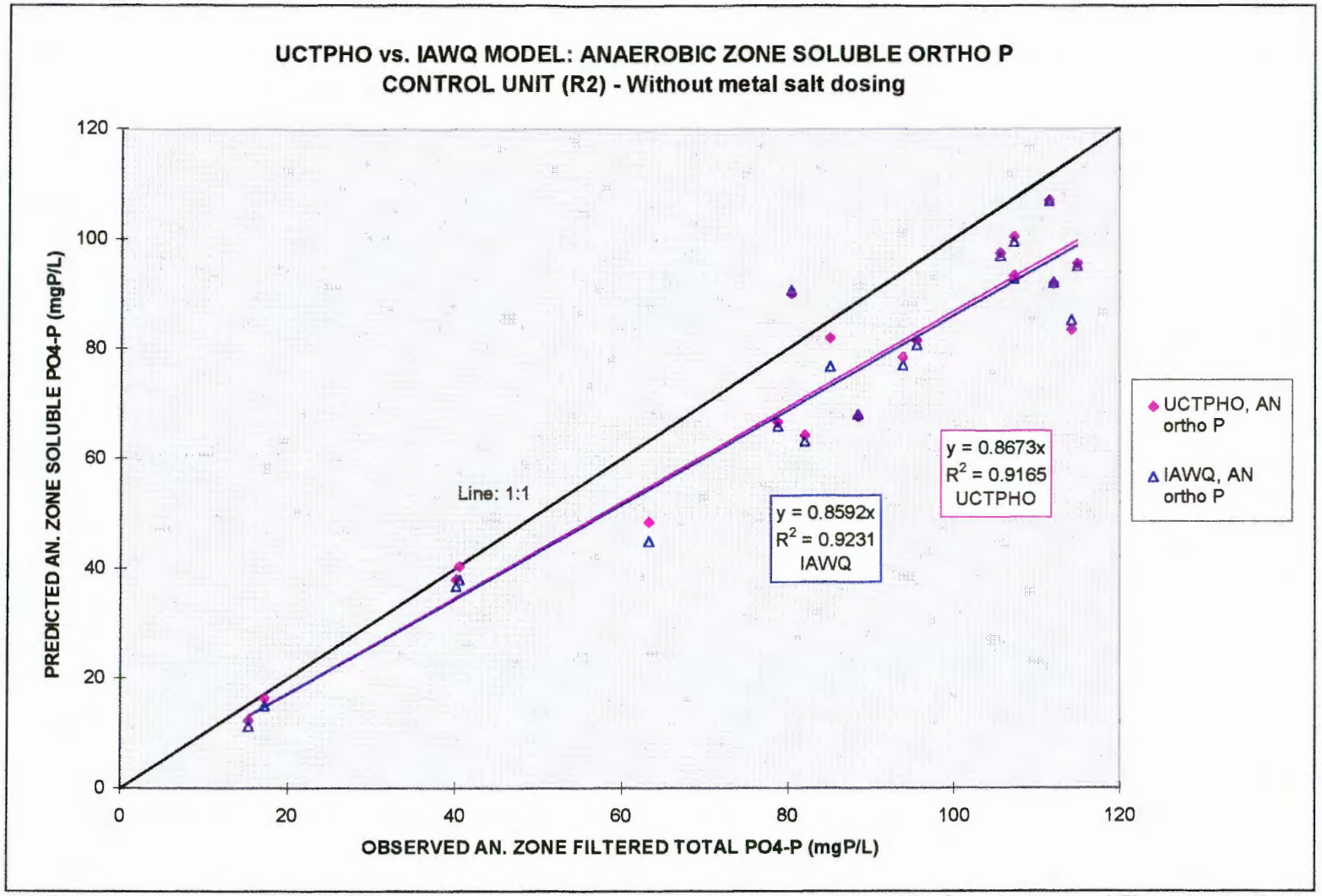


Figure 7.7b: **Comparison of predicted and observed anaerobic zone soluble ortho P and observed filtered total P.**

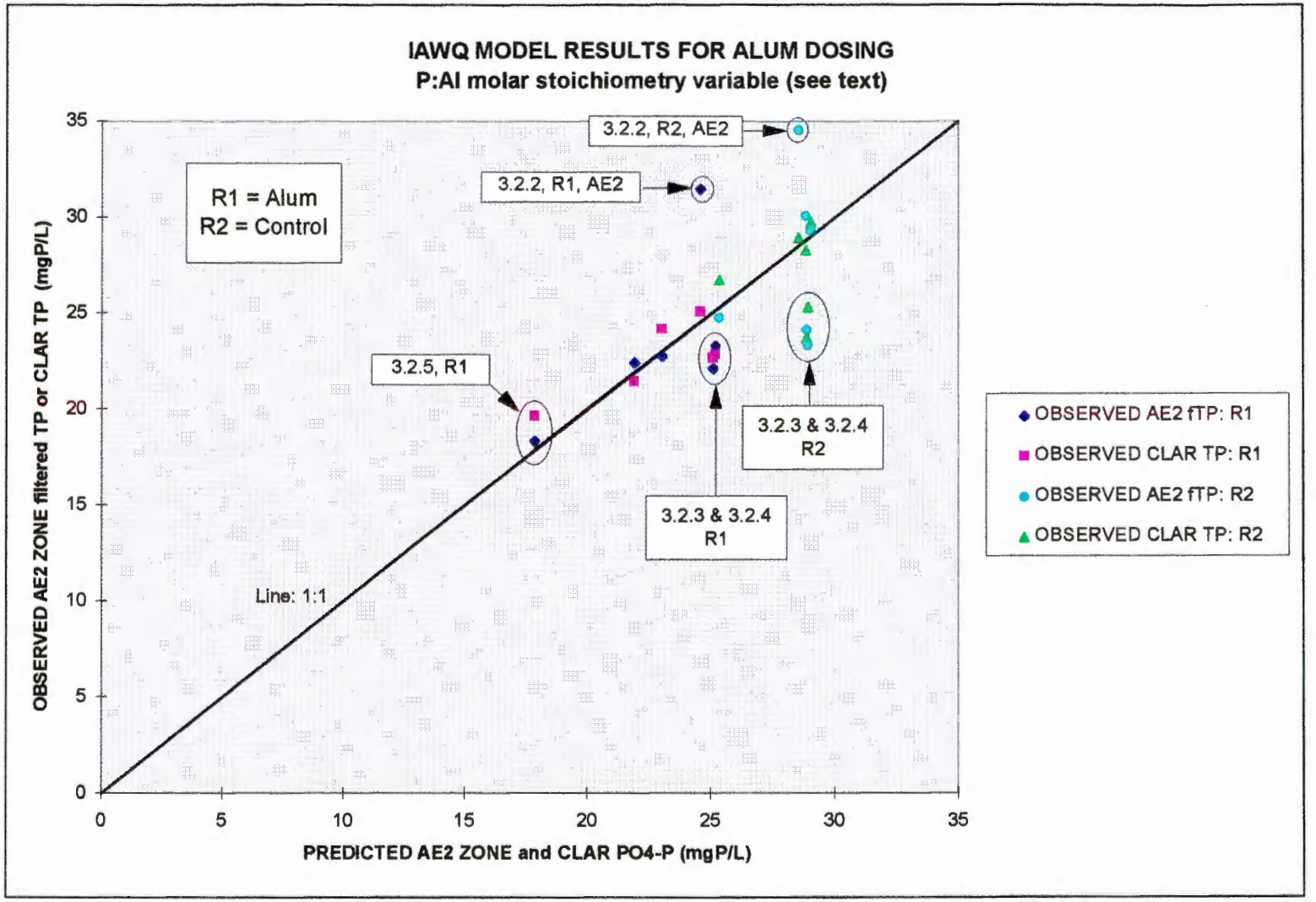


Figure 7.8a: Predicted (IAWQ) versus observed results for alum dosing periods.

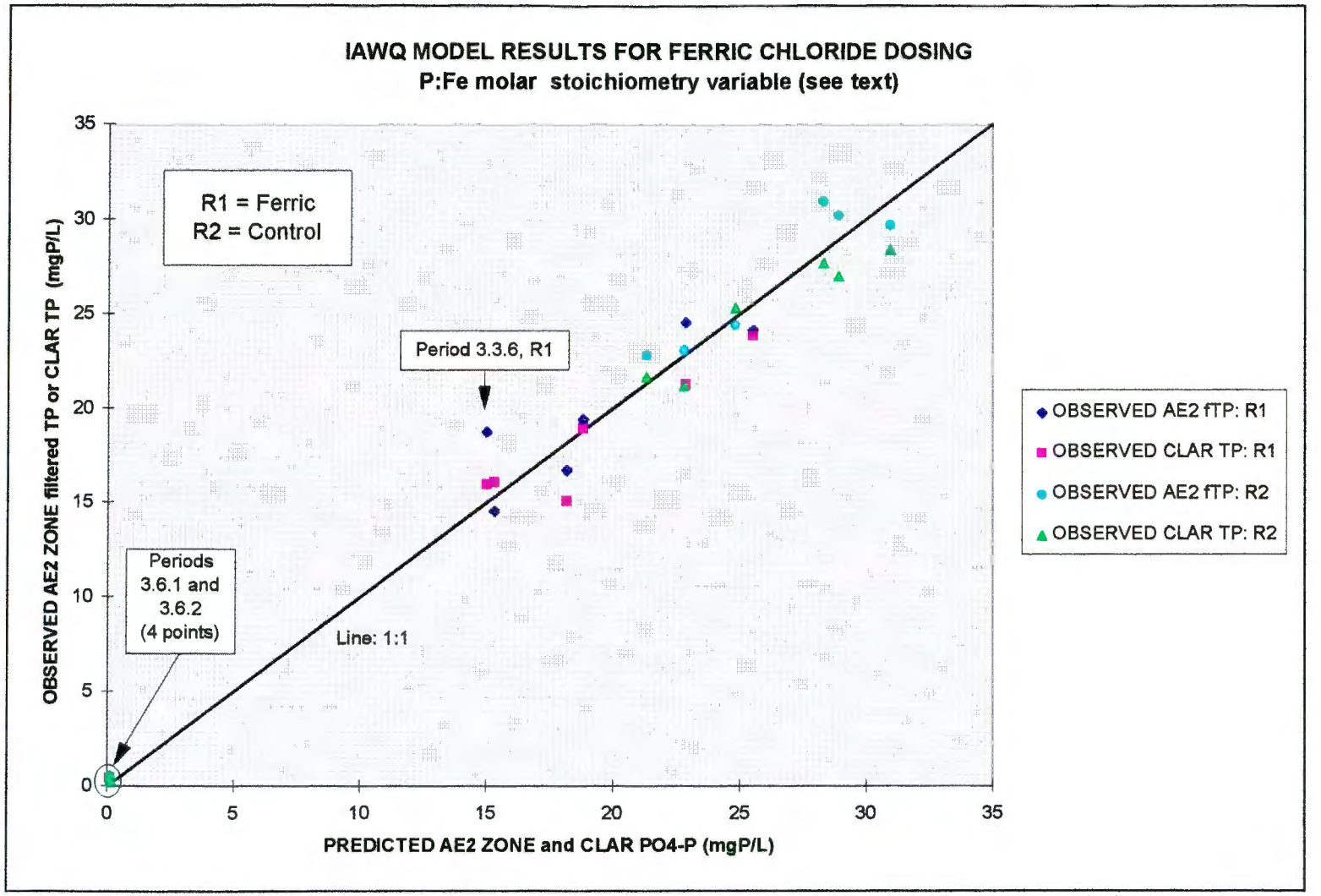


Figure 7.8b: **Predicted (IAWQ) versus observed results for ferric chloride dosing periods.**

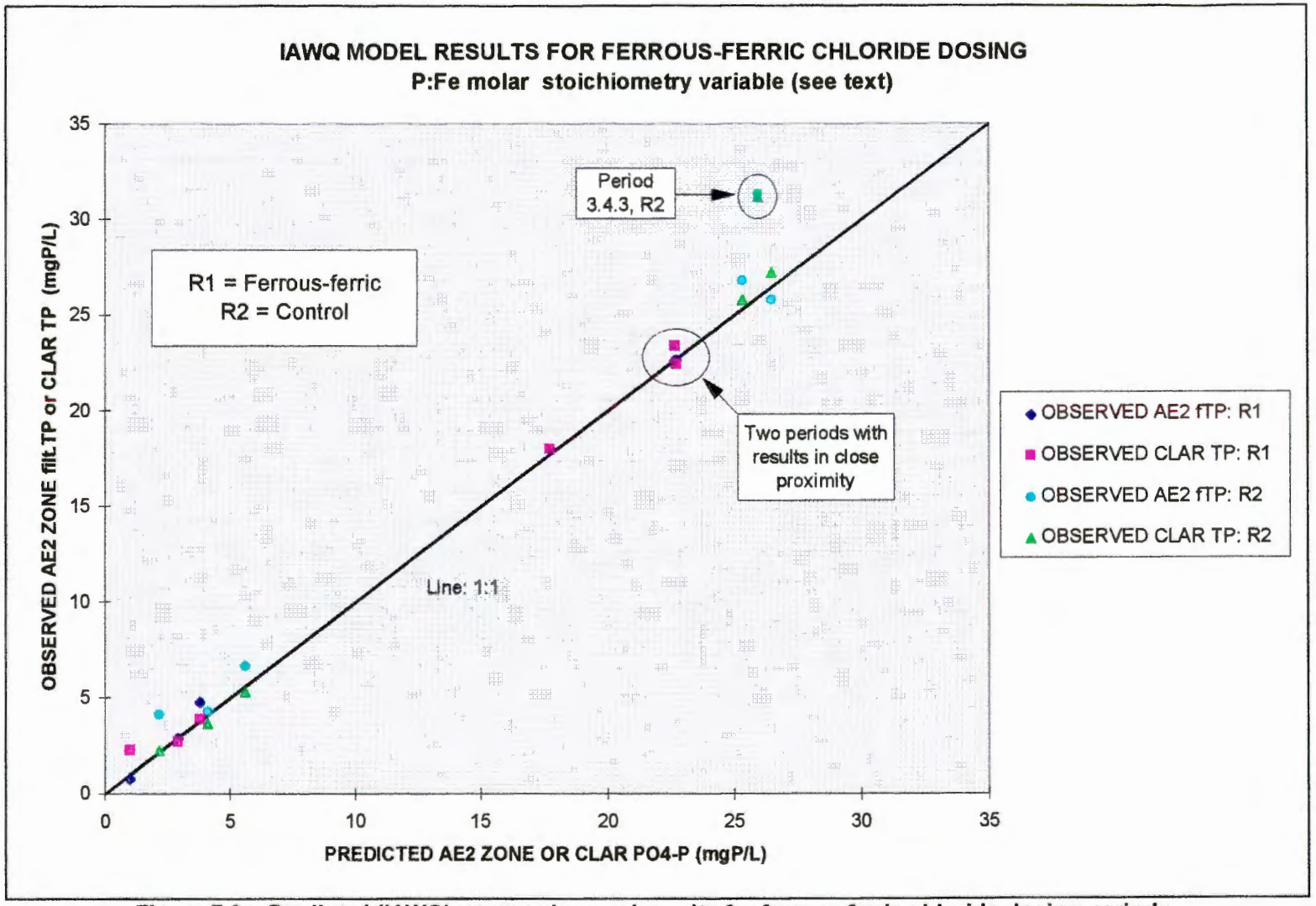


Figure 7.8c: Predicted (IAWQ) versus observed results for ferrous-ferric chloride dosing periods.

Table 7.8a: Comparison between observed and predicted results for pilot plants according to IAWQ model: TEST UNIT (R1).

ALUM DOSING TO TEST UNIT (R1). Dosage given in mg/ℓ as Al based on influent flow.

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_I mg COD/ℓ	O_t $mgO_2/(ℓ.h)$	VSS / X_{VSS} mg VSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P	MeP mg/ℓ as precipitate	MeOH mg/ℓ as precipitate
3.2.2	AN	OBSERVED	123.03	0.01				N.D.		N.D.	N.D.	N.D.	N.D.
4.8 mg/ℓ Al		IAWQ	103.0	0.00				0.0		151	377	456	3
AE 1	AX	OBSERVED	65.86	0.41				N.D.		N.D.	N.D.	N.D.	N.D.
R_s = 20d		IAWQ	54.5	1.2				0.0		79	423	456	6
Bicarb. = 50	AE1	OBSERVED	44.87	3.00				N.D.		N.D.	N.D.	N.D.	N.D.
		IAWQ	35.5	4.3				29.2		53	439	456	8
	AE2	OBSERVED	31.48	2.52				18.84	3040	N.D.	N.D.	N.D.	N.D.
		IAWQ	24.7	5.1	0.2	2.82	24	18.1	2705	35	451	452	10
	CLAR	OBSERVED	25.07	2.8	0.30	2.67	25	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
3.2.3	AN	OBSERVED	114.16	0.07				N.D.		N.D.	N.D.	N.D.	N.D.
4.6 mg/ℓ Al		IAWQ	91.3	0.0				0.0		129	338	456	3
AE 1	AX	OBSERVED	57.42	2.86				N.D.		N.D.	N.D.	N.D.	N.D.
R_s = 20d		IAWQ	49.9	1.8				0.0		68	377	456	6
Bicarb.= 100	AE1	OBSERVED	35.29	7.38				N.D.		N.D.	N.D.	N.D.	N.D.
		IAWQ	34.7	4.1				21.3		46	390	456	8
	AE2	OBSERVED	23.32	7.64				16.09	2756	N.D.	***403***	***425***	N.D.
		IAWQ	25.2	5.0	0.38	3.76	22	14.3	2654	31	400	452	10
	CLAR	OBSERVED	22.83	7.63	0.57	3.80	23	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

Table 7.81 continued: Comparison between observed and predicted results for pilot plants according to IAWQ model.

ALUM DOSING TO TEST UNIT (R1).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_I mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mg VSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P	MeP mg/ℓ as precipitate	MeOH mg/ℓ as precipitate
3.2.4	AN	OBSERVED	96.16						N.D.		N.D.	N.D.	N.D.
4.6 mg/ℓ Al		IAWQ	87.1						N.D.		321	462	3
AN	AX	OBSERVED	51.84						N.D.		N.D.	N.D.	N.D.
R_s = 20d		IAWQ	47.8						N.D.		360	458	6
Bicarb.= 100	AE1	OBSERVED	31.95						N.D.		N.D.	N.D.	N.D.
		IAWQ	34.0						N.D.		374	457	8
	AE2	OBSERVED	22.12						2422		***372***	***427***	N.D.
		IAWQ	25.1						2419		383	452	10
	CLAR	OBSERVED	22.67						N.D.		N.D.	N.D.	N.D.
3.2.5	AN	OBSERVED	70.60	0.05					N.D.	N.D.	N.D.	N.D.	N.D.
9.3 mg/ℓ Al		IAWQ	68.1	0.04					N.D.	94	302	764	8
AN	AX	OBSERVED	41.34	2.48					N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 20d		IAWQ	39.3	2.90					N.D.	48	331	758	12
Bicarb.= 150	AE1	OBSERVED	28.84	5.63				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	29.2	4.48				13.9	N.D.	33	342	755	15
	AE2	OBSERVED	22.75	5.97				10.79	2110	N.D.	***301***	***790***	N.D.
		IAWQ	23.0	5.24	0.4	2.2	16	9.5	1789	22	349	750	19
	CLAR	OBSERVED	24.14	5.84	0.46	2.09	16		N.D.	N.D.	N.D.	N.D.	N.D.

Table 7.81 continued: Comparison between observed and predicted results for pilot plants according to IAWQ model.

ALUM DOSING TO TEST UNIT (R1).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_I mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mgVSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P	MeP mg/ℓ as precipitate	MeOH mg/ℓ as precipitate
3.2.6	Not modelled - experimental period too short												
3.2.7	AN	OBSERVED	71.58	0.03					N.D.	N.D.	N.D.	N.D.	N.D.
9.3 mg/ℓ Al		IAWQ	83.6	0.01					N.D.	121	300	811	7
AN	AX	OBSERVED	40.53	1.96					N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 20d		IAWQ	44.9	2.0					N.D.	64	336	811	14
Bicarb.= 150	AE1	OBSERVED	28.54	5.21				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	30.3	4.7				24.8	N.D.	44	349	811	19
	AE2	OBSERVED	22.40	5.11				10.76	2095	N.D.	N.D.	N.D.	N.D.
		IAWQ	21.9	5.3	0.1	2.03	17	14.4	1980	29	358	805	24
	CLAR	OBSERVED	21.41	4.80	0.01	2.16	16		N.D.	N.D.	N.D.	N.D.	N.D.
3.2.8a	AN	OBSERVED	73.90						N.D.			N.D.	N.D.
9.3 mg/ℓ Al		IAWQ	81.5						N.D.			827	8
AE 1	AX	OBSERVED	39.46						N.D.			N.D.	N.D.
R_s = 20d		IAWQ	40.7						N.D.			825	15
No Bicarb.	AE1	OBSERVED	26.25						N.D.			N.D.	N.D.
		IAWQ	25.9						N.D.			823	21
	AE2	OBSERVED	18.32						2069			***790***	N.D.
		IAWQ	17.9						1940			814	28
	CLAR	OBSERVED	19.63						N.D.			N.D.	N.D.

Table 7.8a continued: Comparison between observed and predicted results for pilot plants according to IAWQ model.

FERRIC CHLORIDE DOSING TO TEST UNIT (R1).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_I mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mgVSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P	MeP mg/ℓ as precipitate	MeOH mg/ℓ as precipitate
3.3.1(b)	AN	OBSERVED	93.53	0.08				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
10 mg/ℓ Fe		IAWQ	91.23	0.0				0.0	N.D.	134	350	606	4
R_s = 20d	AX	OBSERVED	49.74	3.75				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
AE1		IAWQ	48.79	1.8				0.0	N.D.	71	390	606	8
	AE1	OBSERVED	34.58	6.66				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	32.58	5.1				31.3	N.D.	48	404	606	11
	AE2	OBSERVED	24.52	6.48				16.12	2273	N.D.	***321***	***550***	N.D.
		IAWQ	22.86	5.7	0.1	2.52	22	18.1	2321	32	415	601	15
	CLAR	OBSERVED	21.63	6.76	0.27	2.34	21	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
3.3.2	AN	OBSERVED	104.07	0.11				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
20 mg/ℓ Fe		IAWQ	78.42	0.01				N.D.	N.D.	122	316	1210	10
AE1	AX	OBSERVED	51.23	1.10				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	39.65	1.8				N.D.	N.D.	63	353	1207	20
	AE1	OBSERVED	27.09	4.96				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	25.38	3.8				22.80	N.D.	43	366	1203	29
	AE2	OBSERVED	16.70	5.15				14.92	2357	N.D.	***398***	***1024***	N.D.
		IAWQ	18.16	5.1	0.9	2.52	20	17.3	2492	28	375	1191	37
	CLAR	OBSERVED	15.05	6.11	1.46	2.34	19	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

Table 7.8a continued: Comparison between observed and predicted results for pilot plants according to IAWQ model.
FERRIC CHLORIDE DOSING TO TEST UNIT (R1).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_I mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mgVSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P	MeP mg/ℓ as precipitate	MeOH mg/ℓ as precipitate
3.3.3	AN	OBSERVED	101.20	0.08				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
10 mg/ℓ Fe		IAWQ	92.9	0.01				0.0	N.D.	134	344	615	5
AN	AX	OBSERVED	63.55	1.30				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 20d		IAWQ	50.3	2.5				0.0	N.D.	70	386	611	8
	AE1	OBSERVED	36.07	7.15				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	35.1	5.2				29.4	N.D.	47	401	608	10
	AE2	OBSERVED	24.11	7.07				14.48	2437	N.D.	***295***	***496***	N.D.
		IAWQ	25.5	7.0	0.9	2.92	20	22.1	2345	31	412	603	13
	CLAR	OBSERVED	23.80	6.05	1.24	3.11	26	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
3.3.4	AN	OBSERVED	105.71	0.07				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
10 mg/ℓ Fe		IAWQ	78.2	0.01				N.D.	N.D.	118	209	284	3
AN	AX	OBSERVED	56.61	1.56				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 10d		IAWQ	40.8	2.3				N.D.	N.D.	63	246	281	5
	AE1	OBSERVED	31.86	6.29				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	27.8	4.1				20.0	N.D.	43	259	280	6
	AE2	OBSERVED	19.40	6.18				14.03	2009	N.D.	N.D.	N.D.	N.D.
		IAWQ	18.8	5.5	1.3	2.71	20	15.8	1860	29	269	277	8
	CLAR	OBSERVED	18.88	6.39	1.74	3.38	22	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

Table 7.8a continued: Comparison between observed and predicted results for pilot plants according to IAWQ model.

FERRIC CHLORIDE DOSING TO TEST UNIT (R1).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_I mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mgVSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P	MeP mg/ℓ as precipitate	MeOH mg/ℓ as precipitate
3.3.5	AN	OBSERVED	82.23	0.05				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
20 mg/ℓ Fe		IAWQ	67.4	0.01				0.0	N.D.	109	191	598	7
AN	AX	OBSERVED	50.46	0.80				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 10d		IAWQ	33.9	2.9				0.0	N.D.	57	226	591	12
	AE1	OBSERVED	26.73	6.25				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	22.5	4.7				17.7	N.D.	40	238	586	15
	AE2	OBSERVED	14.56	6.80				12.44	1581	N.D.	N.D.	N.D.	N.D.
		IAWQ	15.3	6.0	1.3	3.49	20	14.0	1585	27	246	578	21
	CLAR	OBSERVED	16.03	5.69	1.87	3.12	23	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
3.3.6	AN	OBSERVED	79.12	0.07				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
20 mg/ℓ Fe		IAWQ	71.4	0.01				0.0	N.D.	108	192	524	5
AE 1	AX	OBSERVED	46.27	1.18				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 10d		IAWQ	35.4	1.9				0.0	N.D.	57	226	529	10
	AE1	OBSERVED	22.46	5.55				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	22.7	3.3				16.5	N.D.	39	237	532	15
	AE2	OBSERVED	18.75*	4.92				11.76	1510	N.D.	N.D.	N.D.	N.D.
		IAWQ	15.0	4.3	0.7	2.65	21	12.4	1327	27	245	526	19
	CLAR	OBSERVED	15.94	4.69	0.64	2.61	21	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

*: Observed effluent ortho P (S_{PO4}) = 15.6 mgP/ℓ (Appendix 5)

Table 7.8a continued: Comparison between observed and predicted results for pilot plants according to IAWQ model.
FERRIC CHLORIDE DOSING TO TEST UNIT (R1).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_I mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mgVSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P	MeP mg/ℓ as precipitate	MeOH mg/ℓ as precipitate
3.6.1	AN	OBSERVED	25.38/22.50	0.25				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
10 mg/ℓ Fe		IAWQ	30.92	0.01				0.0	N.D.	82	33	238	9
AE 1	AX	OBSERVED	7.99/7.04	3.60				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 10d		IAWQ	10.06	3.06				0.0	N.D.	44	55	221	29
Low P	AE1	OBSERVED	1.27/1.01	6.94				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
With bicarb.		IAWQ	1.89	5.51				20.72	N.D.	30	64	210	42
	AE2	OBSERVED	0.41/0.31	7.20				13.13	1291	N.D.	***61***	***257***	N.D.
		IAWQ	0.14	6.65	0.46	2.20	57	13.42	1226	21	68	186	61
	CLAR	OBSERVED	0.45/0.24	7.08	1.04	2.44	52	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
3.6.2a	AN	OBSERVED	25.73/23.19	0.25				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
10 mg/ℓ Fe		IAWQ	31.8	0.01				0.0	N.D.	89	30	238	9
AE1	AX	OBSERVED	8.44/7.53	2.83				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 10d		IAWQ	10.2	2.32				0.0	N.D.	48	53	220	29
Low P	AE1	OBSERVED	1.51/1.29	5.34				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
No bicarb.		IAWQ	1.50	4.71				22.21	N.D.	33	62	206	44
	AE2	OBSERVED	0.41/0.32	5.43				11.36	1223	N.D.	***47***	***256***	N.D.
		IAWQ	0.09	5.82	0.49	1.74	41	14.64	1238	23	66	183	65
	CLAR	OBSERVED	0.53/0.44	5.33	1.13	2.06	44	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

*: Observed effluent ortho P (S_{PO4}) = 0.6 mgP/ℓ (Appendix 5)
**: Observed effluent ortho P (S_{PO4}) = 0.2 mgP/ℓ (Appendix 5)

Table 7.8a continued: Comparison between observed and predicted results for pilot plants according to IAWQ model.

FERROUS-FERRIC CHLORIDE DOSING TO TEST UNIT (R1).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	iP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_I mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mgVSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P	MeP mg/ℓ as precipitate	MeOH mg/ℓ as precipitate
3.4.1	AN	OBSERVED	69.76	0.08				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
19 mg/ℓ Fe		IAWQ	59.9	0.1				0.0	N.D.	78	140	553	6
AE 1	AX	OBSERVED	34.83	1.97				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 10d		IAWQ	32.1	1.9				0.0	N.D.	39	165	559	11
	AE1	OBSERVED	24.10	3.42				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	23.0	2.6				7.59	N.D.	27	173	563	15
	AE2	OBSERVED	18.01	3.29				7.88	1332	N.D.	***142***	***658***	N.D.
		IAWQ	17.7	3.1	0.8	1.71	19	5.88	1091	18	179	559	17
	CLAR	OBSERVED	18.00	3.32	1.51	2.29	14	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
3.4.2	AN	OBSERVED	82.30	0.06		N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
10 mg/ℓ Fe		IAWQ	65.2	0.01		N.D.	N.D.	0.0	N.D.	80	130	277	3
AE 1	AX	OBSERVED	42.44	2.68		N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 10d		IAWQ	38.1	2.2		N.D.	N.D.	0.0	N.D.	41	156	281	5
Low P	AE1	OBSERVED	30.52	5.01		N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	28.7	3.6		N.D.	N.D.	14.71	N.D.	28	164	283	6
	AE2	OBSERVED	22.64	4.96		N.D.	N.D.	9.27	999	N.D.	***171***	***246***	N.D.
		IAWQ	22.6	4.6	0.7	1.71	16	11.05	920	19	170	282	7
	CLAR	OBSERVED	23.37	4.66	0.75	2.17	15	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

Table 7.8a continued: Comparison between observed and predicted results for pilot plants according to IAWQ model.
FERROUS-FERRIC CHLORIDE DOSING TO TEST UNIT (R1).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_I mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mgVSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P	MeP mg/ℓ as precipitate	MeOH mg/ℓ as precipitate
3.4.3	AN	OBSERVED	80.46	0.07				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
10 mg/ℓ Fe		IAWQ	59.1	0.02				0.0	N.D.	72	86	287	3
AN	AX	OBSERVED	41.93	2.96				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 10d		IAWQ	36.0	2.7				0.0	N.D.	38	110	285	5
	AE1	OBSERVED	29.82	5.14				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	28.2	4.3				15.18	N.D.	27	118	283	6
	AE2	OBSERVED	22.63	5.18				9.02	901	N.D.	***173***	***264***	N.D.
		IAWQ	22.7	5.3	0.54	2.59	16	10.85	862	18	124	282	7
	CLAR	OBSERVED	22.41	5.09	0.52	2.95	16	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
3.4.4	AN	OBSERVED	49.67	0.08				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
10 mg/ℓ Fe		IAWQ	42.0	0.01				0.0	N.D.	91	76	240	5
AE 1	AX	OBSERVED	16.68	3.15				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 10d		IAWQ	14.8	3.1				0.0	N.D.	48	104	231	17
Low P	AE1	OBSERVED	4.96	6.03				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	5.0	5.4				19.38	N.D.	33	114	227	24
	AE2	OBSERVED	0.77	6.32				13.35	939	N.D.	***93***	***230***	N.D.
		IAWQ	1.0	6.3	0.35	2.48	19	12.62	1043	23	121	207	40
	CLAR	OBSERVED	2.27	6.46	0.36	2.28	26	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

Table 7.8a continued: Comparison between observed and predicted results for pilot plants according to IAWQ model.

FERROUS-FERRIC CHLORIDE DOSING TO TEST UNIT (R1).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_I mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mgVSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P	MeP mg/ℓ as precipitate	MeOH mg/ℓ as precipitate
3.5.1	AN	OBSERVED	13.76	0.57				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
10 mg/ℓ Fe		IAWQ	9.05	0.15				0.0	N.D.	11.8	22	211	17
AE 1	AX	OBSERVED	6.59	6.85				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 10d		IAWQ	5.71	6.10				0.0	N.D.	6.4	26	209	24
Low P	AE1	OBSERVED	5.19	10.55				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Low acetate		IAWQ	4.43	9.43				18.6	N.D.	4.4	27	208	28
	AE2	OBSERVED	4.76	10.74				12.31	974	N.D.	***19***	***240***	N.D.
		IAWQ	3.78	10.82	0.34	2.28	19	10.52	963	3.0	28	206	30
	CLAR	OBSERVED	3.87	10.51	0.21	2.33	19	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
3.5.2	AN	OBSERVED	12.77	0.08				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
10 mg/ℓ Fe		IAWQ	10.69	0.02				0.0	N.D.	20	37	219	18
AN	AX	OBSERVED	6.39	3.93				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 10d		IAWQ	5.71	4.9				0.0	N.D.	11	43	211	26
Low P	AE1	OBSERVED	3.84	7.68				N.D.	N.D.	N.D.	N.D.	N.D.	N.D.
Low acetate		IAWQ	3.9	8.4				24.0	N.D.	7.5	45	207	28
	AE2	OBSERVED	2.88	8.26				13.73	1061	N.D.	***30***	***235***	N.D.
		IAWQ	2.9	9.9	0.34	3.52	22	14.81	952	5.1	47	202	33
	CLAR	OBSERVED	2.68*	8.86	0.25	3.74	21	N.D.	N.D.	N.D.	N.D.	N.D.	N.D.

*: Observed effluent ortho P (S_{PO4}) = 1.3 mgP/ℓ (Appendix 5)

Table 7.8b continued: Comparison between observed and predicted results for pilot plants according to IAWQ & UCTPHO models. CONTROL UNIT (R2).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_I mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mgVSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P
3.2.2	AN	OBSERVED	111.5	0.02			N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 20d		IAWQ	106.8	0.0			N.D.	0.0	N.D.	151	377
Bicarb. = 50		UCTPHO	106.9	0.0			23	0.0	2717	149	366
	AX	OBSERVED	66.06	0.61			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	58.8	1.2			N.D.	0.0	N.D.	79	423
		UCTPHO	61.8	0.6			26	0.0	2723	81	410
	AE1	OBSERVED	46.35	3.10			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	40.5	4.3			N.D.	29.2	N.D.	53	439
		UCTPHO	42.2	3.5			27	27.8	2725	54	429
	AE2	OBSERVED	34.53	2.35			N.D.	20.86	2693	N.D.	N.D.
		IAWQ	28.5	5.1	0.2	2.82	24	18.1	2705	35	451
		UCTPHO	29.1	4.3	0.2	2.53	28	16.8	2725	36	442
	CLAR	OBSERVED	28.91	2.43	0.27	2.92	26	N.D.	N.D.	N.D.	N.D.
3.2.3	AN	OBSERVED	114.89	0.06			N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 20d		IAWQ	95.0	0.0			N.D.	0.0	N.D.	129	338
Bicarb.= 100		UCTPHO	95.4	0.0			18	0.0	2661	130	331
	AX	OBSERVED	57.42	1.90			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	54.0	1.8			N.D.	0.0	N.D.	68	377
		UCTPHO	57.2	1.5			21	0.0	2676	71	369
	AE1	OBSERVED	35.29	5.81			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	39.0	4.1			N.D.	21.3	N.D.	46	391
		UCTPHO	40.5	3.9			22	21.0	2680	48	385
	AE2	OBSERVED	23.32	6.03			N.D.	16.60	2749	N.D.	***419***
		IAWQ	28.9	5.0	0.4	3.76	22	14.3	2654	31	401
		UCTPHO	29.2	4.9	0.4	2.59	23	13.2	2683	32	396
	CLAR	OBSERVED	25.29	5.78	0.42	3.68	22	N.D.	N.D.	N.D.	N.D.

Table 7.8b continued: Comparison between observed and predicted results for pilot plants according to IAWQ & UCTPHO models. CONTROL UNIT (R2).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_I mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mgVSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P
3.2.4	AN	OBSERVED	107.28	0.02			N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 20d		IAWQ	92.6	0.00			N.D.	0.0	N.D.	123	321
Bicarb.= 100		UCTPHO	93.2	0.0			17	0.0	2419	125	318
	AX	OBSERVED	58.02	0.71			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	52.7	0.7			N.D.	0.0	N.D.	64	361
		UCTPHO	56.1	0.3			20	0.0	2436	69	354
	AE1	OBSERVED	35.95	2.69			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	38.4	2.1			N.D.	16.9	N.D.	43	375
		UCTPHO	40.0	1.5			21	16.3	2419	46	370
	AE2	OBSERVED	24.11	2.69			N.D.	15.42	2386	N.D.	***390***
		IAWQ	28.8	2.9	0.7	2.38	20	12.7	2404.	28	384
		UCTPHO	29.1	2.4	0.9	2.98	22	11.6	2444	31	381
	CLAR	OBSERVED	23.72	3.28	0.79	2.44	20	N.D.	N.D.	N.D.	N.D.
3.2.5	AN	OBSERVED	85.06	0.05			N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 20d		IAWQ	76.7	0.04			N.D.	0.0	N.D.	94	302
Bicarb.= 150		UCTPHO	81.9	0.1			13	0.0	1814	100	254
	AX	OBSERVED	49.76	2.91			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	46.8	2.9			N.D.	0.0	N.D.	48	331
		UCTPHO	52.5	2.8			15	0.0	1825	55	283
	AE1	OBSERVED	35.71	5.82			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	36.1	4.5			N.D.	13.9	N.D.	33	342
		UCTPHO	39.7	4.6			15	13.7	1831	37	295
	AE2	OBSERVED	29.28	6.13			N.D.	12.1	1911	N.D.	***346***
		IAWQ	29.0	5.2	0.4	2.2	16	9.5	1789	22	349
		UCTPHO	31.1	5.4	0.5	2.3	16	9.0	1833	25	304
	CLAR	OBSERVED	29.74	6.0	0.43	1.93	16	N.D.	N.D.	N.D.	N.D.

Table 7.8b continued: Comparison between observed and predicted results for pilot plants according to IAWQ & UCTPHO models. CONTROL UNIT (R2).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_I mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mgVSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P
3.2.6	Not modelled : short experimental period (<10 sample results for some determinands)										
3.2.7	AN	OBSERVED	75.65	0.04			N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 20d		IAWQ	90.9	0.01			N.D.	0.0	N.D.	121	301
Bicarb.= 150		UCTPHO	90.0	0.0			14	0.0	2002	120	308
	AX	OBSERVED	47.61	1.61			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	52.7	2.0			N.D.	0.0	N.D.	64	337
		UCTPHO	54.5	1.7			16	0.0	2007	66	342
	AE1	OBSERVED	36.52	5.02			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	38.4	4.7			N.D.	24.8	N.D.	44	350
		UCTPHO	39.0	4.6			17	24.6	2009	45	357
	AE2	OBSERVED	30.04	4.84			N.D.	11.37	1894	N.D.	N.D.
		IAWQ	28.8	5.3	0.1	2.0	17	14.4	1968	29	360
		UCTPHO	28.5	5.2	0.1	2.3	18	13.5	2009	30	368
	CLAR	OBSERVED	28.27	4.33	0.04	2.03	18	N.D.	N.D.	N.D.	N.D.
3.2.8a	AN	OBSERVED	80.40	0.00			N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 20d		IAWQ	90.6	0.0			N.D.	0.0	N.D.	127	330
No Bicarb.		UCTPHO	90.0	0.0			13	0.0	1928	125	318
	AX	OBSERVED	48.80	0.65			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	49.9	1.0			N.D.	0.0	N.D.	66	368
		UCTPHO	52.9	1.2			16	0.0	1943	69	354
	AE1	OBSERVED	33.56	3.12			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	35.1	2.8			N.D.	19.1	N.D.	44	382
		UCTPHO	36.9	3.3			17	19.2	1948	47	370
	AE2	OBSERVED	24.77	3.08			N.D.	11.05	1885	N.D.	N.D.
		IAWQ	25.3	3.5	0.3	2.38	16	12.9	1940	30	392
		UCTPHO	26.0	4.2	0.4	2.71	17	12.2	1950	31	381
	CLAR	OBSERVED	26.75	3.62	0.25	2.30	16	N.D.	N.D.	N.D.	N.D.

Table 7.8b continued: Comparison between observed and predicted results for pilot plants according to IAWQ & UCTPHO models. CONTROL UNIT (R2).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_i mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mgVSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P
3.3.1(b)	AN	OBSERVED	102.31	0.11			N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 20d		IAWQ	96.8	0.0			N.D.	0.0	N.D.	134	354
With bicarb.		UCTPHO	97.3	0.0			16	0	2389	133	337
	AX	OBSERVED	60.41	3.11			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	55.0	1.8			N.D.	0.0	N.D.	71	393
		UCTPHO	58.0	1.1			19	0	2386	73	375
	AE1	OBSERVED	42.20	6.09			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	39.0	5.1			N.D.	31.0	N.D.	48	408
		UCTPHO	40.6	4.4			20	30.0	2386	49	392
	AE2	OBSERVED	30.91	6.13			N.D.	16.23	2490	N.D.	***371***
		IAWQ	28.3	5.7	0.1	2.52	22	18.1	2355	32	419
		UCTPHO	29.0	5.2	0.2	2.51	21	17.7	2383	33	404
	CLAR	OBSERVED	27.65	6.26	0.24	2.34	19	N.D.	N.D.	N.D.	N.D.
3.3.2	AN	OBSERVED	112.02	0.11			N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 20d		IAWQ	92.0	0.01			N.D.	0.0	N.D.	122	319
With bicarb.		UCTPHO	91.8	0.0			15	0	2355	121	309
	AX	OBSERVED	63.80	1.58			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	52.7	1.8			N.D.	0.0	N.D.	63	357
		UCTPHO	55.8	1.0			17	0	2353	66	343
	AE1	OBSERVED	43.31	4.01			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	38.4	3.8			N.D.	22.8	N.D.	43	369
		UCTPHO	40.2	3.0			18	23.7	2353	45	359
	AE2	OBSERVED	30.18	4.44			N.D.	18.16	2509	N.D.	***409***
		IAWQ	28.9	5.1	0.9	2.52	20	17.3	2545	28	379
		UCTPHO	29.6	4.3	1.0	3.37	19	17.7	2351	30	369
	CLAR	OBSERVED	26.98	5.49	1.19	2.61	20	N.D.	N.D.	N.D.	N.D.

Table 7.8b continued: Comparison between observed and predicted results for pilot plants according to IAWQ & UCTPHO models. CONTROL UNIT (R2).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_I mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mgVSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P
3.3.3	AN	OBSERVED	107.24	0.15			N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 20d		IAWQ	99.4	0.01			N.D.	0.0	N.D.	134	345
With bicarb.		UCTPHO	100.3	0.0			16	0.0	2405	133	337
	AX	OBSERVED	60.98	2.78			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	57.3	2.5			N.D.	0.0	N.D.	70	387
		UCTPHO	60.4	1.7			19	0.0	2401	73	376
	AE1	OBSERVED	40.75	6.91			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	41.5	5.2			N.D.	29.4	N.D.	47	402
		UCTPHO	43.1	4.5			20	28.8	2400	49	393
	AE2	OBSERVED	29.67	6.94			N.D.	15.54	2424	N.D.	***344***
		IAWQ	30.9	7.0	0.9	2.90	20	22.1	2345	31	413
		UCTPHO	31.5	6.3	1.0	3.37	20	21.0	2398	33	404
	CLAR	OBSERVED	28.34	6.27	1.16	2.64	21	N.D.	N.D.	N.D.	N.D.
3.3.4	AN	OBSERVED	114.17	0.10			N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 10d		IAWQ	83.4	0.01			N.D.	0.0	N.D.	118	209
With bicarb.		UCTPHO	85.1	0.0			18	0.0	1832	119	203
	AX	OBSERVED	60.62	1.86			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	45.6	2.3			N.D.	0.0	N.D.	63	247
		UCTPHO	48.7	1.9			19	0.0	1839	67	239
	AE1	OBSERVED	36.30	6.01			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	32.3	4.1			N.D.	20.0	N.D.	43	260
		UCTPHO	33.8	3.9			20	20.6	1842	47	253
	AE2	OBSERVED	23.03	5.98			N.D.	13.89	1987	N.D.	N.D.
		IAWQ	22.8	5.5	1.32	2.71	20	15.8	1863	29	269
		UCTPHO	23.1	5.5	1.8	4.0	20	16.1	1842	32	264
	CLAR	OBSERVED	21.17	6.04	1.74	3.21	20	N.D.	N.D.	N.D.	N.D.

Table 7.8b continued: Comparison between observed and predicted results for pilot plants according to IAWQ & UCTPHO models. CONTROL UNIT (R2).

PERIOD POINT OF DOSING	ZONE	OBSERVED /MODEL	fP_t or Pt_e / S_{PO4} mgP/ℓ	NO_3 / S_{NO3} mg N/ℓ	N_{ae} / S_{NH4} mg N/ℓ	N_{te} / S_{TKN} mg N/ℓ	S_{te} / S_{us} / S_i mgCOD/ℓ	O_t $mgO_2/(\ell.h)$	VSS / X_{VSS} mgVSS/ℓ	S_{PHB} / X_{PHA} mg/ℓ as PHB	$P_{poly\ P}$ X_{PP} mg/ℓ as P
3.3.5	AN	OBSERVED	95.59	0.07			N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 10d		IAWQ	80.7	0.01			N.D.	0.0	N.D.	109	193
With bicarb.		UCTPHO	81.5	0.0			18	0.0	1553	108	183
	AX	OBSERVED	57.59	2.48			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	45.8	2.9			N.D.	0.0	N.D.	57	227
		UCTPHO	48.7	2.5			19	0.0	1559	60	215
	AE1	OBSERVED	37.15	7.16			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	33.5	4.7			N.D.	17.7	N.D.	40	239
		UCTPHO	35.3	4.4			19	18.3	1562	42	229
	AE2	OBSERVED	24.36	7.44			N.D.	12.83	1546	N.D.	N.D.
		IAWQ	24.8	6.0	1.3	3.49	20	14.0	1585	27	248
		UCTPHO	25.6	5.9	1.6	3.73	20	14.2	1563	29	238
	CLAR	OBSERVED	25.29	6.59	1.66	2.75	21	N.D.	N.D.	N.D.	N.D.
3.3.6	AN	OBSERVED	93.89	0.05			N.D.	N.D.	N.D.	N.D.	N.D.
R_s = 10d		IAWQ	77.0	0.01			N.D.	0.0	N.D.	108	195
With bicarb.		UCTPHO	78.4	0.0			18	0.0	1300	110	188
	AX	OBSERVED	36.66	1.18			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	41.9	1.9			N.D.	0.0	N.D.	57	228
		UCTPHO	45.2	1.5			19	0.0	1309	62	220
	AE1	OBSERVED	28.70	5.55			N.D.	N.D.	N.D.	N.D.	N.D.
		IAWQ	29.8	3.34			N.D.	16.5	N.D.	39	239
		UCTPHO	31.5	3.2			20	17.7	1313	43	234
	AE2	OBSERVED	22.79	4.92			N.D.	14.72	1319	N.D.	N.D.
		IAWQ	21.3	4.3	0.7	2.65	21	12.4	1327	27	248
		UCTPHO	21.6	4.3	0.9	3.04	20	12.9	1314	29	243
	CLAR	OBSERVED	21.64	6.06	0.64	2.48	21	N.D.	N.D.	N.D.	N.D.

affecting the overall yield, especially since the PAOs may not be the only group of organisms capable of taking up SCFA anaerobically (Mino *et al.*, 1987).

3. Once suitable model calibration had produced satisfactory agreement between observed and predicted P removal for the Control reactor, satisfactory agreement was also obtained for the Test unit (with chemical addition) using the IAWQ model.

   - For ferric chloride, using the kinetic and stoichiometric constants suggested in IAWQ ASM2, the assumption of 1:1 (molar) precipitation stoichiometry for P:Fe appeared to be valid for three of six experimental periods examined where phosphate was never limiting. For the remaining three (without P limitation), a lower P:Fe stoichiometry was required, in the range 0.60 to 0.90 mol P/mol Fe. These results suggest reduced precipitation efficiency either after sustained ferric chloride dosing at low dose (10 mg/ℓ Fe, based on influent), or after shorter periods at higher dose (20 mg/ℓ Fe).

   - For alum and ferrous-ferric dosing, P precipitation also appeared to be less efficient. For alum, the stoichiometry of precipitation was estimated to be 0.70 to 0.75 mol P/ mol Al, except in one experimental period when a value of 0.60 mol P/ mol Al was estimated (see below). For ferrous-ferric chloride, the stoichiometry was also estimated to be close to 0.75 mol P/ mol Fe.

   - Under P-limiting (i.e. low effluent P) conditions, precipitation efficiency appeared to be lower, with an estimated P:Fe stoichiometry of ca. 0.4 mol P/mol Fe. This is in agreement with the model precipitate stoichiometry of 2.5 mol Fe/mol P accepted by Luedecke *et al.* (1989) for limiting phosphorus conditions with ferric chloride in batch and continuous tests using activated sludge in a completely aerobic system.

4. A significant advantage of the kinetic approach to modelling chemical precipitation processes in (IAWQ, 1995) is that it integrates well with processes describing biological carbon, nitrogen and phosphorus removal in activated sludge systems, and offers the potential for incorporation of processes for pH and alkalinity. A kinetic-based model for mixed, three-phase[39], weak acid-base systems using the AQUASIM model platform has recently been proposed by Musvuto *et al.* (1997). This could form a further extension to the AQUASIM application of IAWQ ASM2 used here, which included simultaneous precipitation with iron or aluminium salts. Precipitation efficiency in relation to alkalinity (and/ or pH) in simultaneous precipitation processes needs to be further investigated and, if possible, a function describing this relationship could be incorporated in the model. This study has found evidence (refer to Chapters 3 and 4) to suggest that reactor pH (and hence system alkalinity) plays an important role in determining the extent of inhibition of the biological P removal mechanism in the presence of simultaneous metal salt addition, particularly with alum. Furthermore, the question of alkalinity consumption in relation to the metal:P stoichiometry of precipitation has not been adequately addressed in the IAWQ model.

5. For alum dosing, this study found some evidence to suggest that precipitation efficiency with alum is influenced to some extent by the point of dosing. Dosing with alum to the anaerobic zone appeared to be somewhat less efficient than dosing to the aerobic zone. Furthermore, the data presented in Chapter 3, suggested that the efficiency of precipitation with alum in the anaerobic zone may also be dependent on the magnitude of the alum dose, presumably due to interfering complexation from (soluble) influent organic material in this zone. In its current simple format, the IAWQ model of chemical precipitation does not suggest suitable stoichiometry for precipitation with alum. From this study, a tentative suggestion would be for P:Al molar stoichiometry in the range 0.70 to 0.75 for aerobic zone alum dosing and 0.60 for anaerobic zone alum dosing. Phosphate limiting conditions were not tested with alum, but a lower P:Al molar stoichiometry (ca. 0.4) would be expected. Further investigation may it possible to be more definitive in this respect.

6. Precipitation efficiency for ferric chloride or ferrous-ferric chloride did not appear to be dependent on the point of dosing, which is in agreement with the results of Rabinowitz and

[39] Three phases of matter: solid, liquid, gaseous

Marais (1980). However, as noted above, the stoichiometry of precipitation with ferric chloride sometimes fell into the range 0.6 to 0.75 (i.e. less than 1 mol P/mol Fe as suggested in the IAWQ model, and reported by Rabinowitz and Marais (1980) for ferric salts). In the case of ferrous chloride, a tentative suggestion would be for stoichiometry of 0.75 mol P/mol Fe, based on results for a blend containing ca. 90% ferrous/10 % ferric chloride. Precipitation of phosphate to some extent as ferrous phosphate could explain the lower P:Fe stoichiometry when dosing the ferrous-ferric chloride blend.

7. The results of this study suggest that precipitation "efficiency" (Rabinowitz and Marais, 1980) is a potentially misleading term in that it could include the effects of partial inhibition of biological P removal in activated sludge systems with simultaneous chemical dosing. Good evidence for partial inhibition of the bio-P mechanism was presented in Chapters 3, 4 and 5, although the extent of the inhibition tended to be small (ca. <25% for the metal dose range tested), in periods without P-limitation. However, using the IAWQ ASM2 model, it is presently not possible to separate out the effect of this inhibition from the stoichiometry of precipitation *per se*. In the IAWQ model formulation, for the conditions tested in this study, it was found that the effluent P concentration and bio-P removal processes (e.g. poly P concentration in the system) were relatively insensitive to changes in the kinetic constants for precipitation/ redissolution. As an alternative, the weaker bio-P mechanism due to metal addition, can be compensated for by a reduced P:metal stoichiometry for the chemical precipitate. This will produce agreement for the overall P removal by the system, but may lead to errors in the interpretation of results for other model compounds (e.g. poly P or PHA content; P release in the anaerobic zone; and possibly also denitrification, if anoxic P uptake processes are included in the model). Furthermore, it will be difficult to link observed alkalinity consumption to the stoichiometry of precipitation if the latter also needs to be manipulated However, in order to accurately determine the stoichiometry of simultaneous precipitation, very careful calibration of the model is required. This in, turn, demands operating results from Test and Control systems (with and without chemical addition) where the influent is very well characterised and shows minimal variation. In this regard, the variation in source sewage composition posed a constraint during this study, and reduced confidence in the model calibration. Future studies could investigate the use of a source sewage which shows as little variation as possible (especially in wet weather) and which is well characterised.

8. Satisfactory agreement between (IAWQ model) predicted and observed values for poly P in the Control system was obtained when comparing the model results with those obtained from fractionation data. For the Test system (metal dosed) the differences between the predicted and observed poly P data tended to be larger in some experimental periods. This supports the observation that relatively high metal doses or sustained periods at lower metal dose are partially inhibitory to the bio-P removal mechanism in a manner which the IAWQ ASM2 model is not able to predict. However, better agreement between the fractionation data and IAWQ model poly P predictions were obtained for relatively long experimental periods with ferric chloride dosing under conditions of phosphate limitation. This implies that the model formulation is correct in so far as the principal interaction between the chemical and biological mechanisms is competition for available phosphate. Most real applications of the model will be for conditions which are basically P-limited, due to the need to achieve the lowest possible effluent P concentrations.

9. Broad agreement was found between IAWQ model predictions and observed increases in inorganic suspended solids (ISS) due to chemical addition, provided the necessary stoichiometric adjustments were made for metal hydroxy phosphate precipitation and conversion of metal hydroxide to metal oxide during ashing. The latter appears to have been an oversight in the IAWQ model. Correction in a similar manner is also required where metal hydroxy phosphate is assumed to form (i.e. for stoichiometry where P:metal < 1 mol P/mol metal). Where differences were found between model predictions and observed ISS, these could be accounted for on the basis that the mixed liquor suspended solids of the experimental systems did not appear to have approximated steady-state in all cases. Aside from these cases, the differences were usually small (<8%) in relation to average TSS in the Test unit. Since differences of this order are unlikely to be of major significance in design and operation of an activated sludge plant, it appears that the IAWQ precipitation model will adequately predict the expected increase in TSS due to chemical addition. However, in its existing form,

the IAWQ model is deficient in that provision has not been made for predicting the contribution of chemical precipitate to inorganic suspended solids (ISS). This will be significant where the predicted VSS/TSS ratio is of interest, and will show up particularly where the P:metal molar stoichiometry applied is significantly less than unity, and/or the accumulation of metal hydroxide in the system is relatively high (typically under P-limiting conditions).

10. A review of the experimental data for P uptake and P release on a mass balance basis revealed that significant P uptake sometimes took place in the anoxic reactor of both the Test and Control systems (i.e. with or without metal addition). This behaviour varied significantly between experimental periods and no simple explanation could be found for these changes on the basis of parameters measured. Shifts in the population(s) of phosphate accumulating organisms with/ without denitrifying capability appeared to have occurred for reasons which were not apparent.

REFERENCES

Arun, V, Mino, T and Matsuo, T. (1988) Biological mechanism of acetate uptake mediated by carbohydrate consumption in excess biological phosphorus removal system. *Water Res.*, 22, 565-570.

Aspegren, H. (1995) *Evaluation of a high loaded activated sludge process for biological phosphorus removal.* Ph.D. Thesis, Dept. of Water and Environmental Engineering, Lund University of Technology, Lund, Sweden.

Barker, PS and Dold, PL. (1997). General model for biological nutrient removal activated-sludge systems: model presentation. *Water Env. Res.* 69 (5), 969-984.

Briggs, TA. (1996) *Dynamic modelling of chemical phosphorus removal in the activated sludge process.* M. Eng. Thesis, School of Graduate Studies, McMaster University, Hamilton, Ontario, Canada.

CRC (1988). CRC *Handbook of Chemistry and Physics.* 1st Student Edition. Weast, RC (ed.), CRC Press.

De Haas, DW and Adam N. (1995) Use of a simple titration procedure to determine $H_2CO_3^*$ alkalinity and volatile fatty acids for process control in waste-water treatment. *Water SA* 21 (4), 307-318.

Dold, PL and Briggs, TA. (1995) Simultaneous chemical phosphorus removal: modelling and case studies. Proceedings of the Water Environment Federation 68th Annual Conference and Exhibition, Miami Beach, Florida, USA (21-25 October 1995), Vol. I, 523-534.

Dold, PL, Wentzel, MC, Billing, AE, Ekama, GA and Marais, GvR. (1991) *Activated sludge system simulation programs*. Water Research Commission, PO Box 824, Pretoria, South Africa.

Ekama, GA and Wentzel, MC. (1997) Denitrification kinetics in biological N&P removal activated sludge systems treating municipal wastewaters. Paper presented at *BNR3* Conference, Brisbane, Australia, 30 November - 3 December, 1997.

Galarneau, E and Gehr, R. (1997) Phosphorus removal from wastewaters: experimental and theoretical support for alternate mechanisms. *Water Res.* 31 (2), 328 - 338.

Gerber, A, de Villiers, RH, Mostert, ES and van der Riet, CJJ. (1987) The phenomenon of simultaneous phosphate uptake and release and release, and its importance in biological nutrient removal. In: *Advances in Water Pollution Control: Biological Phosphate Removal from Wastewaters*, R. Ramadori (ed.). Pergamon Press, p123-134.

He, QH, Leppard, G, Paige, CR and Snodgrass, WJ. (1996) Transmission electron microscopy of a phosphate effect on the colloid structure of iron hydroxide. *Water. Res.*, 30 (6), 1345-1352.

Henze, M, Grady, CPL (Jr), Gujer, W, Marais, GvR and Matsuo, T. (1987). *Activated Sludge Model No. 1.* IAWPRC Scientific and Technical Report No. 1, IAWPRC, Queen Anne's Gate, London.

IAWQ (1995) *Activated Sludge Model No. 2.* IAWQ Task Group on Mathematical Modelling for Design and Operation of Biological Nutrient Wastewater Treatment Processes. International Association on Water Quality, 1 Queen Anne's Gate, London.

Kerm-Jespersen, JP and Henze, M. (1993) Biological phosphorus uptake under anoxic and oxic condition. Water Research 27 (4), 617-624.

Liu, W, Mino, T, Nakamura, K and Matsuo, T. (1994) Role of glycogen in acetate uptake and polyhydroxyalkanoate synthesis in anaerobic-aerobic activated sludge with a minimized polyphosphate content. *J. Ferment. Bioeng.* 77 (5), 535-540.

Kuba, T, Smolders, G, van Loosdrecht, MCM and Heinen, JJ. (1993) Biological phosphorus removal from wastewater by anaerobic-anoxic sequencing batch reactor. *Water Sci. Technol.*, 27 (5/6), 241-252.

Kuba, T, van Loosdrecht, MCM, Brandse, FA and Heijnen, JJ. (1997). Occurrence of denitrifying phosphorus removing bacteria in modified UCT-type wastewater treatment plants. *Water Res.* 31 (4), 777-786.

Loewenthal, RE and Marais GvR. (1976) *Carbonate Chemistry of Aquatic Systems, Vol. I: Theory and Application*. Ann Arbor Science, Ann Arbor, Michigan.

Lötter , LH, Wentzel, MC, Ekama, GA and Marais, GvR. (1986). A study of selected characteristics of *Acinetobacter* spp. isolated from activated sludge in anaerobic/anoxic/ aerobic systems. *Water SA*, 12 (4), 203-208.

Luedecke, C, Hermanowicz, SH and Jenkins, D. (1989) Precipitation of ferric phosphate in activated sludge: a chemical model and its verification. *Water Sci. Technol.* 21 (Brighton), 325-327.

Mamais, D, Jenkins, D and Pitt, P. (1993) A rapid-physico-chemical method for the determination of readily biodegradable soluble COD in municipal wastewater. *Water Res.* 27 (1), 195-197.

Mino, T, Arun, V, Nakamura, K and Matsuo, T. (1987). Effect of phosphorus accumulation on acetate metabolism in the biological phosphorus removal processes. *In: Biological phosphate removal from wastewaters. Advances in Water Pollution Control 4.* (Ramadori, R (ed.), Pergamon Press, Oxford, p27-88.

Musvuto, EV, Wentzel, MC, Loewenthal, RE and Marais, GvR. (1997) Kinetic based model for mixed acid/base systems. *Water SA* 23 (4), 311-322.

Narasiah, KS, Morasse, C and Lemay, J. (1991) Nutrient removal from aerated lagoons using alum and ferric chloride. *Water Sci. Technol.* 23 (Kyoto), 1563.

Ostgaard, K, Christensson, M, Lie, E, Jonsson, K and Welander, T. (1997) Anoxic biological phosphorus removal in a full-scale UCT process. *Water Res.* 31 (11), 2719-2726.

Rabinowitz, B and Marais, GvR. (1980) *Chemical and biological phosphorus removal in the activated sludge process.* Research Report No. W32, University of Cape Town, Dept. of Civil Engineering, March 1980.

Reichert, P. (1994) Concepts underlying a Computer Program for the Identification and Simulation of Aquatic Systems. Swiss Federal Institute for Environmental Science and Technology (EAWAG), Dübendorf, Switzerland.

Siebritz, IP, Ekama, GA and Marais, GvR. (1983*) Biological excess phosphorus removal in the activated sludge process.* Research Report No. W47, Dept. of Civil Engineering, University of Cape Town, South Africa.

Smolders, GJF, van der Meijm J, van Loosdrecht, MCM and Heijnen, JJ. (1994) Model of the anaerobic metabolism of the biological phosphorus removal process; stoichiometry and pH influence. *Biotechnology and Bioengineering.* 43, 461-470.

Snoeyink, VL and Jenkins, D. (1980) *Water Chemistry.* John Wiley, Toronto.

Standard Methods for the Examination of Water and Wastewater (16th edn.) (1985). American Public Health Association, Washington DC.

Thornberg, D. (1995) Improved design and operation with a dynamic activated sludge model. Paper presented at Conf. On New and Emerging Environmental Technologies and Products for Wastewater Treatment and Stormwater Collection. Sheraton Centre, Toronto, Ontario, Canada. 4-7 June 1995.

Wentzel, MC and Ekama, GA. (1995) Modelling of biological nutrient removal activated sludge systems - an overview. Paper presented at Bio-P Hannover 95 International Conference, Hannover, Germany, 1995.

Wentzel, MC, Ekama, GA and Marais, GvR. (1992) Processes and modelling of nitrification denitrification biological excess phosphorus removal systems - a review. *Water Sci. Technol.* 25 (6), 59-82.

Wentzel, MC, Ekama, GA and Marais, GvR. (1992) Processes and modelling of nitrification denitrification biological excess phosphorus removal systems - a review. *Water Sci. Technol.* 25 (6), 59-82.

Wentzel, MC, Ekama, GA, Dold, PL and Marais, GvR. (1990) Biological excess phosphorus removal - Steady state process design. *Water SA* 16 (1), 29 -48.

Wentzel, MC, Ekama, GA, Loewenthal, RE, Dold, PL and Marais, GvR. (1989) Enhanced organism cultures in activated sludge systems. Part II: Experimental behaviour. *Water SA* 15 (2), 71-88.

Wentzel, MC, Loewenthal, RE, Ekama, GA and Marais, GvR. (1988) Enhanced polyphosphate organism cultures in activated sludge systems - Part 1: Enhanced culture development. *Water SA,* 14 (2), 81-92.

Wentzel, MC, Lötter, LH, Loewenthal, RE and Marais, GvR. (1986) Metabolic behaviour of *Acinetobacter* spp. in enhanced biological phosphorus removal - a biochemical model. *Water SA,* 12, 209-224.

Wentzel, MC. (1997) *Personal communication.* Dept. of Civil Engineering, University of Cape Town, South Africa.

Wentzel, MC, Mbewe, A and Ekama, GA. (1995) Batch test for measurement of readily biodegradable COD and active organism concentrations in municipal waste waters. *Water SA* 21 (2), 117-124.

WRC. (1984) *Theory, design and operation of nutrient removal activated sludge processes.* Water Research Commission, PO Box 824, Pretoria, South Africa.

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting biological enhanced phosphate removal.

Chapter 8

Final discussion and conclusions

DW de Haas

CHAPTER EIGHT

FINAL DISCUSSION AND CONCLUSIONS

8.1 EFFECT OF SIMULTANEOUS CHEMICAL ADDITION ON BIOLOGICAL P REMOVAL

The primary research objective of this study was to determine the extent to which simultaneous chemical dosing using metal salts interferes with (or inhibits) the biological excess P removal (BEPR) mechanism of modified activated sludge systems. The results of this study suggest that :

- The chemical precipitation and biological P removal mechanisms mainly interact through competition for available (soluble) phosphate;
- As expected, the extent of competition between the two mechanisms is dependent on the magnitude of the metal precipitant dose in relation to the influent P load (which determines the available phosphate);
- Under P-limiting conditions (i.e. effluent ortho P approximately 0.5 mgP/ℓ or less), competition between the two mechanisms is most significant. The BEPR mechanism is able to compete effectively with the chemical precipitation under conditions where the simultaneous chemical dose is stoichiometrically smaller than the influent P load. The biological removal mechanism appears to be capable of "surviving" for long periods (probably indefinitely) under these conditions. However, the size of the biologically stored poly P fraction(s) is reduced in the presence of metal precipitant, compared to a Control without chemical precipitant addition. The P:metal stoichiometry of precipitation is also smaller under these conditions, relative to conditions in which phosphate is not limiting.
- Under conditions where phosphate was never limiting, a degree of inhibition of the BEPR mechanism was also found, as evidenced by the size of the poly P fractions in the mixed liquor and the magnitude of P release under anaerobic conditions. The degree of inhibition noted under these conditions was less than that for P-limiting conditions, for a comparable dose of metal precipitant. Nevertheless, it appeared that chemical dosing interferes in some secondary manner with the BEPR mechanism of activated sludge, irrespective of the surplus soluble phosphate in the bulk liquid.
- Phosphate may be "exchanged" to some extent between the biological and chemical fractions during anaerobic P release (i.e. as part of the BEPR mechanism). Changes in these fractions were comparatively minor in relation to overall P release to the supernatant, but may provide clues to the nature of interaction between the chemical and biological removal mechanisms. These changes were more noticeable for mixed liquor subject to dosing with iron salts than with alum, and more so when the iron dose was relatively high, or at low effluent phosphate concentrations.
- Bicarbonate alkalinity and reactor pH appeared to play an important role in the stable operation of simultaneous chemical-biological P removal systems. The systems tested here were operated with a reactor pH seldom below 6.9 and with median values in the range 7.0 to 7.6. Circumstantial evidence suggested that BEPR was more susceptible to inhibition in the presence of alum dosing when the median reactor pH (at the point of dosing) fell below approx. pH 7.2 (i.e. under relatively low alkalinity conditions). The same effect was not found for iron salts, although this aspect was not extensively tested.

The combined experimental evidence from Chapters 3 to 7 may be further considered in the light of the above-mentioned salient points.

8.1.1 Competition for available phosphate

Experimental Periods 3.6.1 and 3.6.2 (a & b) examined ferric chloride dosing under conditions in which effluent phosphate concentrations became limiting. For an iron dose of 10 mg/ℓ as Fe

(based on influent), with a system P removal averaging close to 10 mgP/ℓ, fractionation data[1] showed that the removal in the Test unit (with iron dosing) was approximately 58 to 65% biological and 35 to 42% chemical. This compares with 88 to 90% biological and 10 to 12% chemical removal in the Control for the same period. Comparing the ratio of biological to chemical removal observed during periods under P limitation with those using the same ferric chloride dose but without P limitation (and at least double the system removal[2]), showed that biological removal in the Test unit was proportionally slightly greater (viz. 67 to 72% biological and 27 to 32% chemical), while that in the Control unit was the same (87 to 89% biological and 10 to 12% chemical). This suggests that the biological mechanism is able to compete for available phosphate almost as effectively as the chemical mechanism. This point is further borne out by the fact that the stoichiometry of chemical precipitation[3] was significantly lower under low effluent phosphate (P-limiting) conditions than in the presence of surplus phosphate.

However, it is important to consider the *magnitude* of the biological P removal fraction(s) in relation to the extent of inhibition in the presence of metal precipitant. In the absence of P limitation, with a relatively high acetate dose, (semi) enhanced cultures emerged which strongly exhibited the BEPR phenomenon. At an expected minimum metal:P ratio of 2:1 for the precipitate, a metal ion dose of approximately 175 mM (based on influent) was designed to remove approximately 90 mM additional ortho P (2.5 to 3 mg/ℓ as P, depending on flow). This was generally achieved in periods without P limitation. During these periods, the relative magnitudes of the biological fractions in the Test and Control units showed inhibition in the range 0 to 16% (i.e. inhibition by up to 26 mgP/gVSS). The degree of inhibition was usually greater (up to 23%, or 44 mgP/gVSS) at a higher metal dose (approx. 350 mM). In general terms, the fractionation results for these periods showed good agreement with the extent of depression in P release (on a mass balance basis) in the anaerobic zone of the Test unit, relative to the Control.

Considering periods with P limitation, at a metal (iron) dose of approximately 175 mM, the magnitude of inhibition of the biological fractions was 27 mgP/gVSS on average. This was very similar to the maximum magnitude of depression in the absence of P limitation, but *on a relative basis the extent of inhibition was significantly greater (26 to 37%).* The latter was somewhat less than the average extent to which P release in the anaerobic zone of the Test unit was depressed (42%), on a mass balance basis, relative to the Control.

It follows that depression (or inhibition) of the biological mechanism becomes much more significant under conditions of P limitation because the mixed liquor contains a smaller "pool" of polyphosphate (poly P) , or a smaller number of poly P accumulating organisms (PAOs)[4]. This means that given the same influent, a system with chemical precipitant addition will develop a smaller biological P removal potential, compared to one without chemical addition. If the P limitation were to be lifted (i.e. influent P concentration increased), the bio-P removal potential in the Test system with metal dosing would recover somewhat, moving closer to that of the Control system (without metal dosing) as the numbers of PAOs increased, but probably still remaining about 10 to 20% lower than the Control[5]. Importantly, however, the Test system dosed with metal precipitant may exhibit a higher effluent phosphate than the Control during the period in which the bio-P mechanism "recovers" (i.e. the *combined* chemical-biological removal potential in the Test system may be *lower* than that of the Control at the time when P-limitation is lifted). This was observed experimentally during the first week of Period 3.6.2b, immediately after the influent P

[1] Interpretation of fractionation data in this respect attempted to take uncertainty in the residue (unextracted) P fraction into account.

[2] The greater system P removal was partly due to a surplus of influent phosphate during these periods and partly to a greater influent acetate dose.

[3] As judged from fractionation data estimates and the data of Luedecke et al. (1989)

[4] This may be seen as a sequence of events in which a limitation on P availability for aerobic P uptake results in a limitation of stored poly P for the anaerobic uptake of readily biodegradable substrate. That is, carbon flow to the PAOs becomes restricted by P availability. Hence, the number of PAOs in the system would be expected to decline in both the Test and Control systems under conditions of P limitation. However, competition from the chemical removal mechanism(s) for available P further restricts carbon flow to (and number of) PAOs in the Test system dosed with metal precipitant, thereby reducing the extent to which the BEPR potential is "exploited". A detailed review of the biochemical models of BEPR lies beyond the scope of this study. These models are reviewed *inter alia* by Wentzel et al. (1992), Smolders et al. (1994) and Barker and Dold (1997).

[5] Based on observations of BEPR systems receiving metal doses aimed to remove between approximately 2.5 to 5 mgP/l additional ortho P by chemical means.

concentration was increased, but preceded by a prolonged period with P-limitation (Periods 3.6.1 and 3.6.2a).

8.1.2 Interaction between biological and chemical mechanisms without P limitation

It appears that the biological and chemical P removal mechanisms do not operate entirely independently of each other. The two mechanisms are indirectly linked by way of the available phosphate in the bulk liquid, as discussed in section 8.1.1 above. In addition, several pieces of evidence suggest that the two mechanisms interact on a secondary level, but also via phosphate ions. This evidence includes the following:

- In section 8.1.1 it was noted that the extent to which P release in the anaerobic zone was depressed under P-limiting conditions in the presence of iron (ferric chloride) dosing was, on average, greater than the extent of inhibition of the biological P fractions found in fractionation studies (refer to Table 8.1 below, Periods 3.6.1 and 3.6.2a). The same observation was made when dosing ferrous-ferric chloride to the anaerobic zone under partially P limiting conditions (Table 8.1, Period 3.5.2)[6]. This suggests that biological P release may in fact be potentially *greater* than that observed from samples of filtered mixed liquor supernatant from the anaerobic zone. Hence, metal dosing may produce precipitate with "spare" capacity for binding phosphate, particularly when the system is P-limited and effluent P concentrations are very low.
- Batch P release tests showed that ortho P fractions extracted with cold perchloric acid and attributed to chemical precipitate often showed a small increase (of the order of 10 mgP/gVSS) after the anaerobic period, compared with before. This observation was made more regularly for mixed liquor from the Test unit (dosed with metal precipitant) than for the Control. Witt et al. (1994) made similar observations using a different fractionation procedure and ascribed these (relatively minor) changes to adsorption of phosphate by accumulated metal hydroxides in the mixed liquor solids. Witt et al. (1994) also showed that the effect was reversible upon re-aeration after the anaerobic batch test. In the fractionation studies performed here, the effect was more noticeable under low effluent P conditions (i.e. with at least partial P limitation) and for metal dosing to the anaerobic zone, despite the fact that the mixed liquor sample for the batch test was always taken from the aerobic zone. Furthermore, the effect seemed somewhat more pronounced when dosing a blend of ca. 90% ferrous-10% ferric chloride dosing; during ferrous-ferric chloride dosing to the anaerobic zone, a very pronounced effect was noted, with an alkaline-soluble complex P fraction also showing an increase during the batch P release test). On average, dosing with ferrous-ferric chloride produced a low level of inhibition in the biological P fractions when comparing the Test and Control units, with an apparent stimulation noted for two of the four periods tested, without P-limitation[7] (Table 8.1).
- During periods in which soluble phosphate concentrations in the bulk liquid of the mixed liquor (and, hence, effluent) were never limiting, a degree of inhibition of the biological P fractions was found (Table 8.1 and refer to section 8.1.1). However from the fractionation data, compared to the Control, the extent of this inhibition in the Test system dosed with metal precipitant was usually <20% for these periods, and sometimes ≤ 5% (Table 8.1).
- The stoichiometry of precipitation increased with sludge age, as observed from system P removals for the Test and Control units. This implied that part of the chemical removal mechanism involves processes which are slow to reach completion, causing solids retention time of the order of 10 to 20 days to play a role.

[6] Compared to the fractionation results, mass balance P release data for the anaerobic zone also showed a significant depression in the Test relative to the Control system with a high alum dose to the anaerobic zone, but not for the same dose to the aerobic zone (see Table 8.1, Periods 3.2.5 & 3.26). This observation was not made for ferric chloride (Table 8.1, Periods 3.3.2, 3.3.3 & 3.3.5).

[7] The apparent stimulation of the biological mechanism in the Test unit may have been an indirect artefact the addition of ferrous ions. The suspected septic nature of the influent, particularly during Periods 3.4.2/ 3.4.3, may have produced sulphide inhibition of the BEPR mechanism in the Control, which was ameliorated in the Test unit by the presence of ferrous ions (see section 5.3.1.1 of Chapter 5).

The evidence presented above appears to be consistent with the hypothesis put forward by Rabinowitz and Marais (1980) that simultaneous chemical precipitation in activated sludge systems involves not only a rapid precipitation of metal (e.g. iron) phosphate and metal hydroxide, but a slower, competing side-reaction involving ion-exchange between hydroxide ions and phosphate ions on the metal hydroxide. However, the reactions producing chemical phosphate removal in such systems are not well understood, as a recent transmission electron microscopic study of iron hydroxide colloids by He *et al.* (1996) has shown. He et al. (1996) went as far as to suggest that direct iron phosphate precipitation is unlikely in most wastewater treatment systems: using current surface complexation models, they showed that the relatively low phosphate and iron concentrations in such systems fail to produce saturation conditions required for precipitation. He *et al.* (1996) concluded that, for wastewater treatment (activated sludge) systems, phosphate incorporation by colloidal iron hydroxide is the main mechanism for the removal of phosphorus by simultaneous iron dosing into biological (activated sludge) treatment systems. They found evidence indicating that phosphate forms a surface complex with primary particles of iron hydroxide[8] and so becomes incorporated in a macromolecular colloidal structure. These colloids of chemical origin then form particles approximately 60 to 90 nm in diameter, which appear to become trapped by meshes of biological fibrils, some of which are attached to other extracellular (organic) polymers, and some of which adhere directly to the surface of biological cells (He *et al.*, 1996).

Accepting the work of He *et al.* (1996), it follows that the chemical and biological P removal reactions take place in very close physical proximity to each other in the activated sludge floc. In fact, the iron hydroxide colloid forms a three dimensional structure resembling a "highly porous sponge" (He *et al.*, 1996) which will enmesh the bacterial cells of the activated sludge floc to some extent. This could be the cause of the secondary effects of simultaneous chemical addition noted above. For example, despite "surplus" soluble phosphate in the bulk liquid, the phosphate concentration at the surface of the bacterial cells could be lowered due to a type of "partitioning effect" set up by the metal hydroxide colloid. This effect will be more pronounced for high metal ion doses and P-limiting conditions, as the metal hydroxide enmeshes the cells to a greater degree and becomes partly complexed with extracellular polysaccharides that form an important structural component of activated sludge flocs (Brown and Lester, 1979). In this manner, the cells situated in flocs with a significant accumulation of metal hydroxide could be at a disadvantage since more energy may be required to take up phosphate in opposition to the "gradient" or "barrier" resulting from phosphate complexation with (or adsorption to) extracellular metal hydroxide/ polymer. Hence, despite the presence of surplus soluble phosphate in the bulk liquid, simultaneous metal ion addition may nevertheless subject the BEPR mechanism to a constraint in the translocation of phosphate during biological uptake due to metal hydroxide accumulated in the mixed liquor solids. This would explain the following observations:

- Slow kinetics of saturation of the iron hydroxide "ion exchange"/ complexation capacity for phosphate, as evidenced by the effect of solids retention time (sludge age) on the P:Fe stoichiometry;
- Apparent transient minor "exchange" of P between the biological and chemical fractions during anaerobic batch P release/ aerobic P uptake tests. The slow kinetics of ion exchange/complexation between iron hydroxide colloid and phosphate would imply that the "chemical precipitate" fraction would increase only slightly during a batch test lasting for a few hours, despite a relatively large ("surplus") capacity for phosphate complexation;
- Small but detectable inhibition of the biological fractions in the presence of metal dosing, even in the absence of phosphate limitation; and
- Slightly less P release to the supernatant (bulk liquid) from mass balance calculations than would be expected, mainly for periods with P limitation, even after taking into account the relative inhibition of the biological P fractions from fractionation data.
- Minor differences in VSS production in the presence of metal dosing, presumably due to a change in coagulation properties of the mixed liquor toward organic material (e.g.

[8] Technically a "bridging binuclear (bidentate) complex of the type Fe-O-P-O-Fe" (He *et al.*, 1996).

slightly more adsorbed/ enmeshed colloidal COD which is not biodegraded due to complexation with ferric hydroxide).

As pointed out above, these secondary effects were generally comparatively small for metal doses tested here (in the range approximately 175 to 350 mM as metal ion[9] based on influent flow). The principal effect of metal ion addition appears to be a restriction of the mass of phosphate available (and hence carbon flow) to the BEPR mechanism through competition, as discussed in section 8.1.1.

In Chapter 2 (section 2.7.2), a broad definition of "inhibition" of the biological enhanced P removal (BEPR) mechanism was given in the context of this study. If the hypothesis is accepted that the BEPR and chemical P removal mechanisms interact mainly as a result of "competition" for available phosphate, then it may be necessary to give a more specific definition of "inhibition" in this context. For example, it may be argued that the above-mentioned so-called secondary effects resulting from metal precipitant addition do not arise from competition for available P; rather, as suggested above, the metal ions may inhibit translocation of phosphate across the cell membrane in some manner. For example, it may be significant that Röske and Schönborn (1994) found that iron dosing produced a slower rate of P uptake in a BEPR system, relative to before iron dosing. A reduced rate of P release to the bulk liquid was also observed by Röske and Schönborn (1994). Additional research is required at a more detailed level than that provided by this study in order to confirm and extend these observations of Röske and Schönborn (1994). For example, it will be important to attempt to determine whether the true P uptake and release rates (i.e. *kinetics*) change as a result of simultaneous metal ion addition to BEPR systems, or whether the *stoichiometry* of the release and uptake processes changes. The rates of P release and uptake would need to be measured in a series of batch tests for mixed liquor arising from continuous flow systems, with and without metal ion addition, under a range of operating conditions and metal doses. In such kinetic studies, P release and uptake would need to be measured not only in the supernatant (bulk liquid); in the light of the finding here, for example, that biologically released P can become chemically bound, changes in the respective sludge fractions (biological and chemical) will need to be measured. Moreover, if the stoichiometry changes, then changes in P release and uptake in relation to the flow of carbon, either as readily biodegradable substrate or stored PHA (or glycogen) would be expected. The changes in these compounds would therefore also need to be measured in a series of batch tests. Similarly, the results from the kinetics studies of P uptake/ release will need to be interpreted in terms of current models of the BEPR phenomenon (e.g. IAWQ, 1995), where the observed rates are dependent on the active mass of PAOs, the size of poly P pool (or "complex P" fractions), stored PHA (and/or glycogen), and soluble readily biodegradable substrate (acetate). Due to the complexity of these analyses, considerable resources would be required to conduct such batch tests, particularly on a time-related (kinetic) basis. The detailed results emerging will allow a better understanding of the effect of metal ion addition on the stoichiometry and kinetics of BEPR, which are important from an engineering and modelling point of view. However, the exact nature of the interaction at the biochemical or cellular (e.g. membrane) level are likely to continue to be a matter of hypothesis or speculation unless more advanced methods for studying the individual processes are developed.

...../ Table 8.1

[9] Equivalent to approximately 5 to 10 mg/l as Al^{3+} , or 10 to 20 mg/ℓ as Fe^{3+}.

Table 8.1: Comparison of estimated extent of BEPR mechanism inhibition by the methods of fractionation versus P release in the anaerobic zone of pilot plant systems.

PERIOD	Metal salt dosed	Target metal dose mg/ℓ metal ion (mmol/ℓ metal ion) / Zone dosed AN = anaerobic AE1 = 1st aerobic	Anaerobic zone: Depression of P release in Test (R1) vs. Control (R2) system[10] -ve = depression +ve= stimulation 0% = no effect	Fractionation: "Inhibition" of biological fractions in Test (R1) vs. Control (R2) system -ve = depression +ve= stimulation 0% = no effect
3.2.2	Alum	4.9 (0.18) / AE1	+ 20%	No data
3.2.3	Alum	4.6 (0.17) / AE1	- 2%	- 12%
3.2.4	Alum	4.6 (0.17) / AN	- 5%	- 13%
3.2.5	Alum	9.3 (0.34) / **AN**	**- 25%**	- 15%
3.2.6	Alum	9.3 (0.34) / AE1	- 10%	- 17%
3.2.7	Alum	9.3 (0.34)/ AE1	- 3%	No data
3.2.8a	Alum	9.3 (0.34)/ AE1	- 6%	No data
3.2.8b	Alum	9.3 (0.34)/ AE1	- 16%	- 19%
3.3.1	Ferric chloride	10.3 (0.18)/ AE1	- 12%	- 20% to -10%; -8% (transition period)
3.3.2	Ferric chloride	20.6 (0.36)/ AE1	- 3%	- 3%
3.3.3	Ferric chloride	10.3 (0.18)/ AN	- 5%	- 13%
3.3.4	Ferric chloride	10.3 (0.18)/ AN	- 10%	No data
3.3.5	Ferric chloride	20.3 (0.36)/ AN	- 4%	No data
3.3.6	Ferric chloride	20.3 (0.36)/ AE1	- 11%	No data
3.6.1 P limited	Ferric chloride	10.3 (0.18)/ AE1	**- 43%**	- 26 to - 37%
3.6.2a P limited	Ferric chloride	10.3 (0.18)/ AE1	**- 41%**	- 33 to - 35%
3.4.1	Ferrous-ferric chloride	19.2 (0.34)/ AE1	- 11 %	- 5%
3.4.2	Ferrous-ferric chloride	9.6 (0.17)/ AE1	- 10%	*2% + 18%*[11] *(transition to next period)*
3.4.3	Ferrous-ferric chloride	9.6 (0.17)/ AN	+ 10%	*+ 60%*[11]
3.4.4 Partially P limited	Ferrous-ferric chloride	9.6 (0.17)/ AE1	- 24%	-19 to -28%
3.5.1 Low P but not P limited	Ferrous-ferric chloride	9.6 (0.17)/ AE1	- 7%	0 to + 3%
3.5.2 Partially P limited	Ferrous-ferric chloride	9.6 (0.17)/ **AN**	**- 39%**	- 22%

[10] From mass balance calculations (e.g. Chapter 3, Eqn 3.1, p3.11).
[11] BEPR in *Control system (R2)* appeared to be inhibited (possibly by sulphide in influent - see Ch. 5, section 5.3.1.1)

8.2 MATHEMATICAL MODELLING OF SIMULTANEOUS CHEMICAL PRECIPITATION

Both for research and design/ operational purposes, it is clearly advantageous to integrate processes which describe simultaneous chemical precipitation into a general model for activated sludge systems. In order to be useful, the activated sludge model should also include biological phosphate removal, and hence, of necessity, nitrogen and carbon removal. The IAWQ ASM2 model meets these requirements in terms of a general activated sludge model and includes two simple kinetic expressions (precipitation and redissolution) which attempt to incorporate chemical P removal by addition of iron (ferric) salt as precipitant. In this study, the combined chemical-biological ASM2 model was tested against experimental data collected from laboratory-scale (pilot) plants. Data was collected for not only ferric chloride as chemical precipitant, but also for aluminium sulphate and an iron blend containing predominantly ferrous chloride.

8.2.1 Type of model

Briggs (1996) proposed a fairly complex chemical equilibrium model (Briggs, 1996), which was integrated with some of the biological processes from the former IAWPRC activated sludge model, without the BEPR processes *per se*. A critical review of the literature showed that this type of model does not offer significant advantages over the simpler kinetic approach to the chemical precipitation processes used in the IAWQ ASM2 model. In the first place, despite the added complexity of working from fundamental chemical principles, a degree of site-specific calibration of the chemical equilibrium model would still be required, due to uncertainties over certain key equilibrium or solubility product constants. (The data reported in the literature for these constants shows significant variation for ideal (or pure) solutions, and there is a paucity of data either for real solutions or activated sludge). That is, calibration of the chemical model against observed data for simultaneous precipitation activated sludge processes would be essentially the same as calibration of the kinetic model. Whereas the kinetic model lacks sophistication, it is relatively simple to calibrate. Moreover, it appears that current understanding of the actual precipitation processes occurring in activated sludge systems is rather limited. For example, working from assumptions for pure solutions, the chemical equilibrium model (Briggs, 1996) proposed that direct deposition of metal phosphate precipitation occurs; in fact, direct precipitation is "favoured" in Briggs' model, since it is assumed that that chemical equilibrium between metal phosphate and residual soluble orthophosphate is attained virtually instantaneously (and also assumed not to change since metal phosphate redissolution was not modelled). However, as pointed out above, other surface complexation models (refer to He *et al.*, 1996) suggest that rapid, direct metal phosphate precipitation probably does not occur in activated sludge systems at the low soluble phosphate and metal concentrations which usually prevail. Similarly, there is little experimental data upon which to model phosphate *adsorption* to chemical precipitate as distinct from other complexation/ precipitation reactions (He *et al.*, 1996). Briggs (1996) did attempt to model adsorption distinct from precipitation, based on data from metal hydroxide precipitates in pure solutions, but concluded that adsorption played a negligible role (i.e. adsorption was completely dominated by the precipitation reactions defined in that model). In short, until a better understanding has emerged of the basic chemical processes which are relevant for simultaneous chemical precipitation in activated systems, it would appear advisable to use the simplest possible modelling approach. The IAWQ kinetic approach appears to be a good starting point, and offers the significant advantage that it is readily integrated with not only the existing kinetic model for the biological processes, but also with emerging kinetic models of the weak acid-base systems governing pH and alkalinity (Musvuto *et al.*, 1997).

8.2.2 Model calibration

8.2.2.1 Biological processes

In the first place, accurate influent characterisation is an experimental requirement of overriding importance when attempting to model activated sludge systems. In this regard, the experimental set-up for this investigation contained certain deficiencies. For example, the inherent variability and relatively dilute strength of settled sewage (derived from Darvill Wastewater Works) proved to be a real constraint during data interpretation and modelling. It may have been better to have composed an influent for the pilot plants to a greater degree, or even entirely, from a synthetic (i.e. artificially added) COD source[12]. Alternatively, a "stronger" sewage source would have been preferable, to allow dilution to a constant influent COD concentration. Similarly, readily biodegradable COD (RBCOD) should be routinely measured since it is a parameter of crucial importance to successful modelling of the biological P removal systems[13].

Within the constraints of experimental data gained from this study, the IAWQ ASM2 model was tested. For the Control unit (i.e. *without* metal precipitant addition), it was found that the IAWQ model gave adequate prediction of biological P removal. However, in order to match predicted and observed effluent phosphate results, adjustments to one of the yield constants (Y_{PO4}) were sometimes required, although this was done within a range which fitted published data for near-neutral reactor pH. In spite of adjustments to Y_{PO4} and reasonable agreement between predicted and observed P removal of the Control unit, the magnitude of biological P release observed in the anaerobic reactor was still 10 to 15% greater than that predicted. Similarly, influent TKN needed to be adjusted by approximately 5 to 25% in order to match predicted and observed anoxic reactor nitrate concentrations[14]. Although variable, several experimental periods also showed that significant amounts of P uptake occurred in the anoxic reactor (both in the Test and Control units); anoxic P uptake is currently not catered for in the IAWQ model. In this regard, it appeared that significant shifts in the population of polyphosphate accumulating organisms (PAOs) occurred, for reasons that were not apparent, and that different PAOs may show a large variation in denitrification capability. All of these aspects (yield of P release/ P removal; denitrification kinetics; anoxic P uptake) are among those highlighted by Ekama and Wentzel (1997) as requiring further research in order to improve the predictive power of models for modified activated sludge systems.

It is worth noting that the IAWQ model makes provision for a yield constant (Y_{PHA}) which defines the polyhydroxy-alkanoate (PHA) requirement for poly P storage. Effectively, this factor defines a "sacrifice" of sequestered substrate (i.e. energy) made by the PAOs in order to take up phosphate for storage. Since substrate (in the form of PHA here) is sacrificed, the mass of PAOs yielded from growth is reduced; and since the poly P content per unit active mass PAO is fixed, an increase in Y_{PHA} translates into reduced system P removal. Whereas IAWQ (1995) recommended a Y_{PHA} value of 0.2 g COD/ g P, and Aspegren (1995) used a value of 0.3 g COD/ g P in calibration of the IAWQ model, Wentzel and Ekama (1995) recommended a small value (0.03) for this constant. It appears that the calibration of Y_{PHA} requires further research. In this study, the value suggested by Wentzel and Ekama (1995) was accepted. However, it would be logical to adjust the Y_{PHA} constant upwards in order to compensate for the possible inhibitory effect of simultaneous metal dosing on biological P removal process in the absence of P limitation in the bulk liquid. As pointed out above, such inhibition appears to be comparatively minor, but could be due to the accumulation of metal hydroxide in the sludge flocs in close proximity to active sites for biological P uptake, and could become more significant at higher metal doses. By means of Y_{PHA} , the "energy penalty" (or substrate sacrifice) which PAOs would hypothetically "pay" for taking up phosphate in the presence of an extracellular metal hydroxide phosphate "sponge" could be modelled. This effect was not included in the modelling attempts during this study, mainly on account of the problem of accurate

[12] Important considerations here were pH control (desirability of avoiding the need to dose acid for pH control with enhanced cultures fed acetate as sole carbon source), and the undesirability of inducing a selection of a completely artificial population of activated sludge organisms, with behaviour towards simultaneous chemical precipitation processes which would be unrepresentative of full-scale applications.

[13] In this study, RBCOD was measured for some, but not all, experimental periods.

[14] The observed and predicted anoxic reactor nitrate concentrations were matched as far as possible in order to minimise the impact of recycled nitrate on BEPR processes.

model calibration encountered in relation to variance in the experimental data collected. In order to make it possible to calibrate the model more accurately and resolve the effect of adjusting Y_{PHA}, additional experimental data for simultaneously dosed activated sludge systems would need to be collected, under conditions with highly characterised influent showing minimal variation in composition.

8.2.2.2 The question of "G bacteria"

The occurrence of non-poly P accumulating organisms (or so-called glycogen accumulating GAOs, or "G-bacteria") has been reported in modified activated sludge systems exhibiting weak or deteriorated BEPR performance (Mino *et al.*, 1987; Arun *et al.*, 1988; Liu *et al.*, 1994). The metabolism of GAOs seems to be similar to PAOs except that glycogen may serve as in the intracellular energy pool for anaerobic substrate sequestration, instead of poly P.

An investigation into the possible occurrence of G bacteria in the experimental systems was not one of the objectives of this study. Carbon uptake in the anaerobic zone was not specifically measured, nor was the carbohydrate content of the mixed liquor measured. However, it appears that G bacteria occurred to a minimal degree in the experimental systems used in this study. This becomes apparent when examining the modelling approach and results used in Chapter 7:

> The UCTPHO model (i.e. the kinetic mechanistic model developed by Wentzel et al., 1992) was used as the primary basis for modelling the Control system (i.e. for characterising the influent, knowing certain parameters from analytical determination and determining some of the model input parameters by trial-and-error - refer to section 7.2.1 of Ch. 7). Importantly, with the exception of $\mu_{nm,20}$ (max. specific growth rate of the nitrifiers) none of the kinetic or stoichiometry constants in the UCTPHO model where changed when the model was applied to the experimental results of the Control system. The BEPR stoichiometry (and kinetics) in the UCTPHO model is based on the observed behaviour of enhanced poly P organism cultures (or PAOs) in which it was found that, using sodium acetate as sole influent COD source, the maximum observed P content of the PAO biomass was approximately 0.38 g P/ g active VSS. Since this is a fundamental observation built into the stoichiometry of the BEPR processes in the UCTPHO model, an experimental system which gives good agreement between observed and predicted P removal behaviour may be reasonably assumed to have developed a culture of PAOs which closely resembles the behaviour of the enhanced cultures which served as basis for the model development. This would not be possible if the experiment system being modelled developed a significant population of "G bacteria" which sequester readily biodegradable substrate as carbohydrate and do not accumulate poly P. The only factor which would invalidate this deduction from application of the UCTPHO model would be inappropriate influent characterisation. In this regard, the principal influent characteristic which directly affects the BEPR processes is the readily biodegradable COD (RBCOD) concentration and it sub-portion as acetate. The amounts of acetate added as pure chemical to the influent of the experimental systems were known for all experimental periods. The failure to routinely measure RBCOD for all periods was a shortcoming in the experimental procedure, and has already been discussed (see 8.2.2.1 above). However, the available RBCOD data for the settled sewage source showed good agreement with the values deduced for model influent characterisation by trial-and-error. Hence, again, it appears reasonable to accept that the Control system performance agreed with expected BEPR behaviour, without significant interference from G bacteria. The approximations made in arriving at this conclusion do not rule out the possibility that G bacteria were present in the systems as a minor population component, capable of sequestering substrate anaerobically. The presence of G bacteria was speculated upon in Chapter 7 (section 7.2.2.1) in the context of calibration of the IAWQ model with respect to the stoichiometric constant Y_{PO4}. However, it was pointed out that pH effects are also known to influence this parameter and uncertainties in influent characterisation were an over-riding constraint.

It is interesting to note that Sudiana *et al.* (1997) studied the P removal, carbohydrate (i.e. mainly glycogen) content and PHA content of sludges in laboratory-scale sequencing batch reactors fed with acetate or glucose as carbon source at difference P loadings. Glucose and acetate produced similar BEPR removal capacity. The effluent from both systems contained virtually zero phosphate at both the high and influent P loadings selected. That is, P-limiting conditions were established at steady-state. At low P loadings, the mixed liquors of both systems (glucose and acetate-fed) were approximately 20 mgP/gVSS, which is typical of non-BEPR systems; at higher P loadings, the mixed liquors of the systems was 74 to 80 mgP/gVSS which is typical of many full-scale BEPR systems. Compared to the higher P-loaded systems, the lower P loaded systems showed a higher

carbohydrate content per unit VSS [15]. The PHA content of the sludges (taken at the end of the anaerobic phase) was similar for all the systems[16] . These results are in agreement with the Mino model (Mino *et al.*, 1987; Liu *et al.*, 1994) in which glycogen plays an important part in the biochemistry of BEPR[17]. Moreover, the behaviour of so-called GAOs (G-bacteria) vs. PAOs behaviour appear to be variations of the same basic metabolism in response to different conditions. It is interesting that the systems operated by Sudiana *et al.* (1997) did not show any significant differences microbiological classification (i.e no differences in phylogeny of the major bacterial classes, as determined using ribosomal RNA "gene" probes). The work of Sudiana et al. (1997) suggests that glucose feeding is does not always lead to proliferation of "G bacteria" and P limitation may be one of the factors inducing GAO-type behaviour in BEPR-type systems. However, in their experimental "low P" systems, the influent contained only 1-2 mgP/ℓ, which is unrepresentative of typical domestic sewage[18]. It would be useful to include carbohydrate and PHA measurements in future studies of BEPR in response to simultaneous metal ion addition, particularly under P- limiting conditions which are representative of typical full-scale operations.

8.2.2.3 Chemical processes

The IAWQ ASM2 model makes provision for two chemical processes: precipitation and redissolution. Hence, there are two kinetic expressions, each with a rate constant (viz. k_{PRE} and k_{DISS} respectively). Also, the stoichiometry of precipitation is defined as being "ideal" (i.e. 1 mol P/ mol Fe). However, no recommendations were made for application of the model to precipitants other than iron [III] salts (ferric chloride, or equivalent).

In order to calibrate the processes for chemical precipitation in the IAWQ model, either the stoichiometry or the kinetic constants may be adjusted. As a point of departure in this study, the stoichiometric constants were adjusted on the basis that these could be directly linked to the precipitation stoichiometry observed. Moreover, the IAWQ ASM2 provided no guidelines for the choice of k_{PRE} and k_{DISS}, other than suggested values of k_{PRE} =1 ℓ/(mg $FeOH_3$.d) and k_{DISS} = 0.6 /d for ferric chloride. Accordingly, these default values were accepted and stoichiometry adjusted as necessary to match predicted and observed effluent phosphate concentrations in the Test unit (dosed with metal precipitant). Calibration of the biological processes was kept the same as that for the Control (see 8.2.2.1 above). This approach gave acceptable predictions of the observed effluent phosphate concentrations, that is, of overall combined chemical-biological P removal.

However, using the suggested default kinetic constants for precipitation/ redissolution, the IAWQ model predicted very low residual (steady state) metal hydroxide concentrations in the mixed liquor (<40 mg/ℓ as $Me(OH)_3$ where Me is a trivalent metal ion). Also, the predicted metal hydroxide concentration showed very little difference for systems operated at 10d sludge age, compared to 20d sludge age. Even under P-limiting conditions, the predicted steady-state metal hydroxide concentration did not exceed 70 mg/ℓ as $Me(OH)_3$. This seems surprising, but must be seen in the light of the adjusted stoichiometry: For example, under P-limiting conditions, the P:Fe molar ratio (stoichiometry) was adjusted from 1:1 to 0.4:1. Hence the implicit formula for the predicted metal phosphate precipitate ranged from $FePO_4$ (ideal) to $Fe_{2.5}PO_4(OH)_{4.5}$, which is the same as that observed under P-limiting conditions by Luedecke *et al.* (1989). If the models predictions for "metal phosphate" are converted back to ideal precipitates (e.g. $FePO_4$ and $Fe(OH)_3$), as in the IAWQ model formulation, then effectively the steady-state amount of metal hydroxide would be significantly greater for the P-limited case. Hence, it is possible to adapt the IAWQ model for precipitates other than $FePO_4$ and $Fe(OH)_3$, including those for aluminium salts, by adjusting the *input stoichiometry*. However, for obvious reasons, it would be inelegant and tedious to model the effect of sludge age (solids retention time) by means of adjusting the stoichiometry.

---

[15] For glucose: 161 mg/ gVSS compared to 138 mg/ gVSS. For acetate: 159 mg/g VSS compared to 116 mg/g VSS.
[16] Approx. 120 mgC/gVSS as PHA.
[17] As discussed in the introduction to Chapter 7, the exact biochemical mechanism is of secondary importance from an engineering modelling point of view, provided the stoichiometry of P release/ uptake in relation to carbon (substrate) flow is defined and calibrated.
[18] In fact the "high P" conditions (10 to 13 mgP/ℓ influent P) systems of Sudiana *et al.* (1997) were more representative of full-scale plants treating domestric sewage.

In this study, it was not an objective to study the effect of sludge age on simultaneous chemical precipitation. However, as described in Chapter 4, pilot plant operational constraints, posed by reactor solids concentration and sludge settling, forced a change from a 20d sludge age to a 10d sludge age. This was carried out during a period of ferric chloride dosing. From an examination of the difference in system P removal, it appeared that this change resulted in a reduction of the P:Me stoichiometry of precipitation by about half[19]. However, as noted above, using the default precipitation kinetic constants, the IAWQ model would reflect little or no change in predicted P:Me ratio as a result of a change in sludge age, unless forced by a change in input stoichiometry. The change in stoichiometry observed with sludge age suggests that the kinetics of chemical precipitation/ redissolution are considerably slower than the default values suggested by IAWQ (1995). This conclusion concurs with the observation by He *et al.* (1996) that most of the chemical phosphate removal by simultaneous "precipitation" in activated sludge systems probably occurs by complexation/ ion exchange reactions between phosphate and colloidal or particulate metal hydroxide bound up in the mixed liquor solids, rather than by direct precipitation. Hence, surface complexation models of precipitation will probably need to be incorporated into the general activated sludge model in order to improve its predictive power. However, in order to evaluate whether the existing provisions within the IAWQ model for chemical processes could be improved upon, changes in the kinetic constants (viz. k_{PRE} and k_{DISS}) should be investigated.

A preliminary investigation into changing the kinetics of precipitation from those proposed by IAWQ (1995) was carried out, by re-simulating some of the experimental periods modelled in this study, but reducing k_{PRE} in the range 0.0005 to 1 ℓ/(mg $FeOH_3$.d) and keeping k_{DISS} in a constant ratio with k_{PRE} (i.e. k_{DISS} = 0.0003 to 0.6 /d). The results for Periods 3.3.2 and 3.3.6 (R_s = 20d and 10d respectively, with same ferric chloride dose = 10 mg Fe/ℓ) are given in Figure 8.1. This figure shows that using the IAWQ model, irrespective of the choice of k_{PRE} and k_{DISS}, it is not possible to produce a relationship between the predicted P:Fe ratio at sludge age (R_s) =10d which is half that for R_s = 20d. Furthermore, by keeping the *input stoichiometry* (i.e. model set up) constant (1:1), for values of k_{PRE} > 0.018 (-ln k_{PRE} < 4), the predicted P:Fe stoichiometry shows little change at around 0.95:1 (i.e. predicted residual metal hydroxide concentrations are negligible). Considering that the stoichiometry of chemical precipitate calculated from fractionation data[20] was usually in the range approximately 0.4 to 0.75 mol P/ mol metal ion, it appears that re-calibration of the IAWQ model using k_{PRE} in the range approximately 0.005 to 0.0005 (i.e. -ln 5.3 to 7.6) ℓ/(mg MeOH.d) would be required for a constant (1:1) P:Fe *input stoichiometry*.

Figures 8.2a and 8.2b compare the observed and IAWQ model predictions for additional P removal (i.e. Effluent $P_{CONTROL}$ - Effluent P_{TEST}) due to chemical addition using the two modelling approaches:

- Fig. 8.2a - *Adjusted input P:Me stoichiometry* but constant precipitation kinetics using the IAWQ default values (k_{PRE} = 1; k_{DISS} = 0.6), as described in Chapter 7;
- Fig. 8.2b - Adjusted precipitation kinetics ((k_{PRE} = 0.001 or 0.005; k_{DISS} = 0.0006 or 0.003) but *constant input P:Me stoichiometry*, as described above.

Comparing Figs. 8.2a and 8.2b, it can be seen that, in general terms it is possible to obtain similar model predictions using either approach. The results for calibration based on input stoichiometry (Fig. 8.2a) showed better overall agreement between the predicted and observed effluent P data, but this was largely due to greater attention to small differences from one experimental period to the next. If similar detailed adjustments to k_{PRE} and k_{DISS} had been made, improved correlation could have been achieved for Fig. 8.2b.The advantages of calibrating for the "correct" (slower) precipitation kinetic constants is that it should be independent of sludge age. Insufficient

[19] These stoichiometry estimates were based on the difference in system P removal observed between the Test and Control reactor. Comparable fractionation data for R_s = 20d vs. 10d was not available. Further investigation into the effect of sludge age on precipitation stoichiometry would need to be carried out since it is unlikely that the above-mentioned data sets from this study are sufficiently representative of this aspect.

[20] The observed stoichiometry calculated from differences in system P removal between the Test and Control unit may be unreliable because it is susceptible to differences in biological P removal between the units (particularly under conditions of P limitation when no net additional P removal may be noticed between the two systems). Fractionation of the mixed liquor solids attempts to measure the chemical precipitate fraction independently.

comparable data was collected to comment on the possible effect of sludge age on precipitation kinetics. This aspect requires further research, with a comparison of chemical precipitation stoichiometry (or "efficiency" as it is sometimes termed in the literature) for a range of sludge ages. The experimental data from this study did not produce one value for k_{PRE} (or k_{DISS}) which best fitted all the results. For alum, k_{PRE} = 0.001 (k_{DISS} = 0.0006) seemed to fit four of the six periods modelled, while for ferrous and ferric chloride, values of k_{PRE} in the range 0.001 to 0.005 (k_{DISS} 0.0006 to 0.003) seemed to fit most of the data[21].

The proposed slower precipitation kinetic constants deduced from Figs. 8.1 and 8.2b should be regarded as tentative. It is encouraging that to some extent, agreement was found between stoichiometry estimated from fractionation data and that predicted from modelling. This can be seen from Figs. 8.3a, b & c. From these figures it can be seen that, although variance in the data was large, the P:Me ratio estimated from fractionation data was usually in the range ca. 0.4 to 0.75 mol P/ mol Me. Calibration of the IAWQ model by means of input stoichiometry did not always produce predicted P:Me ratios which matched the fractionation data, with Periods 3.3.1 to 3.3.3 (ferric chloride) being notable. In the case of Periods 3.6.1/ 3.6.2a (P limited) the choice of input stoichiometry was somewhat arbitrary since both the Test and Control units removed phosphate virtually completely. For alum, the upward adjustment of stoichiometry in Period 3.2.5 was excessive, in an attempt to correct the effluent P predictions. For ferrous-ferric chloride, the first experimental period fractionation data was suspect[22], but the other periods showed better agreement, although less so for Periods 3.5.1 & 3.5.2 (also due P limitation). Generally, Figs. 8.3 (a to c) show that the IAWQ model predictions of P:Me ratio based on slower precipitation kinetics showed better agreement with fractionation data estimates (either at k_{PRE} 0.001 or 0.005), which suggests that it should be the preferred approach for future work with this model.

Finally, it is worth noting that the P:Me (molar) ratio data plotted in Figs. 8.3 (a, b & c) show fair agreement with values quoted in the literature as dose requirements for simultaneous precipitation (Table 8.2). Note that Experimental Periods 3.6.1, 3.6.2a, 3.4.4, 3.5.1 and 3.5.2 represent periods with P-limitation (at least partially), for comparison with the ratios cited in Table 8.2.

...../ Table 8.2

[21] Problems with slow attainment of steady state conditions in the mixed liquor solids were noted in Chapters 4, 5 and 7 and seemed to apply for Periods 3.2.5, 3.3.5 and 3.3.6 in Fig. 8.2b. Reduced precipitation "efficiency" for dosing alum to the anaerobic zone was noted in Chapter 3 and also showed up in Fig. 8.2b.

[22] Slow attainment of steady-state and a significant change in mixed liquor solids concentration and settling properties was noted for this period, following the change from ferric chloride (high dose) to ferrous-chloride (high dose) - see Chapters 4 and 5.

Table 8.2: Mass and molar ratio dose requirements for simultaneous phosphate precipitation in activated sludge systems from the literature, for comparison with the range of predicted (IAWQ) and observed (fractionation) results in this study (Figs. 8.3a, b &c).

Source	Type of activated sludge system	Recommended *mass* ratio Me:P	Converted *molar* ratio Me:P	Converted *molar* ratio P:Me
EPA (1976) cited by Briggs (1996)	Conventional, for • 95% P removal • 85% P removal • 75% P removal	For alum • 2.0:1 (Al:P) • 1.5:1 (Al:P) • 1.2:1 (Al:P)	 • 2.30:1 • 1.72:1 • 1.38:1	 • 0.43:1 • 0.58:1 • 0.72:1
EPA (1987) cited by Briggs (1996)	? for <1 mgP/ℓ residuals	• 1.6:1 (Al:P) for alum *or* • 1.5:1 (Fe:P) for ferric chloride	• 1.84:1 • 2.70:1	• 0.54:1 • 0.37:1
Spatzierer (1995) cited by Briggs (1996)	Conventional, for ave. 0.3 mgP/ℓ residuals	• 2.8:1 (Fe:P) for ferrous sulphate	• 5.01:1	0.20:1
Lötter (1991)	BEPR Works for <1 mgP/ℓ residuals	• 2.1 to 2.4:1 (Fe:P) for ferrous sulphate *or* • 2.1:1 (Fe:P) for ferric sulphate	• 3.8 to 4.3:1 • 3.8:1	• 0.23 to 0.26:1 • 0.26:1

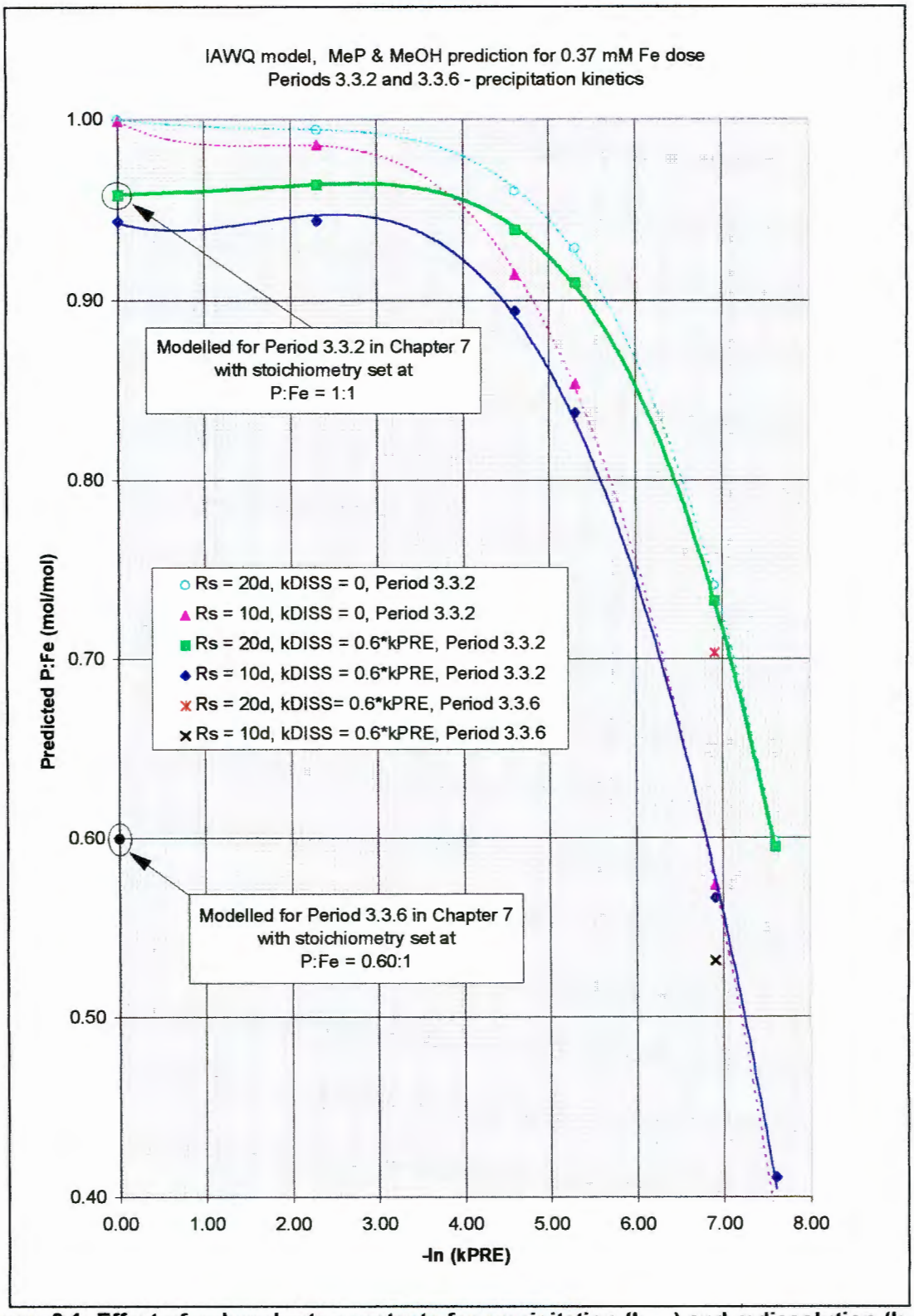


Figure 8.1: Effect of reduced rate constants for precipitation (k_{PRE}) and redissolution (k_{DISS}) on predicted P:Me (i.e. P:Fe) ratio using IAWQ ASM2 model, as applied for ferric chloride dosing : Period 3.3.2 (Rs = 20 d) and 3.3.6 (Rs = 10 d), both at ca. 10 mgFe/ℓ dose (ca. 0.37 mM based on influent). *Note: Input P:Fe stoichiometry was 1:1 for simulations to produce the predictions from which the curves were constructed.*

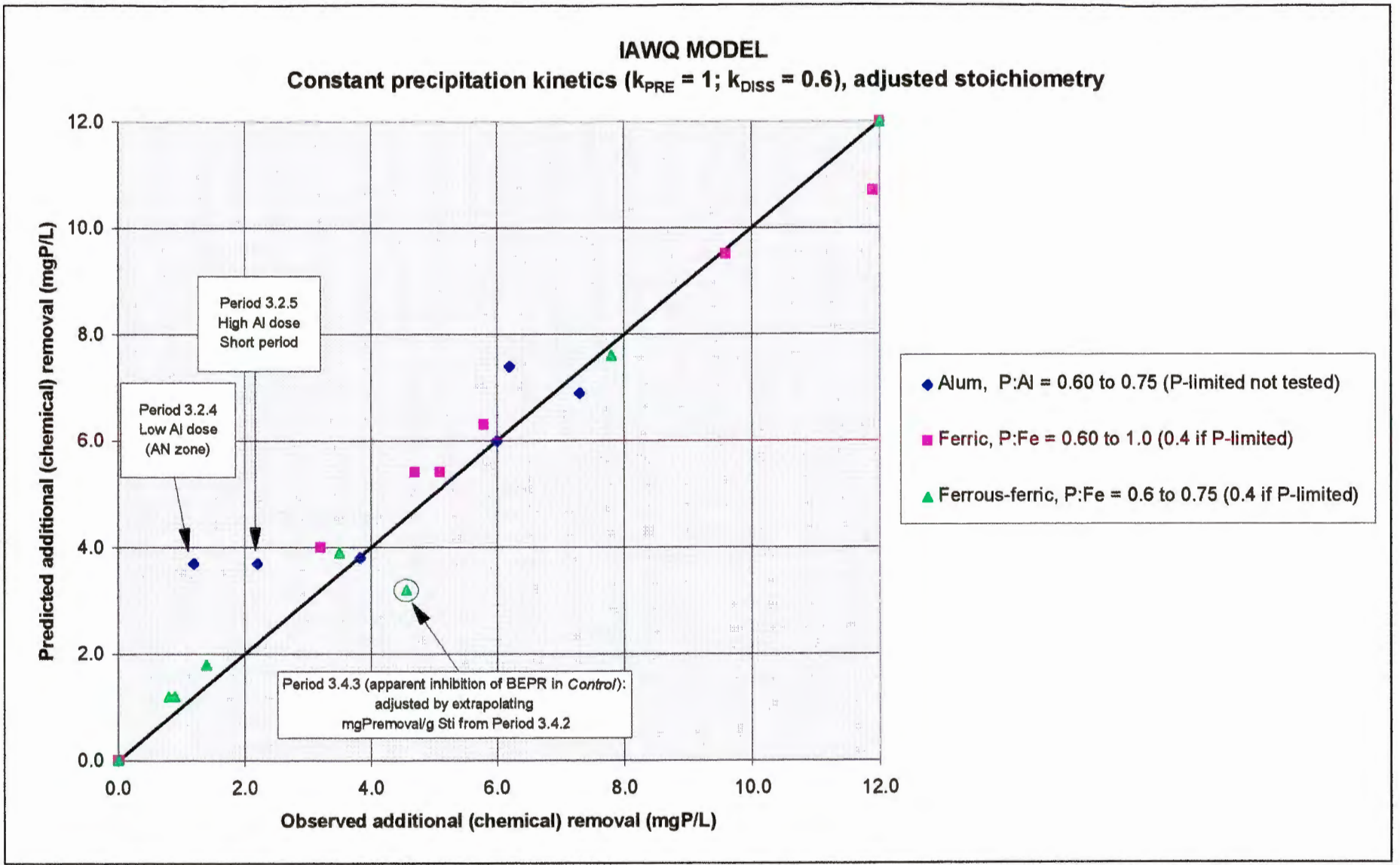


Figure 8.2a: IAWQ model predicted and observed data for additional P removal due to metal precipitant addition using the modelling approach of adjusting the *input P:Me stoichiometry* while keeping the precipitation kinetics constant (k_{PRE} = 1; k_{DISS} = 0.6).

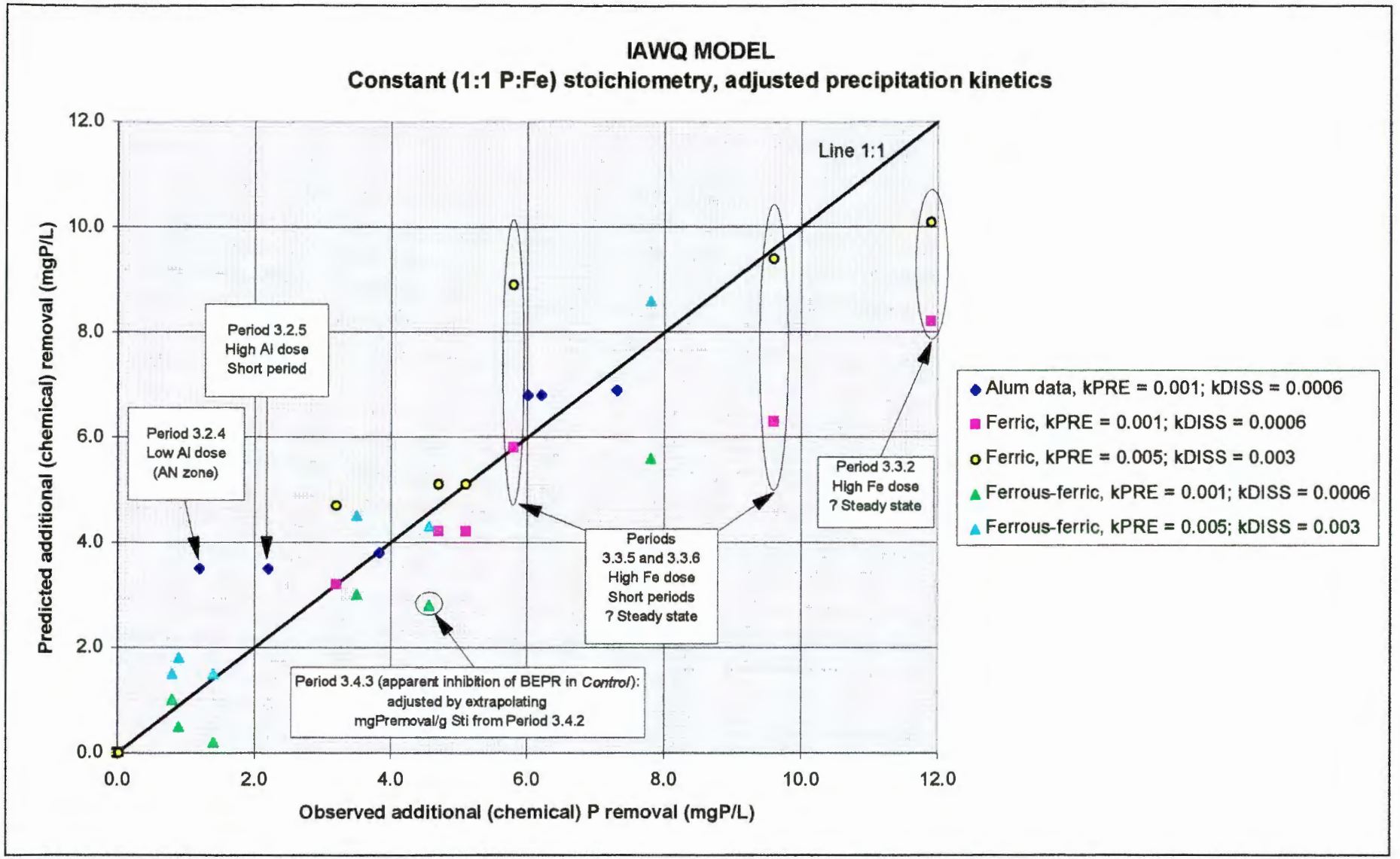


Figure 8.2b: **IAWQ model predicted and observed data for additional P removal due to metal precipitant addition using the modelling approach of adjusting the precipitation kinetics (see legend) while keeping the *input P:Me stoichiometry* constant.**

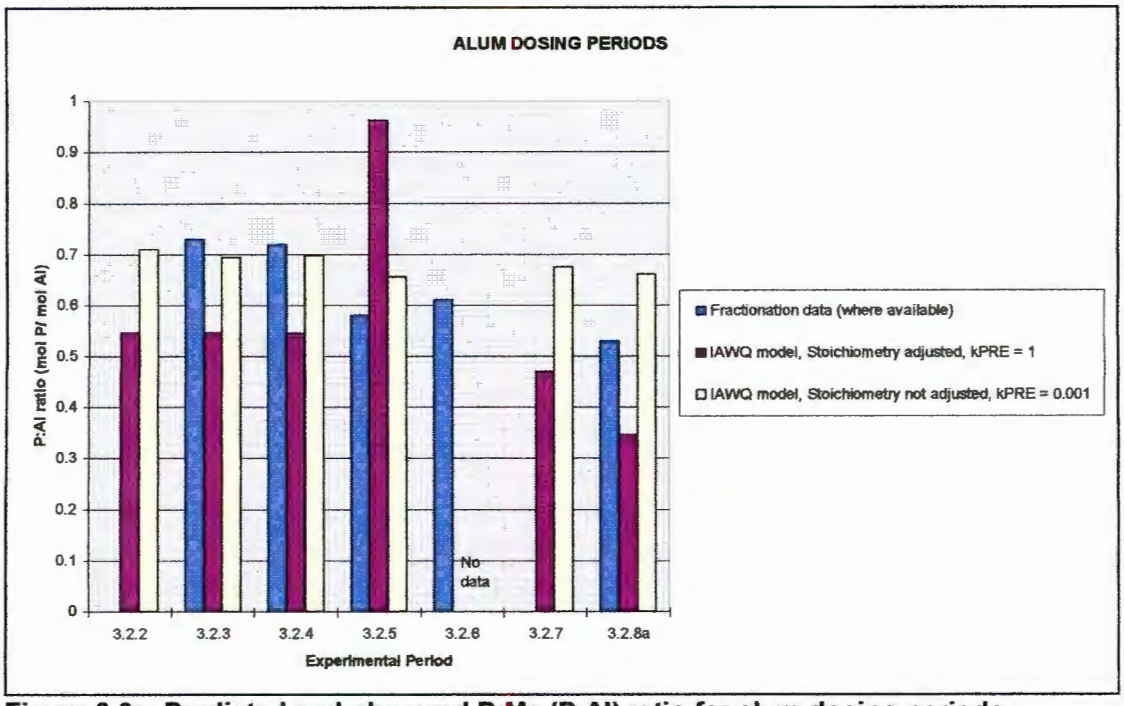


Figure 8.3a: Predicted and observed P:Me (P:Al) ratio for alum dosing periods.

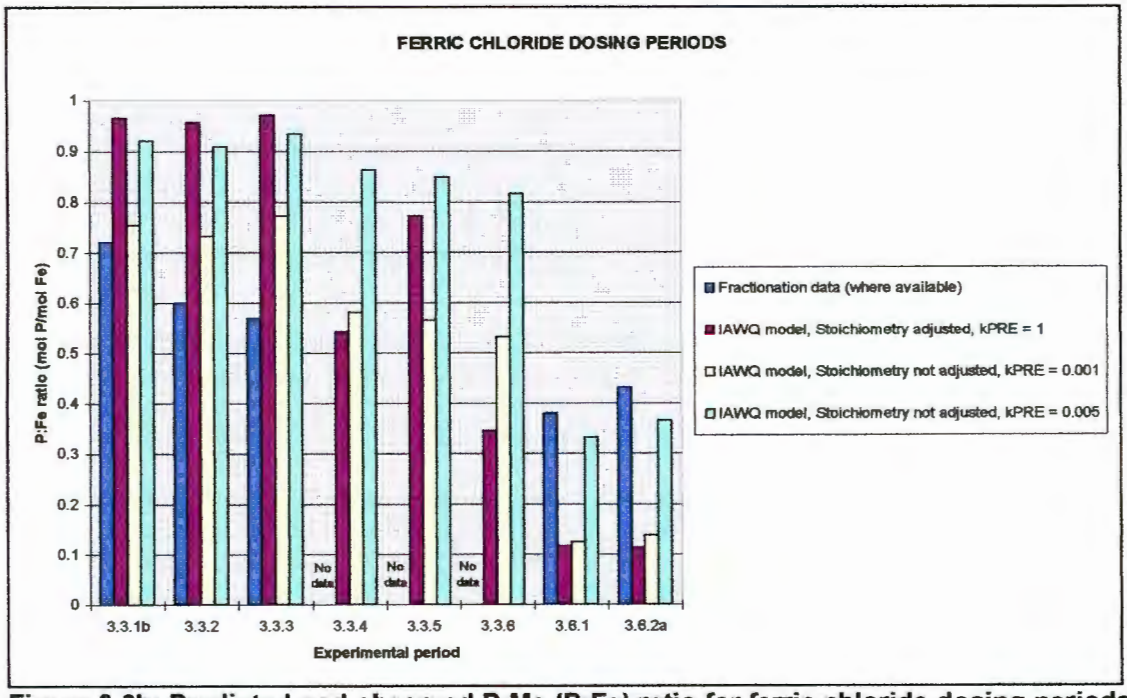


Figure 8.3b: Predicted and observed P:Me (P:Fe) ratio for ferric chloride dosing periods.

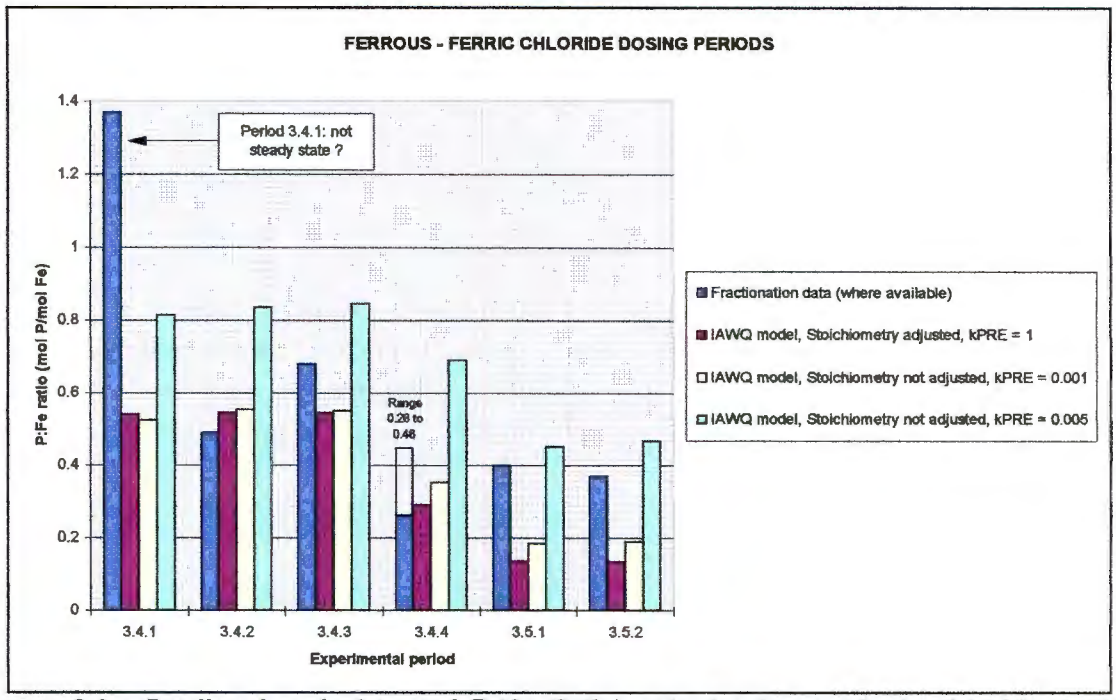


Figure 8.3c: Predicted and observed P:Me (P:Fe) ratio for ferrous-ferric chloride dosing periods.

8.3 FULL-SCALE PLANT TRIAL AT DARVILL WWW

8.3.1 Supplementary P removal using ferrous-ferric chloride vs. alum

Historical data for simultaneous alum dosing in the activated sludge plant at Darvill WWW showed that a dose of ca. 30 to 50 mg/ℓ as alum[23] (ca. 3 to 5 mg/ℓ as Al) did not guarantee 95%(+) compliance with the 1 mgP/ℓ effluent ortho P standard for this works. Average compliance levels in the region of 80 to 90% were achievable, but poor trade effluent control appeared to contribute to the variation in P removal performance.

Ferrous-ferric chloride had shown good performance during pilot plant trials, with little apparent inhibition of the biological P removal mechanism and good sludge settleability, although strictly P-limiting conditions had not been tested. This, together with the potential for cost savings compared to alum, led to a full-scale plant trial being conducted with ferrous-ferric chloride at Darvill WWW.

P removal performance during the first two months of dosing with ferrous-ferric chloride was excellent (95% to 100% compliance with 1 mgP/ℓ standard, for the two months respectively). However, during the third month, compliance with the P standard fell dramatically and reached its lowest in the recent history of the plant (17%). In the absence of a control, it was difficult to attribute this deterioration in P removal directly to the ferrous-ferric chloride. Trade effluent factors have in the past played a major role in dictating P removal performance at this plant. A high incidence of high influent phosphate, vegetable oil, and pH-related incidents were noted during the latter period of the plant trial, but some of these were based on subjective observations by Operators of vegetable oil entering the Works. A reversion to alum dosing did result in improved P removal performance, but this appeared to be mainly linked with lower influent P concentrations and a December shut-down by industries. Relatively poor performance followed subsequently, with alum dosing, but a recurrence of vegetable oil and pH-related trade effluent problems was again noted.

[23] Alum as $Al_2(SO_4)_3.14H_2O$

On balance, the full-scale plant trial gave equivocal results for ferrous-ferric chloride dosing compared to alum. In future trials, it will be essential to use dose both chemicals concurrently and independently into test and control systems. This was not possible on the Darvill full-scale plant. From theoretical (chemical equilibrium) considerations, it was hypothesised that iron dosing systems may be more susceptible to inhibition of the biological P removal system as a result of P limitation. This could be due to iron-precipitated systems establishing a lower equilibrium residual concentration of phosphate, compared with alum, in the pH range 7.0 to 7.4. In turn, this could produce a greater degree of depression of the BEPR mechanism due to the very low P concentrations[24]. With time, the reduced numbers of PAO in the system would result in a smaller BEPR potential, making it more vulnerable (in terms of elevated effluent P concentrations) to transient increases in influent P load (see section 8.1.1 of this chapter). Although a similar effect would be expected with alum under P-limiting conditions, followed by transient increases in P load, the extent of depression of the BEPR mechanism may be smaller if the residual ortho P concentrations are slightly higher, as suggested from theoretical considerations. However, the data for the full-scale trial did not support this hypothesis. It was concluded that ferrous-ferric chloride would provide at least comparable P removal performance to alum by simultaneous addition to activated sludge plants.

Potential cost savings as a result of switching from alum to ferrous-ferric chloride were found to be of the order of 12% for Darvill WWW. This did not provide sufficient incentive for changing from alum to ferrous-ferric chloride on a permanent basis, particularly in view of foaming and settling problems which emerged during the plant trial (see section 8.3.2).

8.3.2 Foaming and sludge settleability

A serious outbreak of *Nocardia*-type foaming and significantly worsened settling occurred during the ferrous-ferric plant trial at Darvill WWW.

The foaming problem appeared to be associated with the above-mentioned high incidence of vegetable oil/ wax related trade effluent problems experienced at this Works[25]. However, these problems had also occurred frequently in the past also, and the severity with which the *Nocardia* foam developed during the plant trial suggested that ferrous-ferric dosing played a role in its development. It was hypothesised that ferric ions played a role in the stabilisation of the biological foam to an extent that aluminium ions do not. This aspect would require further research. The foaming problems appeared to be directly linked to the deterioration in sludge settleability. Although part of annual/ seasonal trend, the highest monthly average DSVI was recorded during the ferrous-ferric plant trial, compared historically to the same of year for this plant using alum as simultaneous precipitant.

[24] During the first two months of the ferrous-ferric plant trial, the average effluent ortho P concentrations were 0.3 mgP/ℓ (±0.3), which is not significantly different from that observed for periods of good P removal using alum.

[25] This effect would not have been observed in the pilot plants, probably mainly because the influent sewage was stored at 4°C (which would have resulted in most of the oil/ grease congealing at the surface). Furthermore, influent to the pilot plant was always pumped from below water surface under conditions which were quiescent compared to the full-scale plant. Hence little oil and grease would have been entrained to reach the pilot plant reactors. Biological foaming was never observed in these units.

8.3.2 Full-scale secondary settling tank stress tests

Using flux theory as a basis, a series of four stress tests were conducted using the Darvill full-scale secondary settling tanks. These clearly demonstrated the effect which impaired settling behaviour (as noted from routine DSVI measurements) has on settling tank performance. Although very low effluent solids concentrations were noted for periods with increased DSVI, it was most notable that the maximum "safe" overflow (or solids loading) rate was significantly reduced with increased DSVI, as judged from measurements of flux theory constants V_0 and n in stirred settling tests. At a DSVI of approx. 104 mℓ/g, the maximum "safe" overflow rate for these clarifiers was less than 1.5 times average dry weather flow, compared to between two and three times average dry weather flow for comparable mixed liquor solids concentrations at DSVIs of approximately 50 to 70 mℓ/g. This illustrated the value of flux theory in setting operational parameters for a works such as Darvill, which is subject to large increases in flow during wet weather.

The stress tests conducted were evaluated in terms of standard flux theory (WRC, 1984) and modified flux theory[26] (Ekama and Marais, 1986). It was found that the data conformed with the provisions of modified flux theory as proposed by Ekama and Marais (1986), namely, that gross clarifier solids overloading is likely at overflow rates in excess of 80% of the permissible maximum overflow rate calculated from standard flux theory. In the case of the Darvill stress tests, solids overloading occurred due to a failure to meet the thickening criterion, as defined by WRC (1984). Confirmation of modified flux theory adds further credibility to the approach followed in the design and operating manual for secondary settling tanks recently published by the IAWQ (Ekama *et al.*, 1997).

---

[26] In terms of modified flux theory, maximum permissible overflow rates are reduced to 80% of that calculated from standard flux theory (Ekama and Marais, 1986).

University of Cape Town

REFERENCES

Arun, V, Mino, T and Matsuo, T. (1988) Biological mechanism of acetate uptake mediated by carbohydrate consumption in excess biological phosphorus removal system. *Water Res.*, 22, 565-570.

Aspegren, H. (1995) *Evaluation of a high loaded activated sludge process for biological phosphorus removal.* Ph.D. Thesis, Dept. of Water and Environmental Engineering, Lund University of Technology, Lund, Sweden.

Barker, PS and Dold, PL. (1997). General model for biological nutrient removal activated-sludge systems: model presentation. *Water Env. Res.* 69 (5), 969-984.

Briggs, TA. (1996) Dynamic modelling of chemical phosphorus removal in the activated sludge process. M. Eng. Thesis, Dept. of Civil Engineering, McMaster University, Hamilton, Ontario, Canada.

Brown, MJ and Lester, JN. (1979) Metal removal in activated sludge: the role of bacterial extracellular polymers. *Water Res.*, 13, 817-837.

Comeau, Y, Hall, KJ, Hancock, REW and Oldham, WK. (1986) Biochemical model for enhanced biological phosphorus removal. *Water Res.*, 20 (12), 1511-1521

Ekama , GA and Marais GvR. (1986) Sludge settleability and secondary settling tank design procedures. *Water Pollut. Control* 1986, 101-113.

Ekama, GA and Wentzel, MC. (1997) Denitrification kinetics in biological N&P removal activated sludge systems treating municipal wastewaters. Paper presented at *BNR3* Conference, Brisbane, Australia, 30 November - 3 December, 1997.

Ekama, GA, Barnard, JL, Gunthert, FW, Krebs, P, McCorquodale, JA, Parker, DS and Wahlberg, EJ. (1997) *Secondary Settling Tanks: Theory, Design and Operation.* IAWQ Scientific and Technical Report No. 6, IAWQ, London.

He, QH, Leppard, G, Paige, CR and Snodgrass, WJ. (1996) Transmission electron microscopy of a phosphate effect on the colloid structure of iron hydroxide. *Water. Res.*, 30 (6), 1345-1352.

IAWQ (1995) *Activated Sludge Model No. 2.* IAWQ Task Group on Mathematical Modelling for Design and Operation of Biological Nutrient Wastewater Treatment Processes. International Association on Water Quality, 1 Queen Anne's Gate, London.

Liu, W, Mino, T, Nakamura, K and Matsuo, T. (1994) Role of glycogen in acetate uptake and polyhydroxyalkanoate synthesis in anaerobic-aerobic activated sludge with a minimized polyphosphate content. *J. Ferment. Bioeng.* 77 (5), 535-540.

Lötter, LH. (1991) Combined chemical and biological removal in activated sludge plants. *Water Sci. Technol.*, 23 (Kyoto), 611-621.

Luedecke, C, Hermanowicz, SH and Jenkins, D. (1989) Precipitation of ferric phosphate in activated sludge: a chemical model and its verification. *Water Sci. Technol.* 21 (Brighton), 325-327.

Mino, T, Arun, V, Nakamura, K and Matsuo, T. (1987). Effect of phosphorus accumulation on acetate metabolism in the biological phosphorus removal processes. *In: Biological phosphate removal from wastewaters. Advances in Water Pollution Control 4.* (Ramadori, R (ed.), Pergamon Press, Oxford, p27-88.

University of Cape Town

Musvuto, EV, Wentzel, MC, Loewenthal, RE and Marais, GvR. (1997) Kinetic based model for mixed acid/base systems. *Water SA* 23 (4), 311-322.

Rabinowitz, B and Marais, GvR. (1980) *Chemical and biological phosphorus removal in the activated sludge process.* Research Report No. W32, University of Cape Town, Dept. of Civil Engineering, March 1980.

Röske, I and Schönborn, C. (1994b) Influence of the addition of precipitants on the biological phosphorus elimination in a pilot plant. *Water Sci. Technol.,* 30 (6), 323-332.

Smolders, GJF, van der Meijm J, van Loosdrecht, MCM and Heijnen, JJ. (1994) Model of the anaerobic metabolism of the biological phosphorus removal process; stoichiometry and pH influence. *Biotechnology and Bioengineering.* 43, 461-470.

Sudiana, IM, Mino, T, Satoh, Nakamura, K and Matsuo, T. (1997) Metabolism of enhanced biological phosphorus removal and nonenhanced biological phosphorus removal sludge with acetate and glucose as carbon source. Proceedings of the *BNR 3* Conference, 30 Nov. to 4 Dec. 1997, Brisbane, Australia, p41 - 48.

Wentzel, MC and Ekama, GA. (1995) Modelling of biological nutrient removal activated sludge systems - an overview. Paper presented at Bio-P Hannover 95 International Conference, Hannover, Germany, 1995.

Wentzel, MC, Ekama, GA and Marais, GvR. (1992) Processes and modelling of nitrification denitrification biological excess phosphorus removal systems - a review. *Water Sci. Technol.* 25 (6), 59-82.

Witt, PC, Grabowski, F and Hahn, HH. (1994) Interactions between biological and physico-chemical mechanisms in biological phosphate elimination. *Water Sci. Technol.,* 30 (6), 271-279.

WRC. (1984) *Theory, design and operation of nutrient removal activated sludge processes.* Water Research Commission, PO Box 824, Pretoria, South Africa.

University of Cape Town

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting enhanced biological phosphate removal.

Volume 2

Appendices

DW de Haas

Ph.D. Thesis

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting enhanced biological phosphate removal.

Appendix 1

Skalar Methods:

Ammonia/ Total (Kjeldahl) Nitrogen

DW de Haas

SKALAR METHODS

ANALYSIS : AMMONIA / TOTAL NITROGEN
RANGE : 0.6 - 30 ppm N
SAMPLE : WATER / WATER DIGEST

catnr. 155-205 issue 072393/MH/93119670

PRINCIPLE

The automated procedure for the determination of Ammonia is based on the modified Berthelot reaction; ammonia is chlorinated to monochloramine which reacts with salicylate to 5-aminosalicylate. After oxidation and oxidative coupling a green colored complex is formed. The absorption of the formed complex is measured spectrophotometrically at 660 nm.

LABORATORY FACILITIES

1. Maximum power consumption depending on the analyzer configuration 2000 VA. Check voltage at the back of instrument before installation.
2. Facilities for chemical wastes. Check environmental regulation for proper disposal of waste.

PROCEDURE SAMPLE PREPARATION

Ammonia
water method 1.2.3

Field of application

Sample preservation for the determination of $N\text{-}NH_4$, C.O.D., D.O.C., NO_2+NO_3, phenols and $P\text{-}PO_4$ in water.

Principle

The sample is preserved with H_2SO_4 to pH < 2.

Reagents

Sulfuric acid (97%)

Procedure

1 Add concentrated H_2SO_4 to the sample until pH < 2 (normally 2 ml/liter sample).
2 Store at 4°C for maximum 28 days.

Remarks

1 The sample does not need preservation if analyzed immediately.
2 In the case of phenols, check for sulfur compounds and oxidizing agents.
3 For dissolved organic carbon, fill the sample bottle completely and keep protected from sunlight and atmospheric oxygen.
4 Turbid samples have to be filtered if necessary.

References

Environmental Protection Agency, methods for chemical analysis on water and wastes, 1983.

Total phosphate
Water digest 2.1.3

Field of application

The digestion is used for the determination of total nitrogen in all kind of water samples. This digestion may also be used for phosphorus determination.

Principle

The water sample is digested with sulfuric acid, potassium sulfate and mercuric sulfate as catalyst. Amino nitrogen of many organic materials is converted into ammonium sulfate. Free ammonia and ammonium-nitrogen are also converted into ammonium sulfate. Phosphorus is transferred into ortho-phosphate.

Apparatus

Block digester for 75 ml tubes. SKALAR SA 5640
Exhaust system for 75 ml tubes. SKALAR SA 5750

Reagents

Mercuric sulfate solution

1 Dissolve 8 g of red mercuric oxide (HgO) in 100 ml sulfuric acid (H_2SO_4 1.8M).

Digestion solution

1 Weigh 134 g of K_2SO_4 in a 1 liter beaker.
2 Add about 650 ml of distilled water and dissolve.
3 Add 200 ml of concentrated H_2SO_4.
4 Add, while stirring, 25 ml of mercuric sulfate solution.
5 Make up to 1 liter with distilled water.

Procedure

1 Pipette 60.0 or 75.0 ml of the sample into the digestion tube. Prepare also a blank, consisting of 20.0 ml distilled water.
2 Add some TFE fluorocarbon boiling stones.
3 Add 15.0 ml of the digestion solution and mix.
4 Pre-heat the digestion block to 180°C.
5 Insert the digestion tube into the digestion block.
6 Heat at 180°C for 1 hour.
7 Heat the digestion block to 380°C.
8 When the temperature is 380°C, leave the digestion tube for 2 1/2 hour at 380°C.
9 Remove the digestion tube from the digestion block and let it cool down.
10 Carefully add 60 ml of distilled water and mix.
11 Make up to the mark and mix.

Remarks

1 Aromatic and heterocyclic nitrogen compounds are not completely determined.
2 Anorganic nitrate and nitrite and some metals could disturb the Kjeldahl determination.
3 Some amines are determined as ammonium as well, even after distillation.

References

1 ASTM 1990, D3590-89.
2 Environmental Protection Agency, methods for chemical analysis of water and wastes, Method 351.2.
3 Environmental Protection Agency, methods for chemical analysis of water and wastes, Method 365.4.

REAGENTS

A1. Distilled water + Brij 35 (for ammonia)

Required chemicals: Distilled water ..... 1000 ml. H_2O
Brij 35 (30%) ..... 3 ml.

Preparation: Dilute the Brij 35 in 1 liter distilledwater and mix.

A2. Sodium chloride solution (for total nitrogen)

Required chemicals: Sodium chloride ..... 30 gr. NaCl
Distilled water ..... 1000 ml. H_2O
Brij 35 (30%) ..... 3 ml.

Preparation: Dissolve the sodium chloride in ± 800 ml distilled water. Fill up to 1 liter dhe Brij 35 and mix.

B. Buffer solution

Required chemicals: Potassium sodium tartrate ..... 33 gr. $C_4H_4O_6KNa.4H_2O$
Sodium citrate ..... 24 gr. $C_6H_5O_7Na_3.2H_2O$
Distilled water ..... 1000 ml. H_2O
Brij 35 (30%) ..... 3 ml.

Preparation: Dissolve the potassium sodium tartrate in ± 800 ml distilled water. Add the sodium citrate and dissolve. Fill up to 1 liter, add the Brij 35 and mix.

Note: Check the pH and correct if necessary with HCl to 5.2 ± 0.1.

C. Sodium salicylate

Required chemicals: Sodium hydroxide ..... 25 gr. NaOH
Sodium salicylate ..... 80 gr. $C_7H_5NaO_3$
Distilled water ..... 1000 ml. H_2O

Preparation: Dissolve the sodium hydroxide in ± 50 ml distilled water. Add ± 700 ml distilled water. Add the sodium salicylate. Fill up to 1 liter and mix well.

Note: Store in a dark colored bottle. The solution is stable for one week.

D. Sodium nitroprusside

Required chemicals: Sodium nitroprusside ..... 1 gr. $Na_2[Fe(CN)_5NO].2H_2O$
Distilled water ..... 1000 ml. H_2O

Preparation: Dissolve the sodium nitroprusside in ± 800 ml distilled water. Fill up to 1 liter and mix.

Note: Store in a dark colored bottle. The solution is stable for one week.

E. Sodium dichloroisocyanurate

Required chemicals: Sodium dichloroiso cyanurate ..... 2 gr. $C_3N_3O_3Cl_2Na.2H_2O$
Distilled water ..... 1000 ml. H_2O

Preparation: Dissolve the sodium dichloroisocyanurate in ± 800 ml distilled water. Fill up to 1 liter and mix.

Note: The solution is stable for one week.
If the calibration curve is not lineair, change the pump tube to 0.16 ml/min.

F. Rinsing liquid sampler for ammonia

Required chemicals: Distilled water
H_2O

G. Rinsing liquid sampler for total nitrogen

Required chemicals: Sulfuric acid .....45 ml.
H_2SO_4 (97%)
Potassium sulfate .....26.8 gr.
K_2SO_4
Distilled water.....955 ml.
H_2O

Preparation: Dilute the sulfuric acid in ± 800 ml distilled water. Add the potassium sulfate and dissolve. Fill up to 1 liter with distilled water and mix.

STANDARDS

Stock solution 1000 ppm N

Required chemicals: Ammonium chloride ..... 3.8190 gr.
NH_4Cl
Distilled water..... 1000 ml.
H_2O

Preparation: Dilute ammonium chloride in ± 800 ml distilled water. Fill up to 1 liter and mix.

Working standards for ammonia

30 ppm N: Dilute 3.0 ml stock solution 1000 ppm N to 100 ml with distilled water.
24 ppm N: Dilute 2.4 ml stock solution 1000 ppm N to 100 ml with distilled water.
18 ppm N: Dilute 1.8 ml stock solution 1000 ppm N to 100 ml with distilled water.
12 ppm N: Dilute 1.2 ml stock solution 1000 ppm N to 100 ml with distilled water.
6 ppm N: Dilute 0.6 ml stock solution 1000 ppm N to 100 ml with distilled water.

Working standards for total nitrogen

30 ppm N: Dilute 3.0 ml stock solution 1000 ppm N to 100 ml with rinsing liquid G.
24 ppm N: Dilute 2.4 ml stock solution 1000 ppm N to 100 ml with rinsing liquid G.
18 ppm N: Dilute 1.8 ml stock solution 1000 ppm N to 100 ml with rinsing liquid G.
12 ppm N: Dilute 1.2 ml stock solution 1000 ppm N to 100 ml with rinsing liquid G.
6 ppm N: Dilute 0.6 ml stock solution 1000 ppm N to 100 ml with rinsing liquid G.

GENERAL REMARKS

1. If a matrix photometer, catnr. 6250 or 6260, is in use, a correction interference filter of 1010 nm ± 10% is advised.
2. In most analysis, the first peak coming from the baseline is much lower than it should be. The first peak coming from the baseline is rejected and will not be included in the calculation of the CV value.
3. If reaction coils with water heating are used, the water bath has to be cooled with tap water when environment temperature is above 25°C.
4. If the sample take up volume is less than 1.00 ml/min., a bypass is required to increase the sample stream to approximately 1.00 ml/min.
5. All reagent bottles must be rinsed thoroughly with distilled water before refilling with fresh reagents. This to prevent precipitation of micro organism and interferences.
6. Rinsing valves catnr. SA 1500/1520 can not be used for organic solutions or acid solution > 4N.

MAINTENANCE

1. To decontaminate the system rinse with 1:10 diluted hypochlorite solution for 30 minutes, rinse clean with distilled water for 30 minutes afterwards.
2. Degas reagents if air bubbles spontaneously appear. Degas by aspirating helium gas at 20 liter/hour for 15 minutes.
3. Avoid any turbidity in reagents, filter if necessary.
4. After 6 months the amount of Brij 35 can be reduced to 1 ml/liter.

SETTINGS

1. The sensitivity of the highest standard 30 ppm N is ± 300 A.U.
2. Sample time: 60 sec., wash time: 60 sec., air: 0 sec.
3. Settings recorder: 100 mV.
4. The connection between the sampler and the sample pump tube is made of 5130 tube.
5. The stabilizing time of the system is approximately 20 minutes.

CARTRIDGE COMPONENTS

manifold holder	catnr. SA 5105	clamps large	catnr. SA 5110
module	catnr. SA 5107	sinkers	catnr. SA 5380
end block	catnr. SA 5109	flow cell 10 mm	catnr. SA 6401
inlet connector	catnr. SA 5232	filter 660 nm	catnr. SA 6565
inlet connector	catnr. SA 5244	filter 520 nm	catnr. SA 6637
inlet connector	catnr. SA 5246 (3x)	pump tubing 0.80 ml/min.	catnr. SA 3030
debubbler	catnr. SA 5250	pump tubing 0.16 ml/min.	catnr. SA 3025
connector	catnr. SA 5220 (3x)	pump tubing 1.40 ml/min.	catnr. SA 3033
glass coil 5W	catnr. SA 5325 (4x)	pump tubing 0.32 ml/min.	catnr. SA 3030
heat exchanger	catnr. SA 5300	pump tube sampler	catnr. SA 1060
clamps small	catnr. SA 5111		

Note: If a pump catnr. SA 2002 or 2005 is in use, the pump tubes with catnr. SA 3020 up to 3039 are replaced by pump tubes with catnr. SA 5020 up to 5039. The inlet connector 5244 can also be a 5231.

CARTRIDGE CONSUMABLES

If only a module is ordered with a flow cell catnr. SA 6401 and filters catnr. SA 6565 and SA 6637, the following components are added to the module:

silicone tube	catnr. SA 3150
polyethylene tube	catnr. SA 5141
	catnr. SA 5142
sleeves	catnr. SA 5400
	catnr. SA 5401
	catnr. SA 5406

pump tubes as listed in the cartridge components

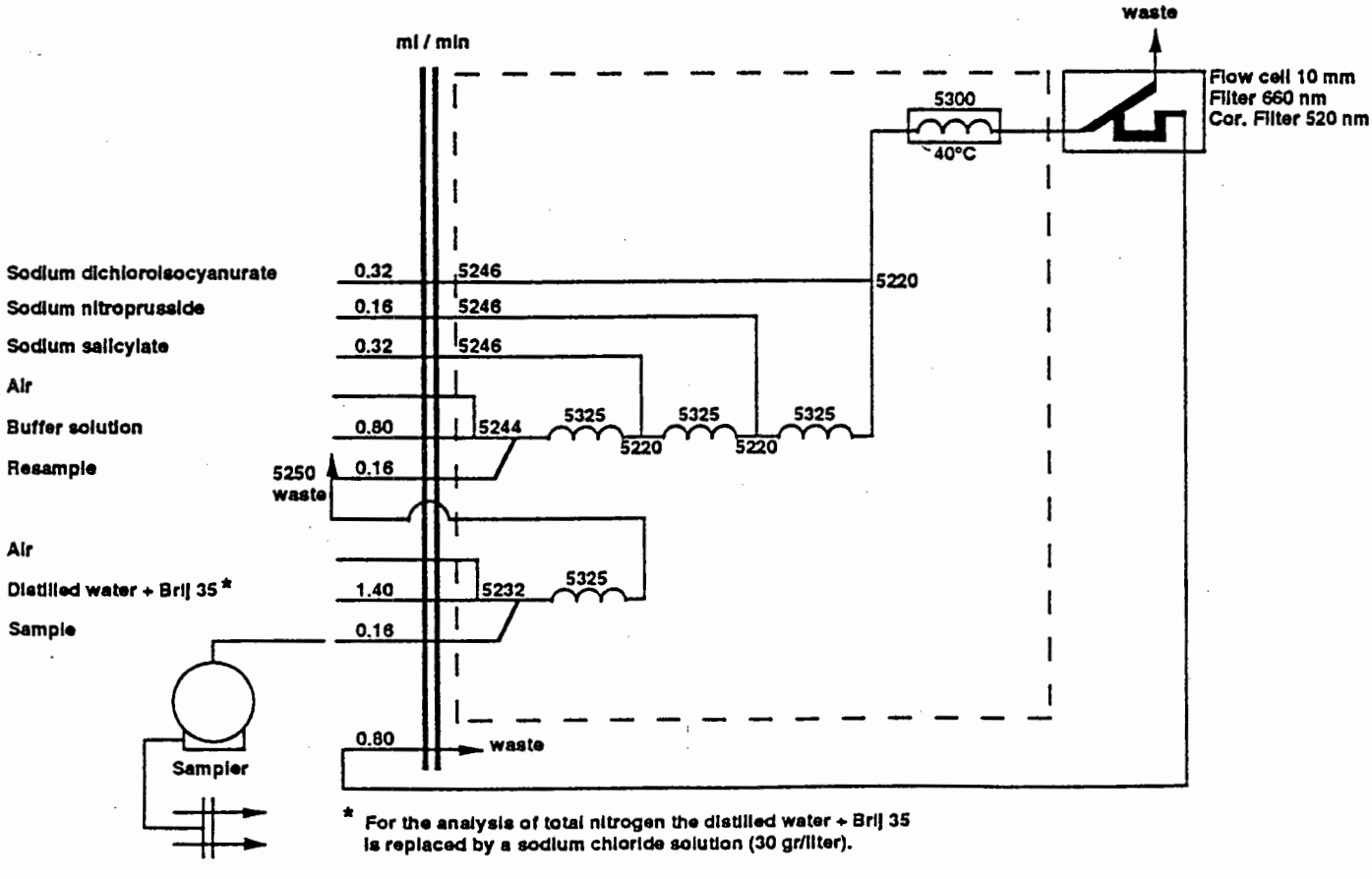
CATALOGUE NUMBERS REQUIRED CHEMICALS

Product	Supplier and Catnr.	Danger classification
Sulfuric acid (97%)	Merck 731	corrosive
Potassium sulfate	Merck 5153	
Mercuric oxide	Merck 4466	very toxic
Sodium chloride	Merck 6404	
Brij 35 (30%)	Skalar 13900	
Potassium sodium tartrate	Merck 8087	
Sodium citrate	Merck 6448	
Sodium hydroxide	Merck 6498	corrosive
Sodium salicylate	Merck 6601	harmful
Sodium nitroprusside	Merck 6541	toxic
Sodium dichloroisocyanurate	Merck 10888	harmful, oxidizing
Ammonium chloride	Merck 1145	harmful

REFERENCES

1. Krom, M.,"Spectrophotometric determination of ammonia; a study of modified Berthelot reaction using salicylate and dichloroisocyanurate", The Analyst, April 1980, Vol. 105, page 305-316.
2. Searle, P.L.,"The Berthelot or indophenol reaction and its use in the analysis chemistry of nitrogen", The Analyst, Vol. 109, May 1984, page 549-565.

FLOW DIAGRAM



The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting enhanced biological phosphate removal.

Appendix 2a

Skalar Methods:

Nitrate + Nitrite

DW de Haas

SKALAR METHODS

ANALYSIS : NITRATE + NITRITE
RANGE : 0.4 - 20 ppm N
SAMPLE : WATER

catnr. 461-106 issue 080593/MH/93119670

PRINCIPLE

The automated procedure for the determination of Nitrate + Nitrite is based on the cadmium reduction method; the sample is passed through a column containing granulated copper-cadmium to reduce the nitrate to nitrite. The nitrite (originally present plus reduced nitrate) is determined by diazotizing with sulfanilamide and coupling with α-naphthylethylenediamine dihydrochloride to form a highly colored azo dye which is measured at 540 nm

LABORATORY FACILITIES

1. Maximum power consumption depending on the analyzer configuration, 2000 VA. Check voltage at the back of the instrument before installation.
2. Facilities for chemical wastes. Check environmental regulation for proper disposal of waste.
3. Cadmium granules sieve twice, first aperture 0.3 mm and secondly aperture 1.0 mm.

PROCEDURE SAMPLE PREPARATION

water method 1.2.3

Field of application

Sample preservation for the determination of N-NH_4, C.O.D., D.O.C., NO_2+NO_3, phenols and P-PO_4 in water.

Principle

The sample is preserved with H_2SO_4 to pH < 2.

Reagents

Sulfuric acid (97%)

Procedure

1 Add concentrated H_2SO_4 to the sample until pH < 2 (normally 2 ml/liter sample).
2 Store at 4°C for maximum 28 days.

Remarks

1 The sample does not need preservation if analyzed immediately.
2 In the case of phenols, check for sulfur compounds and oxidizing agents.
3 For dissolved organic carbon, fill the sample bottle completely and keep protected from sunlight and atmospheric oxygen.
4 Turbid samples have to be filtered if necessary.

References

Environmental Protection Agency, methods for chemical analysis on water and wastes, 1983.

REAGENTS

A. Distilled water + Brij 35

Required chemicals: Distilled water .....1000 ml. H_2O
Brij 35 (30%) .....3 ml.

Preparation: Dilute the Brij 35 in 1 liter distilled water and mix.

B. Buffer solution

Required chemicals: Ammonium chloride .....50 gr. NH_4Cl
Ammonia solution .....± 1 ml. NH_4OH (25%)
Distilled water .....1000 ml. H_2O
Brij 35 (30%) .....3 ml.

Preparation: Dissolve the ammonium chloride in ± 800 ml distilled water. Adjust the pH to 8.2 with the ammonia solution. Fill up to 1 liter, add the Brij 35 and mix well.

Note: It is advised to degas the reagent before adding the Brij 35.

C. Color reagent

Required chemicals: o-Phosphoric acid .....150 ml. H_3PO_4 (85%)
Sulfanilamide .....10 gr. $C_6H_8N_2O_2S$
α-naphthylethylenediamine dihydrochloride .....0.5 gr. $C_{12}H_{16}Cl_2N_2$
Distilled water .....850 ml. H_2O

Preparation: Dilute the o-phosphoric acid carefully in ± 700 ml distilled water. Hereafter the sulfanilamide and the α-naphthylethylenediamine dihydrochloride are added and dissolved. Fill up to 1 liter and mix well.

Note: Store in a dark colored bottle.

D. Rinsing liquid sampler

Required chemicals: Distilled water H_2O

STANDARDS

Stock standard 1000 ppm N

Required chemicals: Sodium nitrate .....6.0681 gr. $NaNO_3$
Distilled water .....1000 ml. H_2O

Preparation: Dissolve the sodium nitrate in ± 800 ml distilled water. Fill up to 1 liter and mix well.

Working standards

20 ppm N: Dilute 2.0 ml stock solution 1000 ppm N to 100 ml with distilled water.
16 ppm N: Dilute 1.6 ml stock solution 1000 ppm N to 100 ml with distilled water.
12 ppm N: Dilute 1.2 ml stock solution 1000 ppm N to 100 ml with distilled water.
8 ppm N: Dilute 0.8 ml stock solution 1000 ppm N to 100 ml with distilled water.
4 ppm N: Dilute 0.4 ml stock solution 1000 ppm N to 100 ml with distilled water.

PROCEDURE ACTIVATION CADMIUM COLUMN

E. Hydrochloric acid 4 N

Required chemicals: Hydrochloric acid .....400 ml. (HCl (32%))
Distilled water .....600 ml. (H_2O)

Preparation: Dilute carefully the hydrochloric acid in 600 ml distilled water.

E. Cupric sulfate 2%

Required chemicals: Cupric sulfate .....20 gr. ($CuSO_4.5H_2O$)
Distilled water .....1000 ml. (H_2O)

Preparation: Dissolve the cupric sulfate in ± 800 ml distilled water. Fill up to 1 liter and mix well.

G. Cadmium

Required chemicals: Cadmium granules .....2.5 gr.
size 0.3-1.0 mm (sieved)

FILLING PROCEDURE

The cadmium granules are mixed with ± 30 ml hydrochloric acid (4N). Stir for ± 1 minute. Wash acid free with distilled water. Add ± 50 ml cupric sulfate solution and stir for ± 5 minutes. Wash out the dirt between the granules with distilled water. Dry the cadmium with the filter paper. Add, with aid of a funnel, the granules to a dry column, with now and then vibrating to pack the column on both sides. Fill up to ± 5 mm from the top. Place a small piece of polyethylene tube (catnr 5144) which is sharpened at the inlet, into the column to avoid granules coming out of the column. Fill with aid of a syringe, containing buffer solution, the column without air. Hereafter place the column into the system.

Note: Avoid air entering the column.
Activated cadmium granules can be stored dry, in a well closed bottle.

INTERFERENCES

1. Iron, copper and other metals present in the sample give negative results on the nitrate values.
   Add 1 gr EDTA Na_2 / liter buffer.
2. Sample turbidity may interfere with this method when no dialyzer is used. Remove by filtration before analysis.
   Sample color (that absorbs in the photometric range used for analysis) will also interfere.

GENERAL REMARKS

1. If a matrix photometer, catnr. 6250 or 6260, is in use, a correction interference filter of 620 nm ± 10% is advised.
2. In most analysis, the first peak coming from the baseline is much lower than it should be. The first peak coming from the baseline is rejected and will not be included in the calculations of the CV-value.
3. If reaction coils with water heating are used, the water bath has to be cooled with tap water when environment temperature is above 25°C.
4. If sample take up volume is less than 1.00 ml/min, a bypass is required to increase the sample stream to approximately 1.00 ml/min.
5. The reagent bottles must be rinsed thoroughly with distilled water before refilling with fresh reagents. This to prevent precipitation of micro organism and interferences.
6. Rinsing valves catnr. SA 1500/1520 can not be used for organic solutions or acid solutions > 4N.

MAINTENANCE

1. To decontaminate the system rinse with 1% hypochlorite solution, once a week for half an hour, but remove the cadmium column before rinsing.
2. Degas reagents if air bubbles spontaneously appear. Degas by aspirating helium gas at 20 liter/hour for 15 minutes.
3. Avoid any turbidity in reagents, filter if necessary.
4. After 6 months the amount of Brij 35 can be reduced to 1 ml/liter.

SETTINGS

1. The sensitivity of the highest standard 20 ppm N, is ± 700 A.U.
2. Settings recorder: 500 mV.
3. Sample time: 60 sec., wash time: 60 sec., air: 1 sec.
4. The connection between the sampler and the sample pump tube is made of 5130 tube.
5. The stabilizing time of the system is approximately 20 minutes.

CARTRIDGE COMPONENTS

module	catnr. SA 5107	flow cell 10 mm	catnr. SA 6401
manifold holder	catnr. SA 5105	filter 540 nm	catnr. SA 6541
end block	catnr. SA 5109	filter 620 nm	catnr. SA 6557
inlet connector	catnr. SA 5244 (2x)	sinkers	catnr. SA 5380
inlet connector	catnr. SA 5246 (2x)	clamps small	catnr. SA 5111
glass coil	catnr. SA 5325 (2x)	pump tube 0.80 ml/min	catnr. SA 3030
glass coil	catnr. SA 5323	pump tube 0.16 ml/min	catnr. SA 3025
connector	catnr. SA 5220 (2x)	pump tube 0.60 ml/min	catnr. SA 3029
debubbler	catnr. SA 5210	pump tube 1.60 ml/min	catnr. SA 3034
Cd column	catnr. SA 5357	pump tube 0.42 ml/min	catnr. SA 3028
mounting clamp	catnr. SA 5112	pump tube sampler	catnr. SA 1060
resampler	catnr. SA 5250		
valve	catnr. SA 5290		

Note: If a pump catnr. SA 2002 or 2005 is in use, the pump tubes with catnr. SA 3020 up to 3039 are replaced by pump tubes with catnr. SA 5020 up to 5039.

CARTRIDGE CONSUMABLES

If only a module is ordered with a flow cell catnr. SA 6401 and filters catnr. SA 6541 and 6557, the following components are added to the module:

silicone tube	catnr. SA 3150
polythene tube	catnr. SA 5141
	catnr. SA 5142
sleeves	catnr. SA 5400
	catnr. SA 5401
	catnr. SA 5406

Pump tubes and membranes as listed in the cartridge components

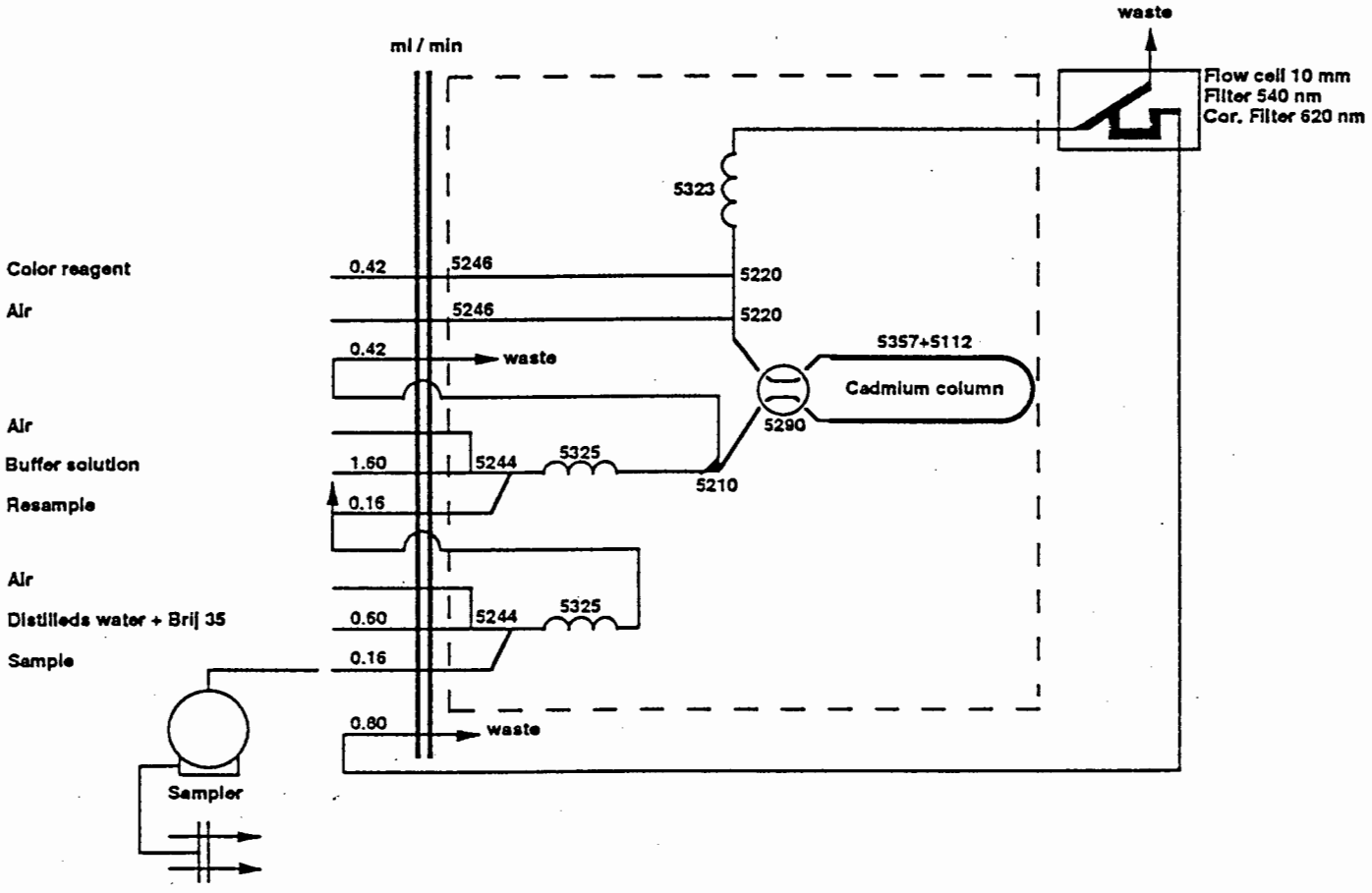
CATALOGUE NUMBERS REQUIRED CHEMICALS

Product	Supplier and catnr.	Danger classifications
Sulfuric acid (97%)	Merck 731	corrosive
Ammonium chloride	Merck 1145	harmful
Ammonium hydroxide (25%)	Merck 5432	irritant
Brij 35 (30%)	Skalar SC 13900	
o-Phosphoric acid (85%)	Merck 573	corrosive
Sulfanilamide	Merck 11799	
α-Naphthylethylenediamine dihydrochloride	Merck 6237	
Sodium nitrate	Merck 6537	oxidizing
Hydrochloric acid (32%)	Merck 319	corrosive
Cupric sulfate	Merck 2790	harmful
Cadmium granules	Merck 2001	harmful
Activated cadmium	Skalar SC 13913	harmful

REFERENCES

1. Standard method for examination of water and waste water, 15th edition, 1980.
2. Navone, R., 1964, Proposed method for nitrate in potable waters, Amer. J., Water works Ass. 56:781.
3. Walinga, I., van Vark, W., Houba, V.J.G., van der Lee, J.J., Plant Analysis Procedures, Part 7, Department of Soil Science and Plant Nutrition, Wageningen Agricultural University, Syllabus 1989, page 197-200

FLOW DIAGRAM



The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting enhanced biological phosphate removal.

Appendix 2b

Skalar Methods:

Nitrite

DW de Haas

SKALAR METHODS

ANALYSIS : NITRITE
RANGE : 0.2 - 10 ppm N
SAMPLE : WATER

catnr. 467-132 issue 072293/MH/93119670

PRINCIPLE

The automated procedure for the determination of Nitrite is based on the following reaction; the diazonium compound formed by diazotation of sulfanilamide by nitrite in water under acid conditions is coupled with α-naphthylethylenediamine dihydrochloride to produce a reddish-purple color which is measured at 540 nm.

LABORATORY FACILITIES

1. Maximum power consumption depending on the analyzer configuration, 2000 VA. Check voltage at the back of the instrument before installation.
2. Facilities for chemical wastes. Check environmental regulation forproper disposal of waste.

PROCEDURE SAMPLE PREPARATION

water no. 1.1.3

Field of application

Sample preparation for the determination of total alkalinity, aluminium, amino acids, ammonia, anionic surfactants (MBAS), calcium, C.O.D., chromium, conductivity, D.O.C., ethanol, hardness, magnesium, manganese, methanol, nitrate + nitrite, nitrite, nonionics, ortho-phosphate, potassium permanganate, potassium, protein, silicate, sodium and urea in water.

Principle

The sample is not preserved and analyzed as soon as possible, at least within 24 hours after colection. Store the sample at 4°C till analysis.

References

1 Environmental Protection Agency, methods for chemical analysis of water and wastes, 1983.
2 Standard Methods for the determination of water and waste water, 17th edition, 1989.
3 ASTM, 1990.
4 International Organisation for Standardization, ISO-5667-3.

REAGENTS

A. Distilled water + Brij 35

Required chemicals: Distilled water ..... 1000 ml. Preparation: Dilute the Brij 35 in 1 liter distilled water and mix.
H_2O
Brij 35 (30%) ..... 3 ml.

B. Color reagent

Required chemicals: o-Phosphoric acid ..... 150 ml.
H_3PO_4 (85%)
Sulfanilamide ..... 10 gr.
$C_6H_8N_2O_2S$
α-Naphthylethylenediamine
dihydrochloride ..... 0.5 gr.
$C_{12}H_{16}Cl_2N_2$
Distilled water ..... 850 ml.
H_2O
Brij 35 (30%) ..... 3 ml.

Preparation: Dilute the o-phosphoric acid carefully in ± 700 ml distilled water. Hereafter the sulfanilamide and the α-naphthylethylenediamine dihydrochloride are added and dissolved. Fill up to 1 liter, add the Brij 35 and mix well.

Note: Store in a well closed dark colored bottle.

C. Rinsing liquid sampler

Required chemicals: Distilled water
H_2O

STANDARDS

Stock standard 100 ppm N

Required chemicals: Sodium nitrite ..... 0.4926 gr.
$NaNO_2$
Distilled water ..... 1000 ml.
H_2O

Preparation: Dissolve the sodium nitrite in ± 800 ml distilled water. Fill up to 1 liter and mix well.

Working standards

10 ppm N: Dilute 10 ml stock solution 100 ppm N to 100 ml with distilled water.
8 ppm N: Dilute 8 ml stock solution 100 ppm N to 100 ml with distilled water.
6 ppm N: Dilute 6 ml stock solution 100 ppm N to 100 ml with distilled water.
4 ppm N: Dilute 4 ml stock solution 100 ppm N to 100 ml with distilled water.
2 ppm N: Dilute 2 ml stock solution 100 ppm N to 100 ml with distilled water.

INTERFERENCES

1. Sample turbidity may interfere with this method, when no dialyzer is used. Remove by filtration before analysis. Sample color (that absorbs in the photometric range used for analysis) will also interfere.

GENERAL REMARKS

1. If a matrix photometer, catnr. 6250 or 6260, is in use, a correction interference filter of 620 nm ± 10% is advised.
2. In most analysis, the first peak coming from the baseline is much lower than it should be. The first peak coming from the baseline is rejected and will not be included in the calculations of the CV-value.
3. If reaction coils with water heating are used, the water bath has to be cooled with tap water when environment temperature is above 25°C.
4. If sample take up volume is less than 1.00 ml/min, a bypass is required to increase the sample stream to approximately 1.00 ml/min.
5. The reagent bottles must be rinsed thoroughly with distilled water before refilling with fresh reagents. This to prevent precipitation of micro organism and interferences.
6. Rinsing valves catnr. SA 1500/1520 can not be used for organic solutions or acid solutions > 4N.

MAINTENANCE

1. To decontaminate the system rinse with 1% hypochlorite solution, once a week for half an hour.
2. Degas reagents if air bubbles spontaneously appear. Degas by aspirating helium gas at 20 liter/hour for 15 minutes.
3. Avoid any turbidity in reagents, filter if necessary.
4. After 6 months the amount of Brij 35 can be reduced to 1 ml/liter.
5. A refrigerator is used for cooling at 4°C.

CARTRIDGE COMPONENTS

module	catnr. SA 5107	sinkers	catnr. SA 5380
manifold holder	catnr. SA 5105	flow cell 10 mm	catnr. SA 6401
end block	catnr. SA 5109	filter 540 nm	catnr. SA 6541
inlet connector	catnr. SA 5244 (2x)	filter 620 nm	catnr. SA 6557
inlet connector	catnr. SA 5246	pump tube 0.80 ml/min	catnr. SA 3030
connector	catnr. SA 5220	pump tube 0.16 ml/min.	catnr. SA 3025
glass coil	catnr. SA 5325	pump tube 0.60 ml/min	catnr. SA 5029
glass coil	catnr. SA 5323	pump tube 0.23 ml/min	catnr. SA 3026
debubbler	catnr. SA 5250	pump tube 1.00 ml/min	catnr. SA 3031
clamps small	catnr. SA 5111	pump tube sampler	catnr. SA 1060

Note: If a pump catnr. SA 2002 or 2005 is in use, the pump tubes with catnr. SA 3020 up to 3039 are replaced by pump tubes with catnr. SA 5020 up to 5039.

CARTRIDGE CONSUMABLES

If only a module is ordered with flow cell catnr. SA 6401 and filter catnr. SA 6541 and 6557, the following components are added to the module:

polyethylene tube	catnr. SA 5141
	catnr. SA 5142
sleeves	catnr. SA 5400
	catnr. SA 5401
	catnr. SA 5406
silicone tube	catnr. SA 3150

pump tubes as listed in the cartridge components

SETTINGS

1. The sensitivity of the highest standard10 ppm N in ± 800 A.U.
2. Sample time: 60 sec., wash time: 60 sec., air: 1 sec.
3. Recorder settings: 500 mV.
4. The connection between the sampler and the sample pump tube is made of 5130 tube.
5. The stabilization time is approximately 20 minutes.

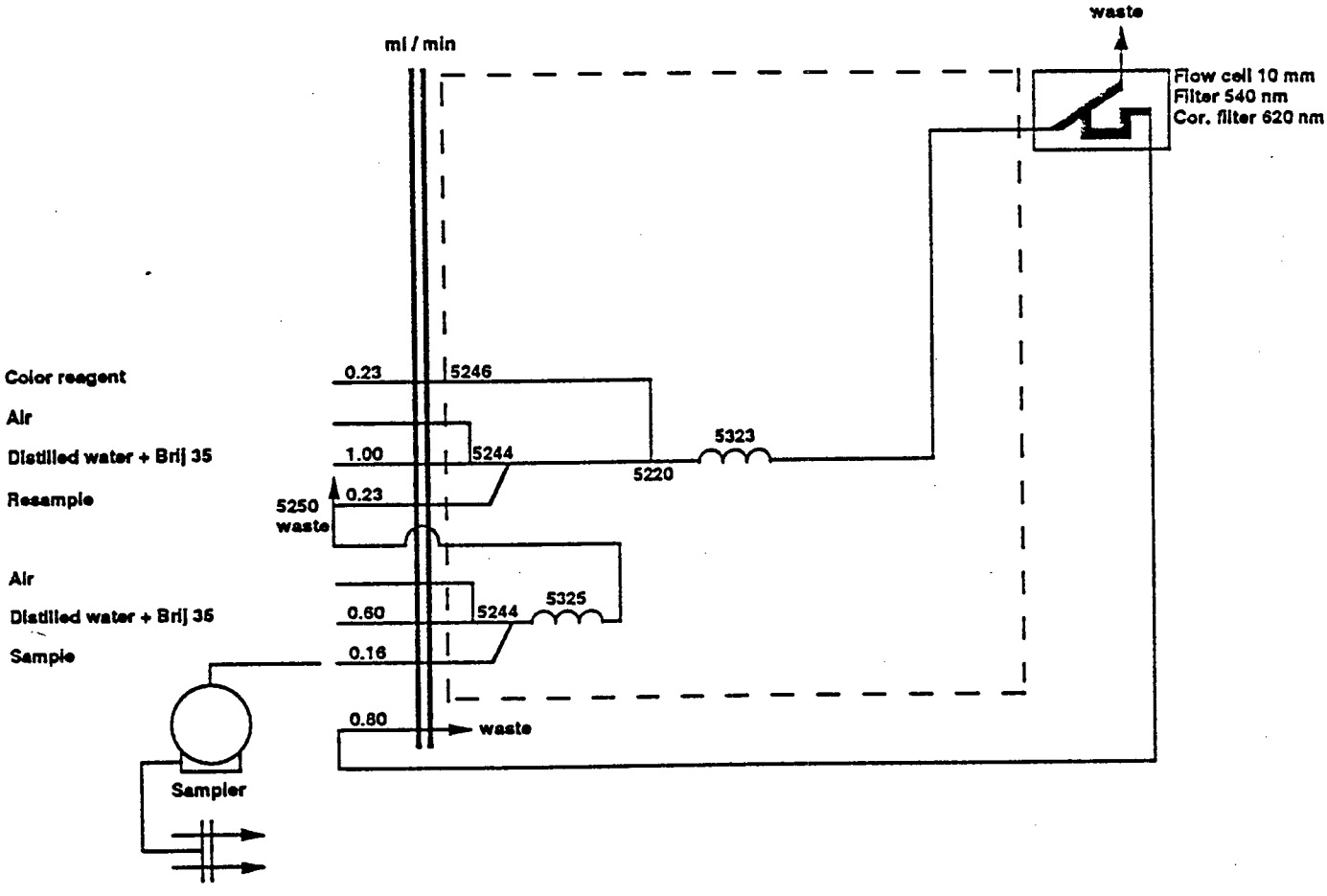
CATALOGUE NUMBERS REQUIRED CHEMICALS

Product	Supplier and catnr.	Danger classifications
Brij 35 (30%)	Skalar SC 13900	
o-Phosphoric acid (85%)	Merck 573	corrosive
Sulfanilamide	Merck 11799	
α-Naphthylethylenediamine dihydrochloride	Merck 6237	
Sodium nitrite	Merck 6549	toxic, oxidizing

REFERENCES

1. Standard methods for examination of water and waste water, 15th edition, 1980.
2. Environmental Protection Agency. Methods for chemical analysis of water and wastes, Off Technol. Transfer, EPA, 1974, Washington D.C.

FLOW DIAGRAM



The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting enhanced biological phosphate removal.

Appendix 3

Skalar Methods:

Orthophosphate/ Total Phosphate

DW de Haas

SKALAR METHODS

ANALYSIS : O-PHOSPHATE / TOTAL PHOSPHATE
RANGE : 0.4 - 20 ppm P
SAMPLE : WATER / WATER DIGEST

catnr. 503-205 issue 072293/MH/93119670

PRINCIPLE

The automated procedure for the determination of Phosphate is based on the following reaction; ammonium molybdate catalyzed by potassium antimony tartrate reacts in an acidic medium with diluted solutions of phosphate to form a phospho-molybdic complex. This complex is reduced to an intensely blue-colored complex by ascorbic acid. The complex is measured at 880 nm.

LABORATORY FACILITIES

1. Maximum power consumption depending on the analyzer configuration, 2000 VA. Check voltage at the back of the instrument before installation.
2. Facilities for chemical wastes. Check environmental regulation for proper disposal of waste.

PROCEDURE SAMPLE PREPARATION

o-Phosphate
water method 1.2.3

Field of application

Sample preservation for the determination of $N\text{-}NH_4$, C.O.D., D.O.C., NO_2+NO_3, phenols and $P\text{-}PO_4$ in water.

Principle

The sample is preserved with H_2SO_4 to pH < 2.

Reagents

Sulfuric acid (97%)

Procedure

1 Add concentrated H_2SO_4 to the sample until pH < 2 (normally 2 ml/liter sample).
2 Store at 4°C for maximum 28 days.

Remarks

1 The sample does not need preservation if analyzed immediately.
2 In the case of phenols, check for sulfur compounds and oxidizing agents.
3 For dissolved organic carbon, fill the sample bottle completely and keep protected from sunlight and atmospheric oxygen.
4 Turbid samples have to be filtered if necessary.

References

Environmental Protection Agency, methods for chemical analysis on water and wastes, 1983.

total Phosphate
Water digest 2.1.3

Field of application

The digestion is used for the determination of total nitrogen in all kind of water samples. This digestion may also be used for phosphorus determination.

Principle

The water sample is digested with sulfuric acid, potassium sulfate and mercuric sulfate as catalyst. Amino nitrogen of many organic materials is converted into ammonium sulfate. Free ammonia and ammonium-nitrogen are also converted into ammonium sulfate. Phosphorus is transferred into ortho-phosphate.

Apparatus

Block digester for 75 ml tubes. SKALAR SA 5640
Exhaust system for 75 ml tubes. SKALAR SA 5750

Reagents

Mercuric sulfate solution

1 Dissolve 8 g of red mercuric oxide (HgO) in 100 ml sulfuric acid (H_2SO_4 1.8M).

Digestion solution

1 Weigh 134 g of K_2SO_4 in a 1 liter beaker.
2 Add about 650 ml of distilled water and dissolve.
3 Add 200 ml of concentrated H_2SO_4.
4 Add, while stirring, 25 ml of mercuric sulfate solution.
5 Make up to 1 liter with distilled water.

Procedure

1 Pipette 60.0 or 75.0 ml of the sample into the digestion tube. Prepare also a blank, consisting of 20.0 ml distilled water.
2 Add some TFE fluorocarbon boiling stones.
3 Add 15.0 ml of the digestion solution and mix.
4 Pre-heat the digestion block to 180°C.
5 Insert the digestion tube into the digestion block.
6 Heat at 180°C for 1 hour.
7 Heat the digestion block to 380°C.
8 When the temperature is 380°C, leave the digestion tube for 2 1/2 hour at 380°C.
9 Remove the digestion tube from the digestion block and let it cool down.
10 Carefully add 60 ml of distilled water and mix.
11 Make up to the mark and mix.

Remarks

1 Aromatic and heterocyclic nitrogen compounds are not completely determined.
2 Anorganic nitrate and nitrite and some metals could disturb the Kjeldahl determination.
3 Some amines are determined as ammonium as well, even after distillation.

References

1 ASTM 1990, D3590-89.
2 Environmental Protection Agency, methods for chemical analysis of water and wastes, Method 351.2.
3 Environmental Protection Agency, methods for chemical analysis of water and wastes, Method 365.4.

REAGENTS

A1. Distilled water + FFD6 (for o-phosphate)

Required chemicals: Distilled water .....1000 ml. Preparation: Add the FFD6 to 1 liter distilled water and mix.
H_2O
FFD6 .....2 ml.

A2. Sodium chloride solution (for total phosphate)

Required chemicals: Sodium chloride .....30 gr. Preparation: Dissolve the sodium chloride in ± 800 ml distilled water. Fill up to 1 liter, add the FFD6 and mix.
NaCl
Distilled water .....1000 ml.
H_2O
FFD6 .....2 ml.

B. Ammonium molybdate solution

Required chemicals: Sulfuric acid .....40 ml. Preparation: Dilute the sulfuric acid in ± 800 ml distilled water. Add the ammonium molybdate and dissolve. Fill up to 1 liter add the FFD6 and mix.
H_2SO_4 (97%)
Ammonium molybdate ..4.8 gr.
$(NH_4)_6Mo_7O_{24}.4H_2O$
Distilled water .....1000 ml.
H_2O
FFD6 .....2 ml.

C. Stock solution potassium antimony tartrate

Required chemicals: Potassium antimony tartrate .....300 mg. Preparation: Dissolve the potassium antimony tartrate in ± 80 ml distilled water. Fill up to 100 ml and mix.
$K(SbO)C_4H_4O_6.0.5\ H_2O$
Distilled water .....100 ml. Note: Stable for one month at 4°C
H_2O

D. Ascorbic acid

Required chemicals: Ascorbic acid .....4.5 gr. Preparation: Dissolve the ascorbic acid in ± 200 ml distilled water. Add the stock solution potassium antimony tartrate. Fill up to 250 ml with distilled water and mix.
$C_6H_8O_6$
Stock solution potassium antimony tartrate .....5 ml.
Distilled water .....250 ml.
H_2O Note: Stable for one week at 4°C.

E. Rinsing liquid sampler for o-phosphate

Required chemicals: Distilled water
H_2O

F. Rinsing liquid sampler for total phosphate

Required chemicals: Sulfuric acid .....45 ml. (H_2SO_4 (97%))
Potassium sulfate .....26.8 gr. (K_2SO_4)
Distilled water .....955 ml. (H_2O)

Preparation: Dilute carefully the sulfuric acid in ± 800 ml distilled water. Add the potassium sulfate and dissolve. Fill up to 1 liter with distilled water and mix.

STANDARDS

Stock standard 1000 ppm P

Required chemicals: Potassium dihydrogen o-phosphate ..... 4.394 gr. (KH_2PO_4)
Distilled water .....1000 ml. (H_2O)

Preparation: Dissolve the potassium dihydrogen o-phosphate in ± 800 ml distilled water. Fill up to 1 liter and mix well.

Working standards for o-phosphate

20 ppm P: Dilute 2.0 ml stock solution 1000 ppm P to 100 ml with distilled water.
16 ppm P: Dilute 1.6 ml stock solution 1000 ppm P to 100 ml with distilled water.
12 ppm P: Dilute 1.2 ml stock solution 1000 ppm P to 100 ml with distilled water.
8 ppm P: Dilute 0.8 ml stock solution 1000 ppm P to 100 ml with distilled water.
4 ppm P: Dilute 0.4 ml stock solution 1000 ppm P to 100 ml with distilled water.

Working standards for total phosphate

20 ppm P: Dilute 2.0 ml stock solution 1000 ppm P to 100 ml with rinsing liquid F.
16 ppm P: Dilute 1.6 ml stock solution 1000 ppm P to 100 ml with rinsing liquid F.
12 ppm P: Dilute 1.2 ml stock solution 1000 ppm P to 100 ml with rinsing liquid F.
8 ppm P: Dilute 0.8 ml stock solution 1000 ppm P to 100 ml with rinsing liquid F.
4 ppm P: Dilute 0.4 ml stock solution 1000 ppm P to 100 ml with rinsing liquid F.

GENERAL REMARKS

1. If a matrix photometer, catnr. 6250 or 6260, is in use, a correction interference filter of 1010 nm ± 10% is advised.
2. In most analysis the first peak coming from the baseline is much lower than it should be. The first peak coming from the baseline is rejected and will not be included in the calculations of the CV-value.
3. If reaction coils with water heating are used, the water bath has to be cooled with tap water when the environment temperature is above 25°C.
4. If the sample take up volume is less than 1.00 ml.min, a bypass is required to increase the sample stream to approximately 1.00 ml/min.
5. All reagent bottles must be rinsed thoroughly with distilled water before refilling with fresh reagents. This to prevent precipitation of micro organism and interferences.
6. Rinsing valves catnr. SA 1500/1520 can not be used for organic solutions or acid solution > 4 N.

MAINTENANCE

1. To decontaminate the system rinse with 1:10 diluted sodium hypochlorite solution for 30 minutes once a week.
2. Degas reagents, if air bubbles spontaneously appear. Degas by aspirating helium gas at 20 liter/hour for 15 minutes.
3. Avoid any turbidity in reagents, filter if necessary.
4. A refrigerator is used for cooling at 4°C.

SETTINGS

1. The sensitivity of the highest standard 20 ppm P is ± 800 A.U.
2. Sample time: 60 sec., wash time: 60 sec., air: 1 sec.
3. Settings recorder: 500 mV.
4. The connection between the sampler and the sample pump tube is made of 5130 tube.
5. The stabilizing time is about 20 minutes.

CARTRIDGE COMPONENTS

manifold holder	catnr. SA 5105	clamps small	catnr. SA 5111
module	catnr. SA 5107	clamps large	catnr. SA 5110
end block	catnr. SA 5109	flow cell 30 mm	catnr. SA 6403
inlet connector	catnr. SA 5232	filter 880 nm	catnr. SA 6609
inlet connector	catnr. SA 5244	filter 1010 nm	catnr. SA 6635
inlet connector	catnr. SA 5246	pump tubing 0.80 ml/min.	catnr. SA 3030
glass coil 5W	catnr. SA 5325 (2x)	pump tubing 0.16 ml/min.	catnr. SA 3025
debubbler	catnr. SA 5250	pump tubing 1.40 ml/min.	catnr. SA 3033
connector	catnr. SA 5220	pump tubing 0.60 ml/min.	catnr. SA 3029
heat exchanger	catnr. SA 5303	pump tubing 0.42 ml/min.	catnr. SA 3028
sinkers	catnr. SA 5380	pump tubing sampler	catnr. SA 1060

Note: If pump catnr. SA 2002 or 2005 is in use, the pump tubes with catnr. SA 3020 up to 3039 are replaced by pump tubes with catnr. SA 5020 up to 5039.

CARTRIDGE CONSUMABLES

If only a module is ordered, with flow cell catnr. SA 6403 and filters catnr. SA 6609 and catnr. SA 6635, the following components are added to the module.

polyethylene tubing	catnr. SA 5141
	catnr. SA 5142
sleeves	catnr. SA 5400
	catnr. SA 5401
	catnr. SA 5406
silicone tube	catnr. SA 3150

pump tubing as listed in the cartridge components.

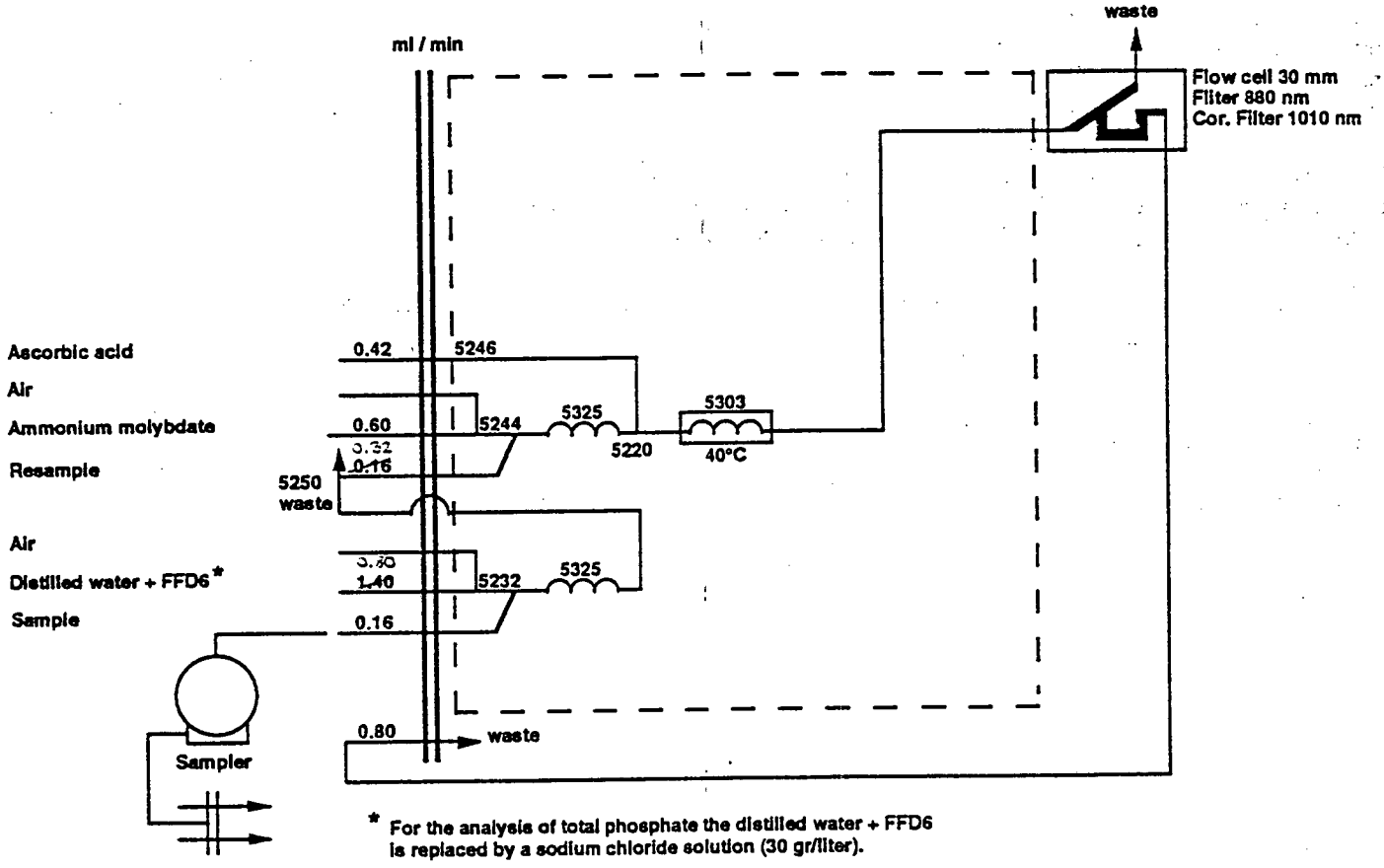
CATALOGUE NUMBERS REQUIRED CHEMICALS

Product	Supplier and catnr.	Danger classifications
Sulfuric acid (97%)	Merck 731	corrosive
Potassium sulfate	Merck 5153	
Mercuric oxide	Merck 4466	very toxic
Sodium chloride	Merck 6404	
Ammonium molybdate	Merck 1182	harmful
Potassium antimony tartrate	Merck 8092	toxic
Ascorbic acid	Merck 127	
Potassium dihydrogen o-phosphate	Merck 4873	

REFERENCES

1. Standard Methods for Examination of Water and Waste Water. 15th edition 1980 APHA-AWWA-WPCF page 410-425.
2. Boltz, D.F., Mellon, M.G.,"Spectrophotometric determination of phosphate as molydiphosphoric acid", Analytical chemistry, Vol. 20, No 8, August 1948, page 749-751.
3. Walinga, I., van Vark, W., Houba, V.J.G., van der Lee, L.L., Plant analysis Procedures, Part 7, Department of Soil Science and Plant Nutrition, Wageningen Argricultural University, Syllabus 1989, Page 138-141.

FLOW DIAGRAM



* For the analysis of total phosphate the distilled water + FFD6 is replaced by a sodium chloride solution (30 gr/liter).

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting enhanced biological phosphate removal.

Appendix 4

Method for determination of Total Aluminium by ICPAE spectrometry

DW de Haas

APPENDIX 4

METHOD FOR DETERMINATION OF TOTAL ALUMINIUM BY ICPAE SPECTROMETRY

1. INTRODUCTION

In this procedure, aluminium extractable with hot nitric acid is measured using Inductively Coupled Plasma Atomic Emission Spectrometry.

2. SCOPE

This method is suitable for the analysis of the above-mentioned elements in water, wastewater and solid samples.

3. INTERFERENCE

Spectral overlap from matrix elements can be problematic in complex matrices. Nebulisation interference and crystallisation in the sample injection tube of the torch must be considered when analysing viscous, high density samples or samples with very high dissolved solids.

4. HAZARDS

4.1 Nitric acid.
4.2 See the manufacturer's manual for instrument related hazards.

Ensure that familiarity with the dangers and treatment associated with each of the substances used.

5. SAMPLE COLLECTION AND PRESERVATION

Samples should be collected in polyethylene bottles with high purity nitric acid added (2 ml stock 50% v/v nitric acid per 100 ml sample).

6. APPARATUS

6.1 Varian 150 AX Axial Inductively Coupled Plasma Spectrometer.
6.2 Precision Instruments USN-557 Ultrasonic nebuliser.
6.3 Varian - Liberty 200 Inductively Coupled Plasma Spectrometer.
6.4 Varian SPS5 sample changer.
6.5 Volumetric glassware for preparation of standards (A grade)
6.6 150 ml Plastic sample bottles
6.7 Centrifuge.

7. REAGENTS

7.1 Concentrated nitric acid (AR grade).
7.2 Nitric acid stock solution 50% v/v - dilute concentrated nitric acid 1:1 with ultrapure water.
7.3 Nitric acid blank solution -2 ml stock 50% v/v nitric acid / 100 ml ultrapure water.
7.4 High purity argon gas.
7.5 Spectroscopic standard solution (1000 mg/l) for the element aluminium.

8. PREPARATION OF STANDARDS

8.1 Stock standard

Element	Volume spectroscopic standard solution in 500 mℓ	Concentration µg/ℓ
Al	5 mℓ	10 000

Add 5 mℓ concentrated nitric acid before making up to the mark in 500 mℓ volumetric flask.

8.2 Working Standards

	Std 1		Std 2		Std 3		Std 4	
Element	Vol. stock std	Conc. µg/ℓ	Vol. stock std	Conc. µg/ℓ	Vol. stock std	Conc. µg/ℓ	Vol. stock std	Conc. µg/ℓ
Al	2.5	250	5	500	10	1 000	50	5 000

Make up to the mark in 100 mℓ volumetric flask and then add 1 mℓ 50% nitric acid.

9. PREPARATION OF ANALYTICAL QUALITY CONTROL (AQC)

9.1 Stock AQC

Element	Volume spectroscopic AQC solution	Concentration µg/ℓ
Al	5 mℓ	10 000

Add 5 mℓ concentrated nitric acid before making up to the mark in 500 mℓ volumetric flask.

9.2 Working AQC solutions

Element	Volume AQC stock solution	Concentration
Al	5	500

Make up to the mark in 100 mℓ volumetric flask and then add 1 mℓ 50% nitric acid.

Stock AQCs must be discarded after three months and working AQCs after one month.

10. ANALYTICAL PROCEDURE

10.1 Sample pre-treatment (for clean water samples)

NB: This procedure only applies to untreated water samples. Treated water samples may be analysed without pre-treatment.

10.1.1 Allow the sample to stand for 24 hours after sampling.
10.1.2 Centrifuge the sample at 3000 rpm for five minutes after weighing to balance the centrifuge.
10.1.3 Decant the supernatant into another clean bottle. Pour slowly so as not to disturb solids.

10.2 Digestion of sludge/ sewage samples

10.2.1 Raw sewage/ sludge samples: Add 50 ml conc. nitric acid to 200 ml sample and digest on a hot-plate under a fume extraction hood until the volume has reduced to about 40 ml. Cool and make up to 200 ml in a volumetric flask, transferring quantitatively.

10.2.2 Treated sewage/ secondary sewage effluents: Add 15 ml conc. nitric acid to 200 ml sample and digest on a hot-plate under a fume extraction hood until the volume has reduced to about 40 ml. Cool and make up to 200 ml in a volumetric flask, transferring quantitatively.

10.3 Procedure

10.3.1 A nitric acid blank must be prepared according to the amount of nitric acid used in the digestion (see 10.1 or 10.2). The nitric acid blank solution and the standard solutions should be placed in the standard rack in the programmed positions. The AQC solution should be placed in position number 12.

10.3.2 A quality control solution must be analysed after every ten samples.

10.3.3 A slope correction ("reslope") must be done after every ten samples.

10.3.4 At least three replicates of each sample should be performed. An average of these results should be reported.

10.3.5 The instrument should be set up as per the parameters below. Refer to the manufacturer's handbook for further instrument set-up and optimisation.

10.3.6 Aluminium may be analysed by Radial ICP. Refer to operating manual of instrument for suitable set-up parameters (e.g. wavelength, search window, scan window, filter position etc.)

REFERENCES

Varian ICPAES Operating Manual (1997) Umgeni Water, PO Box 9, Pietermaritzburg, 3200, South Africa.

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting enhanced biological phosphate removal.

Appendix 5

Pilot plant experiments: Detailed results

DW de Haas

PERIOD 3.1.1
SUMMARY DATA 1
ENHANCED CULTURE DEVELOPMENT

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	CORR COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
23/02/94	50	28.3	27.1	15.44	11.79	372			35.0	2.00	1.30
24/02/94	50	42.7	26.4								
25/02/94	50	28.1	26.4								
26/02/94	50	28.8	30.5								
27/02/94	50	31.7	27.1	14.21	14.03						
28/02/94	50	30.2	23.5						30.3	2.90	2.80
01/03/94	50	31.0	30.7	13.68		430	52	42	37.2	2.30	2.90
02/03/94	50	31.2	30.7								
03/03/94	50	32.4		12.64	15.20		29	45	31.4	2.20	1.70
04/03/94	50	31.4									
06/03/94	50			12.95	12.04	285	42	42	35.3	2.30	3.00
07/03/94	50	31.9		12.26	12.33	167	15	17	42.9	2.30	1.90
08/03/94	50	31.9	31.7	12.11	11.57	216	47	40	63.9	5.60	6.10
09/03/94	50	32.9	30.7	11.34	10.90	194	15	17	37.5	4.60	2.90
10/03/94	50	32.6	31.9	9.46	9.22	173	12	14	21.7	2.10	2.20
11/03/94	50	34.8	34.8								
12/03/94	50	32.4	32.4								
13/03/94	50	33.1	33.1		18.04	320	30	18	55.8	10.10	1.80
14/03/94	50	31.7	29.5	18.84	18.73	353	17	20	42.8	2.10	2.00
15/03/94	50	32.2	35.5	17.77	18.41	335	22	28	42.1	2.50	2.50
verage:	50	32.1	30.1	13.70	13.84	285	28	28	39.7	3.42	2.59
ount:	20	19	16	11	11	10	10	10	12	12	12
aximum:	50	42.7	35.5	18.84	18.73	430	52	45	63.9	10.10	6.10
inimum:	50	28.1	23.5	9.46	9.22	167	12	14	21.7	2.00	1.30
tandard Deviation:	0	3.0	3.2	2.63	3.15	87	14	12	10.8	2.28	1.18

PERIOD 3.1.1
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
23/02/94	11.70	0.53	1.39	11.17	10.31		
24/02/94							
25/02/94							
26/02/94							
27/02/94	11.70	11.30	11.40	0.40	0.30		
28/02/94	15.09	0.62	0.47	14.47	14.62		
01/03/94	12.48	0.70	0.29	11.78	12.19	81.84	
02/03/94							
03/03/94	14.56	4.85	1.32	9.71	13.24		
04/03/94							
06/03/94	14.24	9.92	6.08	4.32	8.16	90.16	89.51
07/03/94	12.92	10.53	8.15	2.39	4.77	81.86	79.32
08/03/94	12.76	12.60	11.96	0.16	0.80	86.21	69.69
09/03/94	12.92	8.61	8.61	4.31	4.31	74.04	74.25
10/03/94	15.47	7.66	7.66	7.81	7.81	76.87	82.71
11/03/94							
12/03/94							
13/03/94	16.26	4.99	5.47	11.27	10.79	59.01	77.08
14/03/94	15.78	0.29	3.06	15.49	12.72	64.48	71.56
15/03/94	15.14	4.99	1.10	10.15	14.04	64.34	71.20
Average:	13.92	5.97	5.15	7.96	8.77	75.42	76.92
Count:	13	13	13	13	13	9	8
Maximum:	16.26	12.60	11.96	15.49	14.62	90.16	89.51
Minimum:	11.70	0.29	0.29	0.16	0.30	59.01	69.69
Standard Deviation:	1.52	4.30	4.01	4.95	4.71	10.18	6.31

ERIOD 3.1.1
UMMARY DATA 3
NHANCED CULTURE DEVELOPMENT

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
23/02/94			2338	1614	1772	1208	69.0	68.2		
24/02/94										
25/02/94										
26/02/94										
27/02/94			2300	1586	1988	1398	69.0	70.3		
28/02/94										
01/03/94	56.81		2377	1650	1922	1390	69.4	72.3		
02/03/94										
03/03/94			2467	1708	2121	1430	69.2	67.4		
04/03/94										
06/03/94	62.52	60.73	2293	1590	2034	1380	69.3	67.8		
07/03/94	56.75	54.62	2305	1598	2091	1440	69.3	68.9		
08/03/94	59.77	48.09	2178	1510	2455	1694	69.3	69.0		
09/03/94	49.70	49.34	2555	1715	2328	1547	67.1	66.5	102	86
10/03/94	52.51	55.51	2382	1627	2092	1404	68.3	67.1	109	96
11/03/94										
12/03/94										
13/03/94	42.53	53.76	2514	1812	2360	1646	72.1	69.7	130	155
14/03/94	46.94	51.70	2552	1858	2442	1764	72.8	72.2	137	152
15/03/94	46.18	49.64	2608	1872	2556	1782	71.8	69.7	138	133
Average:	52.63	52.92	2406	1678	2180	1507	69.7	69.1	123	124
Count:	9	8	12	12	12	12	12	12	5	5
Maximum:	62.52	60.73	2608	1872	2556	1782	72.8	72.3	138	155
Minimum:	42.53	48.09	2178	1510	1772	1208	67.1	66.5	102	86
Standard Deviation:	6.39	3.87	126	111	233	171	1.6	1.8	15	28

PERIOD 3.1.1
SUMMARY DATA 4
ENHANCED CULTURE DEVELOPMENT

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
23/02/94										
24/02/94				7.10		7.24	0	0		
25/02/94			7.40	7.80	7.60	7.57	0	0		
26/02/94										
27/02/94										
28/02/94			7.48	7.40	7.51	7.54	0	0		
01/03/94										
02/03/94			7.34	7.38	7.47	7.43	0	0		
03/03/94			7.37	7.26	7.51	7.51	0	0		
04/03/94			7.52	7.52	7.73	7.60	0	0		
06/03/94										
07/03/94			7.27	7.22	7.33	7.31	0	0		
08/03/94			7.18	7.22	7.39	7.37	0	0		
09/03/94										
10/03/94			7.58	7.64	7.68	7.68	0	0		
11/03/94			7.66	7.58	7.69	7.71	0	0		
12/03/94			7.32	7.30	7.45	7.53	0	0		
13/03/94										
14/03/94			7.44	7.37	7.55	7.42	0	0		
15/03/94			7.30	7.22	7.40	7.33	0	0		
Average:	0.00	0.00	7.41	7.39	7.53	7.48	0	0	0.0	0.0
Count:	0	0	12	13	12	13	13	13	0	0
Maximum:			7.66	7.80	7.73	7.71	0	0		
Minimum:			7.18	7.10	7.33	7.24	0	0		
Standard Deviation:	0.00	0.00	0.13	0.19	0.12	0.14	0	0	0.0	0.0

ERIOD 3.1.1
-JMMARY DATA 5
NHANCED CULTURE DEVELOPMENT

	DATE	NH3 fR1	NH3 fR2	NO3 fR1	NO3 fR2	SRP fR1	SRP fR2
	23/02/94	0.11	0.09	5.58	2.80	0.32	1.01
	24/02/94						
	25/02/94						
	26/02/94						
	27/02/94	0.26	0.26	10.98	9.43		
	28/02/94						
	01/03/94	0.35	0.23	12.83	13.54	0.49	0.24
	02/03/94						
	03/03/94						
	04/03/94						
	06/03/94						
	07/03/94	0.12	0.17	11.36	13.32	10.44	7.32
	08/03/94	0.07	0.08	10.83	12.68	12.02	11.45
	09/03/94	0.80	0.27	24.30	31.00	7.92	9.00
	10/03/94	0.33	0.37	9.77	11.30	6.31	6.83
	11/03/94						
	12/03/94						
	13/03/94		0.35	10.65	12.40		4.92
	14/03/94	0.58	0.23	10.01	12.33	0.06	2.47
	15/03/94	0.28	0.29	5.32	6.96	0.06	0.47
	========	====	====	=====	=====	=====	=====
verage:		0.32	0.23	11.16	12.58	4.70	4.86
ount:		9	10	10	10	8	9
aximum:		0.80	0.37	24.30	31.00	12.02	11.45
inimum:		0.07	0.08	5.32	2.80	0.06	0.24
tandard Deviation:		0.22	0.09	4.94	6.93	4.74	3.82

PERIOD 3.1.1
SUMMARY DATA 6
ENHANCED CULTURE DEVELOPMENT

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
23/02/94								
24/02/94								
25/02/94								
26/02/94								
27/02/94								
28/02/94								
01/03/94								
02/03/94								
03/03/94								
04/03/94								
06/03/94								
07/03/94								
08/03/94								
09/03/94								
10/03/94								
11/03/94								
12/03/94								
13/03/94								
14/03/94								
15/03/94								
Average:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Count:	0	0	0	0	0	0	0	0
Maximum:								
Minimum:								
Standard Deviation:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

PERIOD 3.1.1
SUMMARY DATA 7
ENHANCED CULTURE DEVELOPMENT

	DATE	TP R1 fAN	TP R1 fAX	TP R1 fAB1	TP R1 fAB2	TP R2 fAN	TP R2 fAX	TP R2 fAB1	TP R2 fAB2
	23/02/94								
	24/02/94								
	25/02/94								
	26/02/94								
	27/02/94								
	28/02/94								
	01/03/94								
	02/03/94								
	03/03/94								
	04/03/94								
	06/03/94								
	07/03/94								
	08/03/94								
	09/03/94								
	10/03/94								
	11/03/94								
	12/03/94								
	13/03/94								
	14/03/94								
	15/03/94								
Average:		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Count:		0	0	0	0	0	0	0	0
Maximum:									
Minimum:									
Standard Deviation:		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

PERIOD 3.1.1
SUMMARY DATA 8
ENHANCED CULTURE DEVELOPMENT

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
23/02/94				19.9	
24/02/94				19.9	
25/02/94					
26/02/94				17.2	
27/02/94				20.1	
28/02/94					
01/03/94				19.5	
02/03/94				20.0	
03/03/94				19.5	
04/03/94				20.0	
06/03/94				20.0	
07/03/94				19.5	
08/03/94				19.7	
09/03/94				19.6	
10/03/94				19.6	
11/03/94				19.7	
12/03/94				20.2	
13/03/94				19.7	
14/03/94				20.1	
15/03/94				19.8	
Average:				19.7	0.0
Count:	0	0	0	18	0
Maximum:				20.2	
Minimum:				17.2	
Standard Deviation:				0.6	0.0

=ERIOD 3.1.2
UMMARY DATA 1
=NHANCED CULTURE DEVELOPMENT

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	CORR COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
16/03/94	100	31.2	32.2	18.87	19.44	395		20	43.1	1.50	1.60
17/03/94	100	31.7	30.7	19.55	20.16	398	15	19	27.0	2.00	2.80
18/03/94	100	33.1	32.2	12.38	13.38						
19/03/94	100	32.6	30.0								
20/03/94	100	33.4	38.2	12.38	13.38	251	17	19	30.3	2.40	1.30
21/03/94	100	31.9	31.4	12.38	15.12	301	17	20	22.8	2.00	2.30
22/03/94	100	31.4	30.7			278	18	20		1.90	1.10
23/03/94	100	33.4	33.4	12.90	15.89	343	15	18	23.4	1.80	2.10
24/03/94	100	34.1	34.8	13.92	16.16	316	16	17	27.7	1.60	1.40
25/03/94	100	33.1	33.1	15.12	17.38						
26/03/94	100	33.8	32.9	15.61	14.28						
27/03/94	100	31.9	31.9	16.37	19.70	335	19	19	41.6	2.20	2.20
28/03/94	100	32.4	32.4	15.40	18.00	329	18	20	40.9	2.20	1.60
29/03/94	100	31.4	31.4	14.37	18.15	370	19	20	55.2	3.60	3.60
30/03/94	100	32.9	32.4	14.26	17.04	356	19	21	62.8	3.80	3.60
31/03/94	100	31.9	31.9	14.95	17.40	441		21	28.3	1.60	1.70
01/04/94	100	33.1	32.4								
02/04/94	100	33.1	32.9	14.35							
03/04/94	100	32.6	34.3	16.15							
04/04/94	100	33.4	33.4	15.78	17.06	275	20	20	38.3	1.80	1.30
05/04/94	100	32.2	32.2								
06/04/94	100	32.9	32.9	14.75	18.56	356	20	23	31.4	1.70	1.90
=Average:	100	32.6	32.6	14.97	16.94	339	18	20	36.4	2.15	2.04
Count:	22	22	22	18	16	14	12	14	13	14	14
=Maximum:	100	34.1	38.2	19.55	20.16	441	20	23	62.8	3.80	3.60
=Minimum:	100	31.2	30.0	12.38	13.38	251	15	17	22.8	1.50	1.10
Standard Deviation:	0	0.8	1.6	1.94	2.05	51	2	1	11.7	0.68	0.78

PERIOD 3.1.2
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
16/03/94	20.93	0.23	0.58	20.70	20.35	69.76	77.89
17/03/94	20.12	0.24	0.41	19.88	19.71	74.10	82.35
18/03/94							
19/03/94							
20/03/94	26.81	0.24	0.73	26.57	26.08	105.86	115.64
21/03/94	35.28	3.50	7.25	31.78	28.03	116.16	131.82
22/03/94	34.95	12.14	17.03	22.81	17.92	115.39	
23/03/94	35.44	14.91	18.17	20.53	17.27	132.84	149.06
24/03/94	33.98	15.89	19.15	18.09	14.83	124.61	128.08
25/03/94							
26/03/94							
27/03/94	31.73	7.45	9.71	24.28	22.02	126.40	125.92
28/03/94	30.60	9.88	11.98	20.72	18.62	141.28	116.76
29/03/94	32.06	13.44	14.57	18.62	17.49	134.99	124.08
30/03/94	31.73	17.00	18.94	14.73	12.79	133.72	127.51
31/03/94	31.90	12.63	12.47	19.27	19.43		
01/04/94							
02/04/94							
03/04/94							
04/04/94	33.02	20.27	22.69	12.75	10.33	155.84	159.10
05/04/94							
06/04/94	35.44	28.18	29.31	7.26	6.13	153.67	150.65
Average:	31.00	11.14	13.07	19.86	17.93	121.89	124.07
Count:	14	14	14	14	14	13	12
Maximum:	35.44	28.18	29.31	31.78	28.03	155.84	159.10
Minimum:	20.12	0.23	0.41	7.26	6.13	69.76	77.89
Standard Deviation:	4.83	7.94	8.40	5.72	5.55	25.32	23.54

PERIOD 3.1.2
SUMMARY DATA 3
ENHANCED CULTURE DEVELOPMENT

	DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
	16/03/94	51.15	55.80	2657	1948	2620	1877	73.3	71.6		
	17/03/94	52.99	56.81	2749	1966	2725	1880	71.5	69.0	135	114
	18/03/94										
	19/03/94										
	20/03/94	69.21	72.41	2877	1881	2876	1801	65.4	62.6	139	94
	21/03/94	73.39	75.44	2971	1877	2899	1659	63.2	57.2	131	90
	22/03/94	74.83	75.92	3155	2046	2949		64.8		127	88
	23/03/94	82.20	80.69	3025	1872	2904	1572	61.9	54.1	112	86
	24/03/94	81.13	81.87	3081	2006	2902	1855	65.1	63.9	110	86
	25/03/94										
	26/03/94										
	27/03/94	82.66	84.12	3124	2043	2916	1948	65.4	66.8		
	28/03/94	88.98	72.41	2966	1868	3175	1969	63.0	62.0	118	85
	29/03/94	87.38	81.70	3113	2015	3022	1990	64.7	65.9	109	86
	30/03/94	85.75	82.01	3153	2022	3001	1930	64.1	64.3	111	93
	31/03/94	89.65	83.40	3296		3145				106	89
	01/04/94										
	02/04/94										
	03/04/94										
	04/04/94	94.03	95.32	3303	1993	3021	1810	60.3	59.9		
	05/04/94										
	06/04/94	94.02	92.01	3223	1972	3165	1933	61.2	61.1		
Average:		79.10	77.85	3050	1962	2951	1852	64.9	63.2	120	91
Count:		14	14	14	13	14	12	13	12	10	10
Maximum:		94.03	95.32	3303	2046	3175	1990	73.3	71.6	139	114
Minimum:		51.15	55.80	2657	1868	2620	1572	60.3	54.1	106	85
Standard Deviation:		13.11	10.79	184	64	151	121	3.6	4.7	11	8

PERIOD 3.1.2
SUMMARY DATA 4
ENHANCED CULTURE DEVELOPMENT

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
16/03/94			7.31	7.28	7.40	7.43	0	0		
17/03/94			7.39	7.33	7.45	7.42	0	0		
18/03/94			7.50	7.44	7.57	7.60	0	0		
19/03/94			7.46	7.61	7.42	7.54	0	0		
20/03/94			7.59	7.55		7.69	0	0		
21/03/94			7.46	7.42	7.65	7.57	0	0		
22/03/94			7.54	7.39	7.74	7.63	0	0		
23/03/94			7.68	7.47	7.78	7.68	0	0		
24/03/94			7.45	7.33	7.72	7.56	0	0		
25/03/94			7.43	7.36	7.72	7.57	0	0		
26/03/94			7.42	7.36	7.72	7.53	0	0		
27/03/94			7.44	7.34	7.67	7.56	0	0		
28/03/94			7.46	7.31	7.76	7.63	0	0		
29/03/94			7.49	7.29	7.82	7.61	0	0		
30/03/94			7.39	7.22	7.59	7.54	0	0		
31/03/94			7.36	7.21	7.60	7.44	0	0		
01/04/94			7.22	7.15	7.51	7.33	0	0		
02/04/94			7.28	7.26	7.56	7.60	0	0		
03/04/94			7.32	7.20	7.58	7.50	0	0		
04/04/94			7.24	7.00	7.42	7.52	0	0		
05/04/94			7.17	7.09	7.28	7.17	0	0		
06/04/94			7.10	6.92	7.29	7.13	0	0		
Average:	0.00	0.00	7.40	7.30	7.58	7.51	0	0	0.0	0.0
Count:	0	0	22	22	21	22	22	22	0	0
Maximum:			7.68	7.61	7.82	7.69	0	0		
Minimum:			7.10	6.92	7.28	7.13	0	0		
Standard Deviation:	0.00	0.00	0.13	0.16	0.16	0.14	0	0	0.0	0.0

PERIOD 3.1.2
SUMMARY DATA 5
ENHANCED CULTURE DEVELOPMENT

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
16/03/94	0.19	0.15	6.36	7.59	0.04	0.30
17/03/94	0.21	0.14	3.68	5.06	0.08	0.15
18/03/94						
19/03/94						
20/03/94	0.12	0.08	6.30	6.30	0.19	0.66
21/03/94	0.23	0.12	7.00	4.47	3.24	6.90
22/03/94	0.22	0.19	6.39	3.81		
23/03/94	0.83	0.16	4.18	2.65		
24/03/94	0.33	0.14	2.64	1.84		
25/03/94						
26/03/94						
27/03/94	0.27	0.20	7.53	4.12		
28/03/94	0.31	0.16	11.66	11.86		
29/03/94	0.31	0.16	8.92	9.35		
30/03/94	0.63	0.25	2.82	2.74		
31/03/94						
01/04/94						
02/04/94						
03/04/94						
04/04/94	0.30	0.61	12.55	17.78	21.76	
05/04/94						
06/04/94	0.28	0.14	6.54	7.61	25.99	24.89
Average:	0.33	0.19	6.66	6.55	8.55	6.58
Count:	13	13	13	13	6	5
Maximum:	0.83	0.61	12.55	17.78	25.99	24.89
Minimum:	0.12	0.08	2.64	1.84	0.04	0.15
Standard Deviation:	0.19	0.13	2.93	4.26	10.96	9.50

PERIOD 3.1.2
SUMMARY DATA 6
ENHANCED CULTURE DEVELOPMENT

	DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAB1	NO3 R1 fAB2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAB1	NO3 R2 fAB2
	16/03/94								
	17/03/94								
	18/03/94								
	19/03/94								
	20/03/94								
	21/03/94								
	22/03/94								
	23/03/94								
	24/03/94								
	25/03/94								
	26/03/94								
	27/03/94								
	28/03/94								
	29/03/94								
	30/03/94								
	31/03/94								
	01/04/94								
	02/04/94								
	03/04/94								
	04/04/94								
	05/04/94								
	06/04/94								
Average:		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Count:		0	0	0	0	0	0	0	0
Maximum:									
Minimum:									
Standard Deviation:		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

PERIOD 3.1.2
SUMMARY DATA 7
ENHANCED CULTURE DEVELOPMENT

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
16/03/94								
17/03/94								
18/03/94								
19/03/94								
20/03/94								
21/03/94								
22/03/94								
23/03/94								
24/03/94								
25/03/94								
26/03/94								
27/03/94								
28/03/94								
29/03/94								
30/03/94								
31/03/94								
01/04/94								
02/04/94								
03/04/94								
04/04/94								
05/04/94								
06/04/94								
Average:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Count:	0	0	0	0	0	0	0	0
Maximum:								
Minimum:								
Standard Deviation:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

PERIOD 3.1.2
SUMMARY DATA 8
ENHANCED CULTURE DEVELOPMENT

	DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
	16/03/94				19.8	
	17/03/94				19.7	
	18/03/94				19.7	
	19/03/94				20.1	
	20/03/94					
	21/03/94					
	22/03/94					
	23/03/94				19.8	
	24/03/94				19.4	
	25/03/94				19.8	
	26/03/94				19.3	
	27/03/94				20.5	
	28/03/94				20.0	
	29/03/94				20.2	
	30/03/94				19.8	
	31/03/94				20.0	
	01/04/94					
	02/04/94				20.0	
	03/04/94				20.3	
	04/04/94				19.8	
	05/04/94					
	06/04/94				19.7	
Average:					19.9	0.0
Count:		0	0	0	17	0
Maximum:					20.5	
Minimum:					19.3	
Standard Deviation:					0.3	0.0

PERIOD 3.1.3
SUMMARY DATA 1
ENHANCED CULTURE DEVELOPMENT

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	CORR COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
07/04/94	150	31.9	31.9	15.22		478	20		31.8	2.30	
08/04/94	150	33.4	32.9	15.50	18.20						
09/04/94	150	32.4	31.7	16.60	20.70						
10/04/94	150	33.1	31.9	15.90	21.40	411	19	21	36.2	1.80	1.90
11/04/94	150	32.2	31.4			457	18	20	34.6	1.70	1.80
12/04/94	150	31.9	32.4	15.30	22.20	440	18	20	30.5	1.60	1.70
13/04/94	150	31.2	30.5	14.50	19.80	384	19	22	28.2	1.50	1.20
14/04/94	150	32.6	32.6	14.10	17.70						
15/04/94	150	33.1	31.4	17.10	19.80						
16/04/94	150	33.4	31.2	17.20	23.10						
17/04/94	150	32.4	31.0	19.20	26.10	539	62	55	39.9	3.00	3.30
18/04/94	150	32.2	31.7	17.90	26.40	412	57	61	35.1	3.00	3.00
19/04/94	150	32.2	31.4	16.30	18.50	542	38	43	30.6	3.60	3.40
20/04/94	150	32.2	33.8	16.10	26.80	503	20	20	27.0	3.90	3.80
21/04/94	150	32.9	32.2			566	69		31.1	4.20	8.60
22/04/94	150	31.7	32.4	15.40							
23/04/94	150	32.9	32.4	17.50	19.77						
24/04/94	150	33.4	31.7	16.41	21.40	416	22	19	36.7	2.70	2.70
25/04/94	150	30.0	30.0			435	18	18	42.8	2.40	2.20
26/04/94	150	32.4	31.2	15.40	21.20	414	21	20	44.2	1.80	1.70
27/04/94	150	32.9	33.1	17.40	21.20	411	20	20	44.2	1.60	1.40
28/04/94	150	33.6	29.5	17.90	21.00	460	21	21			
29/04/94	150	32.6	32.6	17.00	20.00						
30/04/94	150	31.4	28.3								
Average:	150	32.4	31.6	16.40	21.40	458	29	28	35.2	2.51	2.82
Count:	24	24	24	20	18	15	15	13	14	14	13
Maximum:	150	33.6	33.8	19.20	26.80	566	69	61	44.2	4.20	8.60
Minimum:	150	30.0	28.3	14.10	17.70	384	18	18	27.0	1.50	1.20
Standard Deviation:	0	0.8	1.2	1.24	2.61	54	17	14	5.6	0.88	1.85

PERIOD 3.1.3
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
07/04/94	38.19	24.95		13.24		153.44	
08/04/94							
09/04/94							
10/04/94	12.44	1.12	0.80	11.32	11.64	132.62	110.16
11/04/94	37.96	2.39	1.28	35.57	36.68	132.62	116.31
12/04/94	36.35	14.83	4.63	21.52	31.72	142.75	135.96
13/04/94	38.92	12.60	5.58	26.32	33.34	166.79	139.64
14/04/94						155.05	141.97
15/04/94							
16/04/94							
17/04/94	36.70	6.20	9.10	30.50	27.60	158.73	155.38
18/04/94	36.70	9.90	14.30	26.80	22.40	164.78	157.25
19/04/94	36.80	9.70	7.20	27.10	29.60	173.82	158.97
20/04/94	36.40	17.80	22.30	18.60	14.10	158.94	134.48
21/04/94	42.07	12.03		30.04			
22/04/94							
23/04/94							
24/04/94	32.54	8.32	2.34	24.22	30.20	192.64	154.48
25/04/94	40.61	7.35	2.50	33.26	38.11	183.39	161.05
26/04/94	40.77	15.42	10.25	25.35	30.52	168.74	177.25
27/04/94	39.48	15.91	10.74	23.57	28.74	187.20	171.16
28/04/94	39.97	18.33	14.78	21.64	25.19	199.18	184.23
29/04/94							
30/04/94							
Average:	36.39	11.79	8.14	24.60	27.68	164.71	149.88
Count:	15	15	13	15	13	15	14
Maximum:	42.07	24.95	22.30	35.57	38.11	199.18	184.23
Minimum:	12.44	1.12	0.80	11.32	11.64	132.62	110.16
Standard Deviation:	6.79	6.14	6.08	6.51	7.51	19.59	20.70

PERIOD 3.1.3
SUMMARY DATA 3
ENHANCED CULTURE DEVELOPMENT

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
07/04/94	96.15		3174	1989			62.7		101	
08/04/94										
09/04/94										
10/04/94	86.52	75.53	3392	2213	3083	2114	65.2	68.6		
11/04/94	82.53	75.49	3614	2249	3317	2153	62.2	64.9	89	90
12/04/94	91.40	90.13	3525	2257	3159	2094	64.0	66.3	96	98
13/04/94	104.51	87.66	3388	2123	3275	2056	62.7	62.8	97	92
14/04/94	100.78	94.14	3334	2167	3155	2092	65.0	66.3	102	98
15/04/94										
16/04/94										
17/04/94	90.96	92.66	3958	2268	3540	2111	57.3	59.6	86	85
18/04/94	105.70	99.73	3576	2294	3349	2124	64.1	63.4	95	90
19/04/94	104.17	96.52	3811	2284	3533	2145	59.9	60.7	92	88
20/04/94	99.55	84.85	4028	2523	3677	2320	62.6	63.1	89	87
21/04/94			4040	2143			53.0		92	
22/04/94										
23/04/94										
24/04/94	100.76	92.92	4191	2192	3797	2284	52.3	60.2		
25/04/94	112.80	101.37	4001	2461	3608	2271	61.5	62.9	95	100
26/04/94	99.85	108.30	4245	2512	3720	2273	59.2	61.1	85	97
27/04/94	108.83	103.15	4147	2411	3624	2184	58.1	60.3	89	99
28/04/94	116.38	111.94	4017	2347	3657	2222	58.4	60.8	95	98
29/04/94										
30/04/94										
Average:	100.06	93.89	3778	2277	3464	2175	60.5	62.9	93	94
Count:	15	14	16	16	14	14	16	14	14	12
Maximum:	116.38.	111.94	4245	2523	3797	2320	65.2	68.6	102	100
Minimum:	82.53	75.49	3174	1989	3083	2056	52.3	59.6	85	85
Standard Deviation:	9.09	10.45	335	142	227	82	3.8	2.6	5	5

PERIOD 3.1.3
SUMMARY DATA 4
ENHANCED CULTURE DEVELOPMENT

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
07/04/94			7.19		7.40		0	0		
08/04/94			7.18	6.74	7.55	6.83	0	0		
09/04/94			7.24	7.01	7.67	7.26	0	0		
10/04/94			7.28	7.15	7.62	7.18	0	0		
11/04/94			7.27	6.79	7.40	6.89	10	0		
12/04/94			7.36	6.83	7.57	7.10	10	0		
13/04/94			7.25	6.93	7.52	7.25	10	0		
14/04/94			7.39	7.10	7.65	7.44	10	0		
15/04/94			7.35	6.90	7.63	7.25	20	0		
16/04/94			7.54	7.37	7.64	7.42	20	0		
17/04/94			7.48	7.34	7.50	7.42	20	0		
18/04/94			7.42	7.06	7.54	7.25	20	0		
19/04/94			7.57	7.22	7.62	7.48	20	0		
20/04/94			7.29	7.16	7.49	7.53	20	0		
21/04/94			7.38		7.57		0	0		
22/04/94							20	0		
23/04/94										
24/04/94			7.43	7.06	7.53	7.42				
25/04/94			7.39	6.56	7.55	7.38	20	0		
26/04/94			7.39	6.59	7.48	6.72	20	0		
27/04/94			7.19	7.19	7.23	7.24	20	0		
28/04/94			7.35	6.56	7.43	6.87	20	0		
29/04/94			7.16	6.90	7.17	7.17	20	0		
30/04/94			7.40	7.13	7.54	7.53	20	10		
Average:	0.00	0.00	7.34	6.98	7.51	7.23	14	0	0.0	0.0
Count:	0	0	22	20	22	20	22	22	0	0
Maximum:			7.57	7.37	7.67	7.53	20	10		
Minimum:			7.16	6.56	7.17	6.72	0	0		
Standard Deviation:	0.00	0.00	0.11	0.24	0.12	0.24	8	2	0.0	0.0

PERIOD 3.1.3
SUMMARY DATA 5
ENHANCED CULTURE DEVELOPMENT

	DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
	07/04/94	0.44		4.45		24.63	
	08/04/94						
	09/04/94						
	10/04/94	0.54	0.25	7.53	9.27		
	11/04/94	0.29	0.23	7.16	8.99	1.63	0.26
	12/04/94	0.30	0.38	2.97	4.00	16.27	3.84
	13/04/94	0.32	0.20	2.99	3.92	14.04	4.55
	14/04/94	0.34	0.24	2.37	3.05		
	15/04/94						
	16/04/94						
	17/04/94	0.37	0.74	9.81	9.52	6.22	
	18/04/94	0.32	1.33	12.19	10.92		
	19/04/94	0.45	0.42				7.22
	20/04/94	0.31	0.18				
	21/04/94	0.44	0.27	10.43	10.70	7.56	
	22/04/94						
	23/04/94						
	24/04/94	0.36	0.23	8.08	9.21	7.54	1.21
	25/04/94	0.31	0.22	9.47	8.08	5.84	1.78
	26/04/94	0.38	0.18	11.91	11.21		11.03
	27/04/94	0.31	0.16	12.52	12.95		12.12
	28/04/94	0.36	0.25	14.25	13.91		16.17
	29/04/94						
	30/04/94						
Average:		0.37	0.35	8.30	8.90	10.47	6.46
Count:		16	15	14	13	8	9
Maximum:		0.54	1.33	14.25	13.91	24.63	16.17
Minimum:		0.29	0.16	2.37	3.05	1.63	0.26
Standard Deviation:		0.07	0.30	3.76	3.26	6.91	5.23

PERIOD 3.1.3
SUMMARY DATA 6
ENHANCED CULTURE DEVELOPMENT

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
07/04/94								
08/04/94								
09/04/94								
10/04/94								
11/04/94								
12/04/94								
13/04/94								
14/04/94								
15/04/94								
16/04/94								
17/04/94								
18/04/94								
19/04/94								
20/04/94								
21/04/94								
22/04/94								
23/04/94								
24/04/94								
25/04/94								
26/04/94								
27/04/94								
28/04/94								
29/04/94								
30/04/94								
Average:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Count:	0	0	0	0	0	0	0	0
Maximum:								
Minimum:								
Standard Deviation:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

PERIOD 3.1.3
SUMMARY DATA 7
ENHANCED CULTURE DEVELOPMENT

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
07/04/94								
08/04/94								
09/04/94								
10/04/94								
11/04/94								
12/04/94								
13/04/94								
14/04/94								
15/04/94								
16/04/94								
17/04/94								
18/04/94								
19/04/94								
20/04/94								
21/04/94								
22/04/94								
23/04/94								
24/04/94								
25/04/94								
26/04/94								
27/04/94								
28/04/94								
29/04/94								
30/04/94								
Average:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Count:	0	0	0	0	0	0	0	0
Maximum:								
Minimum:								
Standard Deviation:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

PERIOD 3.1.3
SUMMARY DATA 8
ENHANCED CULTURE DEVELOPMENT

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
07/04/94	0.0	0.0	0.0	20.1	
08/04/94				19.3	
09/04/94				20.7	
10/04/94				19.7	
11/04/94					
12/04/94				20.4	
13/04/94				19.7	
14/04/94				18.8	
15/04/94				20.0	
16/04/94				18.6	
17/04/94				19.3	
18/04/94				18.6	
19/04/94				19.0	
20/04/94				18.3	
21/04/94					
22/04/94				17.5	
23/04/94				18.2	
24/04/94				17.2	
25/04/94					
26/04/94				17.2	
27/04/94				18.7	
28/04/94				19.4	
29/04/94				19.1	
30/04/94					
Average:				19.0	0.0
Count:	1	1	1	20	0
Maximum:	0.0	0.0	0.0	20.7	
Minimum:	0.0	0.0	0.0	17.2	
Standard Deviation:				1.0	0.0

ERIOD 3.1.4
UMMARY DATA 1
NHANCED CULTURE DEVELOPMENT

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	CORR COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
01/05/94	200	33.4	30.5	16.50	15.70	466	21	18	35.3	1.70	1.90
02/05/94	200	32.9	30.7	17.20	15.40	443	23	17	36.1	1.70	1.50
03/05/94	200	32.9	29.3			520					
04/05/94	200	33.1	30.0	25.40	32.30						
05/05/94	200	31.9	31.9	17.70	16.90	477	18	17			
06/05/94	200	32.9	31.4	16.40	15.30						
07/05/94	200	33.6									
08/05/94	200	33.1	33.1			466	21	21	56.7	3.70	4.90
09/05/94	200	33.1	33.1	18.90	21.80						
10/05/94	200	33.1	33.1			467	22	21	56.7	7.00	5.50
11/05/94	200	31.9	31.4	25.50	29.30						
12/05/94	200	33.4	33.4	19.50	19.90	547		22	54.9	6.20	6.30
13/05/94	200	32.6	31.7	18.60	18.50						
14/05/94	200	33.4	31.4								
15/05/94	200	32.2	31.7			406	24	23	33.5	1.60	3.00
16/05/94	200	31.9	31.2	16.40	17.00	390	21	20	34.8	1.70	2.10
Average:	200	32.8	31.6	19.21	20.21	465	21	20	44.0	3.37	3.60
Count:	16	16	15	10	10	9	7	8	7	7	7
Maximum:	200	33.6	33.4	25.50	32.30	547	24	23	56.7	7.00	6.30
Minimum:	200	31.9	29.3	16.40	15.30	390	18	17	33.5	1.60	1.50
Standard Deviation:	0	0.6	1.2	3.28	5.68	47	2	2	10.5	2.16	1.79

APPENDIX 5

PERIOD 3.1.4
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
07/04/94	38.19	24.95		13.24		153.44	
08/04/94							
09/04/94							
10/04/94	12.44	1.12	0.80	11.32	11.64	132.62	110.16
11/04/94	37.96	2.39	1.28	35.57	36.68	132.62	116.31
12/04/94	36.35	14.83	4.63	21.52	31.72	142.75	135.96
13/04/94	38.92	12.60	5.58	26.32	33.34	166.79	139.64
14/04/94						155.05	141.97
15/04/94							
16/04/94							
17/04/94	36.70	6.20	9.10	30.50	27.60	158.73	155.38
18/04/94	36.70	9.90	14.30	26.80	22.40	164.78	157.25
19/04/94	36.80	9.70	7.20	27.10	29.60	173.82	158.97
20/04/94	36.40	17.80	22.30	18.60	14.10	158.94	134.48
21/04/94	42.07	12.03		30.04			
22/04/94							
23/04/94							
24/04/94	32.54	8.32	2.34	24.22	30.20	192.64	154.48
25/04/94	40.61	7.35	2.50	33.26	38.11	183.39	161.05
26/04/94	40.77	15.42	10.25	25.35	30.52	168.74	177.25
27/04/94	39.48	15.91	10.74	23.57	28.74	187.20	171.16
28/04/94	39.97	18.33	14.78	21.64	25.19	199.18	184.23
29/04/94							
30/04/94							
Average:	36.39	11.79	8.14	24.60	27.68	164.71	149.88
Count:	15	15	13	15	13	15	14
Maximum:	42.07	24.95	22.30	35.57	38.11	199.18	184.23
Minimum:	12.44	1.12	0.80	11.32	11.64	132.62	110.16
Standard Deviation:	6.79	6.14	6.08	6.51	7.51	19.59	20.70

PERIOD 3.1.4
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R2 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
01/05/94	41.74	22.04	21.07	19.70	20.67	196.48	228.87
02/05/94	37.38	16.35	16.99	21.03	20.39	173.25	163.68
03/05/94							
04/05/94	39.97	4.69	4.86	35.28	35.11	150.34	145.17
05/05/94	54.86	2.91	2.91	51.95	51.95	157.22	151.31
06/05/94							
07/05/94							
08/05/94	58.42	11.49	11.99	46.93	46.43	187.02	186.45
09/05/94							
10/05/94	59.72	21.69	20.39	38.03	39.33		
11/05/94							
12/05/94	60.20	25.57	26.06	34.63	34.14	195.43	180.48
13/05/94							
14/05/94							
15/05/94	48.71	20.64	18.68	28.07	30.03	199.35	194.59
16/05/94	46.26	12.81	14.77	33.45	31.49	212.31	204.30
Average:	49.70	15.35	15.30	34.34	34.39	183.93	181.86
Count:	9	9	9	9	9	8	8
Maximum:	60.20	25.57	26.06	51.95	51.95	212.31	228.87
Minimum:	37.38	2.91	2.91	19.70	20.39	150.34	145.17
Standard Deviation:	8.41	7.51	7.17	10.08	9.94	20.30	26.24

PERIOD 3.1.4
SUMMARY DATA 3
ENHANCED CULTURE DEVELOPMENT

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
01/05/94	124.26	142.35	3749	2371	3386	2106	63.2	62.2		
02/05/94	102.49	99.63	3979	2354	3606	2195	59.2	60.9	96	100
03/05/94										
04/05/94	91.07	88.29	3927	2379	3721	2263	60.6	60.8		105
05/05/94	98.09	96.35	3877	2419	3645	2321	62.4	63.7	98	104
06/05/94										
07/05/94										
08/05/94	103.58	105.56	4328	2397	4308	2439	55.4	56.6	88	88
09/05/94										
10/05/94			3807		3908				100	100
11/05/94										
12/05/94	87.76	106.39		2534	4548	2681		58.9		88
13/05/94										
14/05/94										
15/05/94	113.16	112.53	4434	2517	4285	2478	56.8	57.8		
16/05/94	135.15	125.88	3918	2494	3999	2464	63.7	61.6	92	100
Average:	106.95	109.62	4002	2433	3934	2368	60.2	60.3	95	98
Count:	8	8	8	8	9	8	7	8	5	7
Maximum:	135.15	142.35	4434	2534	4548	2681	63.7	63.7	100	105
Minimum:	87.76	88.29	3749	2354	3386	2106	55.4	56.6	88	88
Standard Deviation:	15.26	16.21	230	67	362	172	3.0	2.2	4	7

PERIOD 3.1.4
SUMMARY DATA 4
ENHANCED CULTURE DEVELOPMENT

	DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
	01/05/94			7.05	7.25	6.90	7.13	20	10		
	02/05/94			7.43	7.08	7.62	7.17	20	10		
	03/05/94			7.24	7.53	6.71	7.20	20	10		
	04/05/94			6.89	6.62	6.98	6.81	20	10		
	05/05/94			7.73	7.31	7.68	7.78	20	20		
	06/05/94			7.75	7.08	7.88	7.73	20	20		
	07/05/94										
	08/05/94			7.34							
	09/05/94			7.62	7.03	7.69	7.60	20	20		
	10/05/94			7.68	7.17	7.75	7.57	20	20		
	11/05/94			7.40	7.25	7.97	7.84	20	20		
	12/05/94			7.63	7.68	8.01	8.05	20	20		
	13/05/94			7.14	7.50	7.11	7.48	50	50		
	14/05/94							40	40		
	15/05/94			7.44	7.32	7.78	7.66	40	40		
	16/05/94			7.35	7.18	7.65	7.38	40	40		
Average:		0.00	0.00	7.41	7.23	7.52	7.49	26	24	0.0	0.0
Count:		0	0	14	13	13	13	14	14	0	0
Maximum:				7.75	7.68	8.01	8.05	50	50		
Minimum:				6.89	6.62	6.71	6.81	20	10		
Standard Deviation:		0.00	0.00	0.25	0.25	0.42	0.33	10	13	0.0	0.0

PERIOD 3.1.4
SUMMARY DATA 5
ENHANCED CULTURE DEVELOPMENT

	DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
	01/05/94	0.35	0.23	6.44	6.92		22.42
	02/05/94	0.38	0.25	4.41	5.37		
	03/05/94	5.14	5.03	1.70	1.86		
	04/05/94	0.54	0.27	5.96	7.71	4.25	4.72
	05/05/94	0.10	0.08	5.26	5.02	2.38	2.67
	06/05/94						
	07/05/94						
	08/05/94	0.66	0.37	13.85	11.44		13.13
	09/05/94						
	10/05/94	0.34	0.29	14.89	16.09		
	11/05/94						
	12/05/94	0.78	0.64	6.62	6.53		
	13/05/94						
	14/05/94						
	15/05/94	0.59	0.64	4.48	4.15		
	16/05/94	0.60	0.82	8.87	7.42	12.47	14.26
Average:		0.95	0.86	7.25	7.25	6.37	11.44
Count:		10	10	10	10	3	5
Maximum:		5.14	5.03	14.89	16.09	12.47	22.42
Minimum:		0.10	0.08	1.70	1.86	2.38	2.67
Standard Deviation:		1.41	1.41	3.97	3.79	4.38	7.12

PERIOD 3.1.4
SUMMARY DATA 6
ENHANCED CULTURE DEVELOPMENT

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
01/05/94								
02/05/94								
03/05/94								
04/05/94								
05/05/94								
06/05/94								
07/05/94								
08/05/94								
09/05/94								
10/05/94								
11/05/94								
12/05/94								
13/05/94								
14/05/94								
15/05/94								
16/05/94								
Average:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Count:	0	0	0	0	0	0	0	0
Maximum:								
Minimum:								
Standard Deviation:	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

APPENDIX 5

PERIOD 3.1.4
SUMMARY DATA 7
ENHANCED CULTURE DEVELOPMENT

	DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
	01/05/94								
	02/05/94								
	03/05/94								
	04/05/94								
	05/05/94								
	06/05/94								
	07/05/94								
	08/05/94								
	09/05/94								
	10/05/94								
	11/05/94								
	12/05/94								
	13/05/94								
	14/05/94								
	15/05/94								
	16/05/94								
Average:		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Count:		0	0	0	0	0	0	0	0
Maximum:									
Minimum:									
Standard Deviation:		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

ERIOD 3.1.4
UMMARY DATA 8
NHANCED CULTURE DEVELOPMENT

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
01/05/94				20.1	
02/05/94				20.0	
03/05/94					
04/05/94				20.0	
05/05/94				18.7	
06/05/94				18.0	
07/05/94					
08/05/94					
09/05/94				20.3	
10/05/94					
11/05/94				22.7	
12/05/94				21.4	
13/05/94				20.4	
14/05/94					
15/05/94					
16/05/94				17.3	
.verage:				19.9	0.0
'ount:	0	0	0	10	0
:aximum:				22.7	
:inimum:				17.3	
tandard Deviation:				1.5	0.0

APPENDIX 5

PERIOD 3.1.5
SUMMARY DATA 1
ENHANCED CULTURE DEVELOPMENT

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	CORR COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
17/05/94	250	31.2	30.7	15.40	15.20	609	23	22	39.1	3.30	2.40
18/05/94	250	32.6	32.6	20.50	21.30	555	25	22	67.9	3.00	3.30
19/05/94	250	32.2	33.1	24.50	25.40	542	25	22	47.1	2.80	2.90
20/05/94	250	28.6	29.3	21.40	22.00						
21/05/94	250	33.1	34.8	21.00	19.00						
22/05/94	250	33.6	28.6	18.50	17.50	532	26	25	37.8	2.20	1.60
23/05/94	250	32.2	32.2	18.20	17.30	536	23	22	36.0	2.30	2.00
24/05/94	250	33.1	32.9	18.20	17.40	545	22	21	45.1	1.60	1.70
25/05/94	250	31.9	30.5	17.60	16.60	537	22	20	45.4	1.70	1.60
26/05/94	250	32.4	31.9	19.80	19.60	503	23	21	56.5	2.00	2.60
27/05/94	250	33.1	31.2	19.50	18.80						
28/05/94	250	33.1	31.7								
29/05/94	250	32.6	29.8			540	22	22	49.1	2.20	2.10
30/05/94	250	33.1	32.6	21.70	16.20	540	22	22	49.1	2.20	2.10
31/05/94	250	34.3	31.7			560	20	19	54.2	2.20	2.50
Average:	250	32.5	31.6	19.69	18.86	545	23	22	47.9	2.32	2.25
Count:	15	15	15	12	12	11	11	11	11	11	11
Maximum:	250	34.3	34.8	24.50	25.40	609	26	25	67.9	3.30	3.30
Minimum:	250	28.6	28.6	15.40	15.20	503	20	19	36.0	1.60	1.60
Standard Deviation:	0	1.3	1.6	2.26	2.76	24	2	1	8.8	0.50	0.52

PERIOD 3.1.5
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

	DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
	01/05/94	41.74	22.04	21.07	19.70	20.67	196.48	228.87
	02/05/94	37.38	16.35	16.99	21.03	20.39	173.25	163.68
	03/05/94							
	04/05/94	39.97	4.69	4.86	35.28	35.11	150.34	145.17
	05/05/94	54.86	2.91	2.91	51.95	51.95	157.22	151.31
	06/05/94							
	07/05/94							
	08/05/94	58.42	11.49	11.99	46.93	46.43	187.02	186.45
	09/05/94							
	10/05/94	59.72	21.69	20.39	38.03	39.33		
	11/05/94							
	12/05/94	60.20	25.57	26.06	34.63	34.14	195.43	180.48
	13/05/94							
	14/05/94							
	15/05/94	48.71	20.64	18.68	28.07	30.03	199.35	194.59
	16/05/94	46.26	12.81	14.77	33.45	31.49	212.31	204.30
Average:		49.70	15.35	15.30	34.34	34.39	183.93	181.86
Count:		9	9	9	9	9	8	8
Maximum:		60.20	25.57	26.06	51.95	51.95	212.31	228.87
Minimum:		37.38	2.91	2.91	19.70	20.39	150.34	145.17
Standard Deviation:		8.41	7.51	7.17	10.08	9.94	20.30	26.24

PERIOD 3.1.5
SUMMARY DATA 3
ENHANCED CULTURE DEVELOPMENT

	DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
	17/05/94	107.84	103.97	4564	2543	4397	2180	55.7	49.6	79	86
	18/05/94	114.01	104.91	4384	2593	4314	2504	59.1	58.0	82	90
	19/05/94	108.32	104.02	4530	2631	4468	2620	58.1	58.6	75	87
	20/05/94										
	21/05/94										
	22/05/94	107.89	105.72	4802	2767	4742	2687	57.6	56.7		
	23/05/94	103.89	98.29	4944	2778	4900	2777	56.2	56.7	69	82
	24/05/94	106.07	106.79	4733	2708	4660	2719	57.2	58.3	74	86
	25/05/94	104.64	102.52	4589	2463	4613	2666	53.7	57.8	76	87
	26/05/94	117.25	113.33	4418	2689	4404	2700	60.9	61.3	81	95
	27/05/94										
	28/05/94										
	29/05/94	108.97	107.10	4794	2682	4565	2687	55.9	58.9		
	30/05/94	130.28	131.18	4794	2682	4565	2687	55.9	58.9	75	92
	31/05/94	113.25	115.96	5181	2965	4773	3022	57.2	63.3		
Average:		111.13	108.53	4703	2682	4582	2659	57.0	58.0	76	88
Count:		11	11	11	11	11	11	11	11	8	8
Maximum:		130.28	131.18	5181	2965	4900	3022	60.9	63.3	82	95
Minimum:		103.89	98.29	4384	2463	4314	2180	53.7	49.6	69	82
Standard Deviation:		7.20	8.53	225	126	171	193	1.8	3.2	4	4

PERIOD 3.1.5
SUMMARY DATA 4
ENHANCED CULTURE DEVELOPMENT

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
17/05/94			7.58	7.36	7.86	7.72	60	60		
18/05/94			7.34	7.30	7.83	7.62	60	60		
19/05/94			7.49	7.32	7.89	7.73	80	80		
20/05/94			7.44	7.34	7.89	7.76	80	80		
21/05/94			7.29	7.27	7.79	7.68	80	80		
22/05/94			7.13	7.15	7.57	7.56	100	100		
23/05/94			7.01	7.23	7.42	7.54	80	80		
24/05/94			7.50	7.53	7.90	7.74	80	80		
25/05/94			7.34	7.45	7.89	7.84	100	100		
26/05/94			7.28	7.07	7.77	7.57	120	120		
27/05/94			7.00	6.88	7.45	7.29	120	120		
28/05/94			6.96	6.84	7.45	7.23	120	120		
29/05/94			7.12	6.86	7.85	7.28	120	120		
30/05/94			6.87	6.77	7.46	7.15	120	120		
31/05/94			7.08	6.91	7.49	7.33	120	120		
Average:	0.00	0.00	7.23	7.15	7.70	7.54	96	96	0.0	0.0
Count:	0	0	15	15	15	15	15	15	0	0
Maximum:			7.58	7.53	7.90	7.84	120	120		
Minimum:			6.87	6.77	7.42	7.15	60	60		
Standard Deviation:	0.00	0.00	0.21	0.24	0.19	0.22	22	22	0.0	0.0

PERIOD 3.1.5
SUMMARY DATA 5
ENHANCED CULTURE DEVELOPMENT

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
17/05/94	0.89	1.24	8.38	8.55	26.88	29.06
18/05/94	0.98	0.81	7.42	7.58	18.43	21.90
19/05/94	0.39	0.96	5.62	5.30	14.75	14.42
20/05/94						
21/05/94						
22/05/94	0.36	0.39	3.47	3.72		
23/05/94	0.32	0.23	4.77	5.15	11.23	12.75
24/05/94	0.25	0.21	4.55	4.74	10.10	10.00
25/05/94	0.53	0.19	7.52	7.79	12.59	13.73
26/05/94	0.20	0.17	11.15	10.87		
27/05/94						
28/05/94						
29/05/94	0.64	0.81	9.14	8.98	16.54	18.30
30/05/94	0.64	0.81	9.14	8.98	16.54	18.30
31/05/94						
Average:	0.52	0.58	7.12	7.17	15.88	17.31
Count:	10	10	10	10	8	8
Maximum:	0.98	1.24	11.15	10.87	26.88	29.06
Minimum:	0.20	0.17	3.47	3.72	10.10	10.00
Standard Deviation:	0.25	0.37	2.32	2.19	4.94	5.66

PERIOD 3.1.5
SUMMARY DATA 6
ENHANCED CULTURE DEVELOPMENT

	DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
	17/05/94								
	18/05/94								
	19/05/94								
	20/05/94								
	21/05/94								
	22/05/94								
	23/05/94								
	24/05/94								
	25/05/94								
	26/05/94	0.20	3.28	11.96	12.87	0.24	6.43	12.51	13.41
	27/05/94								
	28/05/94								
	29/05/94								
	30/05/94	0.05	1.85	29.22	32.87	0.15	16.43	40.17	38.35
	31/05/94								
Average:		0.13	2.57	20.59	22.87	0.20	11.43	26.34	25.88
Count:		2	2	2	2	2	2	2	2
Maximum:		0.20	3.28	29.22	32.87	0.24	16.43	40.17	38.35
Minimum:		0.05	1.85	11.96	12.87	0.15	6.43	12.51	13.41
Standard Deviation:		0.08	0.72	8.63	10.00	0.04	5.00	13.83	12.47

PERIOD 3.1.5
SUMMARY DATA 7
ENHANCED CULTURE DEVELOPMENT

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
17/05/94								
18/05/94								
19/05/94								
20/05/94								
21/05/94								
22/05/94								
23/05/94								
24/05/94								
25/05/94								
26/05/94	143.66	86.20	52.17	28.88	142.15	68.05	46.88	31.00
27/05/94								
28/05/94								
29/05/94								
30/05/94	163.32	77.13	40.98	17.69	127.03	63.51	35.69	20.72
31/05/94								
Average:	153.49	81.67	46.58	23.29	134.59	65.78	41.29	25.86
Count:	2	2	2	2	2	2	2	2
Maximum:	163.32	86.20	52.17	28.88	142.15	68.05	46.88	31.00
Minimum:	143.66	77.13	40.98	17.69	127.03	63.51	35.69	20.72
Standard Deviation:	9.83	4.53	5.59	5.60	7.56	2.27	5.59	5.14

RIOD 3.1.5
MMARY DATA 8
HANCED CULTURE DEVELOPMENT

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
17/05/94				18.7	
18/05/94				17.4	
19/05/94				22.6	
20/05/94				21.2	
21/05/94				21.6	
22/05/94				19.3	
23/05/94				19.5	
24/05/94				19.9	
25/05/94				19.8	
26/05/94				19.7	
27/05/94				20.3	
28/05/94					
29/05/94					
30/05/94				19.6	
31/05/94					
verage:				20.0	0.0
ount:	0	0	0	12	0
aximum:				22.6	
inimum:				17.4	
tandard Deviation:				1.3	0.0

APPENDIX 5

PERIOD 3.1.6
SUMMARY DATA 1
ENHANCED CULTURE DEVELOPMENT

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	CORR COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
01/06/94	250	32.6	30.2			557	20	19	68.5	2.30	0.94
02/06/94	250	33.1	30.7	17.60	20.70	491	20	18	69.7	3.40	3.90
03/06/94	250	34.1	30.5	20.00	24.40						
04/06/94	250	41.3	38.6								
06/06/94	250	32.9	29.8		21.70	486	13	14	36.6	2.24	
07/06/94	250	33.1		18.10	20.40	567	25	26	43.5		
08/06/94	250	25.4		11.50	11.40	545	18	24	49.7	1.98	2.20
09/06/94	250	29.0	31.2	15.70	15.10	537	25	22	52.5	2.10	1.90
10/06/94	250	31.7	29.8	17.40	18.10						
12/06/94	250	31.4	33.1	14.90	14.30	491	22	23	50.0	2.95	2.96
13/06/94	250	31.7	31.7	14.60	14.10	440	19	19	49.4		
14/06/94	250	30.7	28.6	12.20	12.20	467	12	7	42.2	1.80	1.80
15/06/94	250	30.5	27.1	11.90	12.40	367	16	17	41.8		
16/06/94	250	31.0	28.6	12.80	11.07	484	19	19			
17/06/94	250	31.7	29.0	12.40	12.10						
18/06/94	250	32.2	30.0	13.40	15.20						
19/06/94	250	31.9	32.9	14.03	15.30	539	21	22	56.0		
20/06/94	250	32.2	32.2	13.40	13.40	515	24	23	35.1		
21/06/94	250	31.2	30.5	13.80	14.80	557	20	20	54.2	1.80	2.30
22/06/94	250	30.2	30.2	12.80	13.30	454	16	16	63.9	2.40	2.20
23/06/94	250	32.2	32.9	14.90	16.50	496	23	22	60.2	2.30	2.40
24/06/94	250	31.0	31.0	15.20	13.40						
25/06/94	250	32.2	30.7								
26/06/94	250	15.6	32.6	14.90	18.20	551	18	18	55.1	2.10	2.60
27/06/94	250	34.8	32.6	16.90	20.70	517	21	23	42.9	2.50	2.60
28/06/94	250	32.9	32.6	14.30	16.10	474	19	22	49.2	1.60	
29/06/94	250	33.4	33.1	15.50	14.70	399	18	20	50.8	1.88	2.14
30/06/94	250	32.2	32.2	14.00	14.70	435	18	21	62.4	1.00	1.90
01/07/94	250	32.9	32.9	14.57	14.21						
02/07/94	250	33.1	32.6	14.57	14.30						
03/07/94	250	33.4	33.4	15.05	14.86	445	18	19	55.2	2.30	2.10
04/07/94	250	33.8	31.9	15.34	14.31	447	21	20	57.3	2.19	1.96
05/07/94	250	31.9	31.9	16.02	13.54	420	21	20	58.8	2.10	1.91
06/07/94	250	31.9	31.9	16.50	13.68	440	23	28	47.6	2.04	1.96
07/07/94	250	32.9	32.9	18.49	16.18	510	21	21	48.0	1.54	1.86
08/07/94	250	32.6	32.6	16.23	13.67						
09/07/94	250	33.4	32.4	15.95	13.26						
10/07/94	250	32.4	32.4			492	22	19	57.4	2.06	1.91
11/07/94	250	33.1	31.9	15.68	13.93	448	16	24	35.7	2.15	3.64
12/07/94	250	31.9	31.2	15.62	13.34	522	18	17	50.9	0.94	2.11
13/07/94	250	32.9	31.7	21.50	21.98	503	19	18	52.4	2.79	2.41
14/07/94	250	32.2	31.4	20.35	20.65	622	22	27	35.9	2.74	2.81
16/07/94	250	31.4	31.9	22.26	20.04						
17/07/94	250	33.1	32.9	20.89	19.82	596	85	57	36.1	1.06	5.95
18/07/94	250	31.4	29.8								
19/07/94	250	32.6	32.6			556	23	33	24.7	2.28	2.78
20/07/94	250	31.2	30.5			565	30	26			
Average:	250	31.9	31.6	15.67	15.80	498	22	22	49.8	2.09	2.45
Count:	47	47	45	39	40	34	34	34	32	27	25
Maximum:	250	41.3	38.6	22.26	24.40	622	85	57	69.7	3.40	5.95
Minimum:	250	15.6	27.1	11.50	11.07	367	12	7	24.7	0.94	0.94
Standard Deviation:	0	3.1	1.8	2.61	3.28	57	11	8	10.2	0.55	0.93

APPENDIX 5

PERIOD 3.1.6
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
01/06/94	52.32	20.57	15.12	31.75	37.20	188.90	193.59
02/06/94	52.48	15.73	14.97	36.75	37.51	197.85	
03/06/94							
04/06/94							
06/06/94	41.74						
07/06/94	44.38	17.69	16.29	26.69	28.09	125.65	181.26
08/06/94	50.90	10.55	18.00	40.35	32.90	144.11	213.92
09/06/94	50.74	10.24	20.33	40.50	30.41	147.08	191.38
10/06/94							
12/06/94	45.62	6.05	18.47	39.57	27.15	166.65	194.42
13/06/94	47.19	12.32	25.46	34.87	21.73	176.00	194.99
14/06/94	49.35	24.16	35.03	25.19	14.32	176.85	191.61
15/06/94	48.65	18.32	41.84	30.33	6.81	179.85	192.58
16/06/94	54.50	18.00	43.62	36.50	10.88	187.13	193.29
17/06/94							
18/06/94							
19/06/94	50.11	20.92	41.51	29.19	8.60	192.62	182.60
20/06/94	52.05	19.09	37.20	32.96	14.85	182.98	158.62
21/06/94	54.98	18.76	39.97	36.22	15.01	195.14	172.41
22/06/94	51.56	25.61	47.15	25.95	4.41	236.16	179.49
23/06/94	50.80	19.64	35.87	31.16	14.93	191.26	159.57
24/06/94							
25/06/94							
26/06/94	54.85	31.32	29.37	23.53	25.48	210.31	155.43
27/06/94	58.26	32.30	29.37	25.96	28.89	205.34	173.57
28/06/94	43.87	32.38	33.51	11.49	10.36	197.78	156.36
29/06/94	46.46	18.52	21.37	27.94	25.09	194.87	157.05
30/06/94	45.64	23.35	24.10	22.29	21.54	184.15	155.34
01/07/94							
02/07/94							
03/07/94	43.98	26.96	21.39	17.02	22.59	178.36	155.73
04/07/94	52.34	27.47	21.74	24.87	30.60	169.49	153.69
05/07/94	51.36	23.05	17.49	28.31	33.87	177.70	166.22
06/07/94	53.16	24.85	21.25	28.31	31.91	179.87	163.04
07/07/94	55.45	25.83	21.25	29.62	34.20	193.72	187.96
08/07/94							
09/07/94							
10/07/94	50.54	26.32	23.87	24.22	26.67	198.20	173.00
11/07/94	49.57	21.01	27.41	28.56	22.16	185.39	167.70
12/07/94	52.03	35.78	34.81	16.25	17.22	181.22	173.73
13/07/94	50.72	10.59	12.97	40.13	37.75	194.62	173.13
14/07/94	56.12	21.02	25.71	35.10	30.41	194.08	170.78
16/07/94							
17/07/94	52.54	27.97	31.37	24.57	21.17	188.30	182.28
18/07/94							
19/07/94	52.50	19.73	32.45	32.77	20.05	185.84	172.23
20/07/94	51.85	20.38	32.61	31.47	19.24	171.50	173.16
Average:	50.55	21.41	27.66	29.41	23.15	184.21	175.32
Count:	34	33	33	33	33	33	32
Maximum:	58.26	35.78	47.15	40.50	37.75	236.16	213.92
Minimum:	41.74	6.05	12.97	11.49	4.41	125.65	153.69
Standard Deviation:	3.78	6.78	9.17	6.90	9.17	19.42	15.05

PERIOD 3.1.6
SUMMARY DATA 3
ALUM TO R1: HIGH ACID DOSE

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
01/06/94	107.66	109.31	5155	2938	4925	2781	57.0	56.5	68	85
02/06/94	111.73		5089	2874			56.5		71	
03/06/94										
04/06/94										
06/06/94			4004	2550	4495	2605	63.7	58.0		
07/06/94	81.37	113.94	4310	2791	4467	2808	64.8	62.9	93	94
08/06/94	89.19	123.04	4419	2735	4717	2713	61.9	57.5	91	85
09/06/94	89.25	108.14	4451	2701	4635	2619	60.7	56.5	85	82
10/06/94										
12/06/94	99.30	113.82	4563	2719	4458	2610	59.6	58.5		
13/06/94	110.89	124.99	4314	2718	3983	2553	63.0	64.1	93	100
14/06/94	112.48	123.24	4426	2815	4092	2632	63.6	64.3	86	93
15/06/94	107.67	115.69	4684	2804	4233	2543	59.9	60.1	77	85
16/06/94	111.28	118.02	4357	2591	3916	2391	59.5	61.1	92	102
17/06/94										
18/06/94										
19/06/94	122.28	126.96	4469	2837	3423	2380	63.5	69.5		
20/06/94	111.29	103.11	4735	2880	4098	2664	60.8	65.0	80	88
21/06/94	117.30	111.75	4590	2759	3752	2432	60.1	64.8	83	96
22/06/94	147.10	123.26	4126	2570	3256	2236	62.3	68.7	97	117
23/06/94	110.05	100.97	4557	2622	3777	2390	57.5	63.3	88	101
24/06/94										
25/06/94										
26/06/94	121.91	101.12	4513	2616	3852	2506	58.0	65.1		
27/06/94	119.93	110.92	4479	2616	4053	2590	58.4	63.9	80	89
28/06/94	116.39	99.65	4576	2693	4045	2578	58.9	63.7	87	94
29/06/94	118.67	99.03	4611	2808	4087	2577	60.9	63.1	89	106
30/06/94	103.10	93.33	4733	2650	4196	2521	56.0	60.1	76	95
01/07/94										
02/07/94										
03/07/94	105.01	102.02	4647	2736	4045	2650	58.9	65.5		
04/07/94	105.79	97.84	4592	2866	4246	2703	62.4	63.7	96	106
05/07/94	105.17	106.13	4790	2835	4423	2824	59.2	63.8	88	99
06/07/94	108.88	98.70	4657	2819	4275	2588	60.5	60.5	86	103
07/07/94	110.42	118.40	4577	2609	4075	2567	57.0	63.0	87	108
08/07/94										
09/07/94										
10/07/94	115.93	111.18	4416	2583	4178	2685	58.5	64.3		
11/07/94	109.14	104.85	4617	2718	4336	2711	58.9	62.5	87	106
12/07/94	107.63	109.65	4529	2690	4251	2683	59.4	63.1	97	108
13/07/94	112.46	103.77	4700	2716	4318	2588	57.8	59.9	89	111
14/07/94	112.87	104.21	4555	2649	4220	2575	58.2	61.0	97	114
16/07/94										
17/07/94	110.77	109.45	4583	2696	4535	2723				
18/07/94										
19/07/94	110.36	104.14	4565	2711	4290	2594	59.4	60.5	92	112
20/07/94	102.56	110.60	4261	2548	4069	2599	59.8	63.9	99	118
Average:	109.87	109.41	4549	2720	4173	2595	59.9	62.5	87	100
Count:	33	32	34	34	33	33	33	32	27	26
Maximum:	147.10	126.96	5155	2938	4925	2824	64.8	69.5	99	118
Minimum:	81.37	93.33	4004	2548	3256	2236	56.0	56.5	68	82
Standard Deviation:	10.99	8.72	220	103	333	125	2.2	3.1	8	10

PERIOD 3.1.6
SUMMARY DATA 4
ALUM TO R1; HIGH ACID DOSE

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
01/06/94			6.88	7.12	7.33	7.32	60	120		
02/06/94			6.98	6.70	7.45	7.09	60	120		
03/06/94			6.96	6.62	7.47	6.91	60	120		
04/06/94			7.16	6.78	7.56	7.17	60	120		
06/06/94			7.07	7.28	7.11	7.66	60	120		
07/06/94			7.20	7.04	7.52	7.42	60	120		
08/06/94			7.56	7.29	7.89	7.68	60	120		
09/06/94			7.53	7.23	7.87	7.67	100	140		
10/06/94			7.62	7.42	7.96	7.74	140	140		
12/06/94			7.21	6.90	7.55	7.26	140	140		
13/06/94			6.98	6.94	7.46	7.35	140	140		
14/06/94			6.85	6.72	7.26	7.15	140	140		
15/06/94			6.67	6.62	6.87	6.81	140	140		
16/06/94			7.59	7.41	7.86	7.80	0	0		
17/06/94			6.97	6.95	7.35	7.29	140	140		
18/06/94			7.12	6.68	7.30	6.98	120	120		
19/06/94			7.08	6.99	7.13	7.03	120	120		
20/06/94			6.93	6.77	7.26	7.23	120	120		
21/06/94			6.94	6.84	7.19	7.17	120	120		
22/06/94			7.08	6.97	7.32	7.26	120	120		
23/06/94			6.84	6.76	7.12	7.12	100	100		
24/06/94			7.11	7.12	7.45	7.48	60	60		
25/06/94			7.30	7.34	7.66	7.72	90	90		
26/06/94			6.02	7.23	7.70	7.55	90	90		
27/06/94			7.13	7.25	7.31	7.46	75	75		
28/06/94			7.20	7.29	7.58	7.69	75	75		
29/06/94			7.13	7.20	7.50	7.56	75	75		
30/06/94			7.18	7.20	7.50	7.56	75	75		
01/07/94			7.09	7.16	7.20	7.54	75	75		
02/07/94			7.30	7.16	7.77	7.65	75	75		
03/07/94			7.23	7.18	7.54	7.68	75	75		
04/07/94			7.56	7.40	7.91	7.59	75	75		
05/07/94			7.30	7.40	7.64	7.79	75	75		
06/07/94			7.43	7.55	7.73	7.94	92	92		
07/07/94			7.26	7.37	7.60	7.79	92	92		
08/07/94			7.16	7.28	7.47	7.65	92	92		
09/07/94			7.01	7.03	7.33	7.36	92	92		
10/07/94			7.12	7.13	7.41	7.52	92	92		
11/07/94			7.10	7.24	7.47	7.68	92	92		
12/07/94			7.09	7.25	7.44	7.64	92	92		
13/07/94			6.93	6.87	7.18	7.20	92	92		
14/07/94			7.19	7.25	7.51	7.65	92	92		
16/07/94			7.13	7.15	7.38	7.41	75	75		
17/07/94			7.16	7.30	7.77	7.67	75	75		
18/07/94			7.27	7.35	7.56	7.65	92	92		
19/07/94			7.10	7.08	7.34	7.34	92	92		
20/07/94			7.03	6.99	7.27	7.23	75	75		
Average:	0.00	0.00	7.12	7.10	7.47	7.45	90	99	0.0	0.0
Count:	0	0	47	47	47	47	47	47	0	0
Maximum:			7.62	7.55	7.96	7.94	140	140		
Minimum:			6.02	6.62	6.87	6.81	0	0		
Standard Deviation:	0.00	0.00	0.26	0.24	0.24	0.26	28	28	0.0	0.0

APPENDIX 5

PERIOD 3.1.6
SUMMARY DATA 5
ALUM TO R1; HIGH ACID DOSE

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
01/06/94	0.41	0.46	14.47	12.17	22.07	13.47
02/06/94	0.31	0.31	15.10	17.13		
03/06/94						
04/06/94						
06/06/94	0.68	0.21	8.67	11.05		
07/06/94	0.32	0.29	3.08	7.90		
08/06/94	0.21	0.26	7.56	10.74	11.26	17.88
09/06/94	0.32	0.46	11.12	13.37	10.59	19.53
10/06/94						
12/06/94	0.21	0.28	11.58	13.00		18.37
13/06/94	0.28	0.18	13.79	14.04	11.59	24.17
14/06/94	0.25	0.12	14.88	15.88	22.35	33.69
15/06/94	0.28	0.11	12.27	12.10	15.32	34.84
16/06/94	0.91	0.50	12.71	13.76	16.51	42.15
17/06/94						
18/06/94						
19/06/94	0.23	0.16	9.59	10.33	18.95	39.63
20/06/94	0.27	0.19	9.75	10.36	17.73	37.85
21/06/94	0.36	0.29	9.49	10.30	17.80	39.07
22/06/94	0.13	0.20	9.80	11.77	23.39	46.78
23/06/94	0.23	0.20	12.90	13.44	19.42	34.41
24/06/94						
25/06/94						
26/06/94	0.45	0.35	9.67	11.14	26.08	29.65
27/06/94	0.28	0.25	9.10	9.59		
28/06/94	0.27	0.41	11.11	12.33		
29/06/94	0.25	0.24	10.87	12.16	19.07	22.60
30/06/94	0.27	0.24	10.91	11.38		
01/07/94						
02/07/94						
03/07/94	0.33	0.34	8.42	10.22		
04/07/94	0.42	0.25	7.68	8.43		
05/07/94	0.23	0.17	10.78	10.74	22.49	17.25
06/07/94	0.23	0.37	9.89	9.44	24.38	20.09
07/07/94	1.16	0.74	5.16	5.57	22.05	20.05
08/07/94						
09/07/94						
10/07/94	0.17	0.08	9.02	9.02	25.41	25.41
11/07/94	0.12	0.07	9.69	7.37	19.35	19.74
12/07/94	0.14	0.07	3.77	3.31	35.54	34.75
13/07/94	0.17	0.10	4.20	3.57	8.99	10.83
14/07/94	0.11	0.06	1.50	1.04	16.12	20.64
16/07/94						
17/07/94	0.13	0.09	0.42	0.43	17.04	16.85
18/07/94						
19/07/94	0.17	0.09	1.59	1.33	18.35	29.67
20/07/94	0.15	0.08	1.77	2.12	18.87	29.30
Average:	0.31	0.24	8.89	9.60	19.23	26.87
Count:	34	34	34	34	25	26
Maximum:	1.16	0.74	15.10	17.13	35.54	46.78
Minimum:	0.11	0.06	0.42	0.43	8.99	10.83
Standard Deviation:	0.22	0.15	3.97	4.20	5.57	9.53

PERIOD 3.1.6
SUMMARY DATA 6
ALUM TO R1; HIGH ACID DOSE

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAR1	NO3 R1 fAR2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAR1	NO3 R2 fAR2
01/06/94								
02/06/94								
03/06/94								
04/06/94								
06/06/94								
07/06/94								
08/06/94								
09/06/94								
10/06/94								
12/06/94								
13/06/94								
14/06/94								
15/06/94								
16/06/94								
17/06/94								
18/06/94								
19/06/94								
20/06/94								
21/06/94								
22/06/94								
23/06/94								
24/06/94								
25/06/94								
26/06/94								
27/06/94								
28/06/94								
29/06/94								
30/06/94								
01/07/94								
02/07/94								
03/07/94								
04/07/94								
05/07/94								
06/07/94	0.07	3.06	6.94	7.37	0.04	2.63	6.60	7.67
07/07/94								
08/07/94								
09/07/94								
10/07/94	0.04	3.47	9.12	10.19	0.03	2.87	8.59	9.51
11/07/94								
12/07/94								
13/07/94	0.04	2.48	7.89	7.84	0.03	2.42	7.99	7.79
14/07/94								
16/07/94								
17/07/94	0.04	0.05	2.03	1.15	0.09	0.05	2.83	2.01
18/07/94								
19/07/94								
20/07/94	0.06	0.25	4.07	3.87	0.07	0.37	3.97	3.84
Average:	0.05	1.86	6.01	6.08	0.05	1.67	6.00	6.16
Count:	5	5	5	5	5	5	5	5
Maximum:	0.07	3.47	9.12	10.19	0.09	2.87	8.59	9.51
Minimum:	0.04	0.05	2.03	1.15	0.03	0.05	2.83	2.01
Standard Deviation:	0.01	1.43	2.60	3.19	0.02	1.20	2.24	2.78

APPENDIX 5

PERIOD 3.1.6
SUMMARY DATA 7
ALUM TO R1; HIGH ACID DOSE

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAB1	TP R1 fAB2	TP R2 fAN	TP R2 fAX	TP R2 fAB1	TP R2 fAB2
01/06/94								
02/06/94								
03/06/94								
04/06/94								
06/06/94								
07/06/94								
08/06/94								
09/06/94	105.52	45.00	25.14	42.67	111.73	55.86	11.48	24.67
10/06/94								
12/06/94	110.18	48.10	27.31	11.95	130.35	55.86	38.92	22.72
13/06/94								
14/06/94								
15/06/94								
16/06/94	121.62	59.03	37.46	24.81	142.70	81.24	62.59	50.92
17/06/94								
18/06/94								
19/06/94	132.97	75.08	56.28	32.92	118.38	57.40	43.95	20.76
20/06/94								
21/06/94								
22/06/94	137.05	71.79	41.93	28.88	146.84	83.04	61.02	48.46
23/06/94								
24/06/94								
25/06/94								
26/06/94								
27/06/94	124.96	71.57	44.95	32.13	124.15	67.35	43.66	30.02
28/06/94								
29/06/94	110.08	57.63	28.49	19.26	114.13	57.15	33.19	21.37
30/06/94								
01/07/94								
02/07/94								
03/07/94	119.74	62.50	37.35	26.06	110.70	54.22	33.29	21.84
04/07/94								
05/07/94								
06/07/94	133.26	70.18	42.22	29.11	124.26	66.74	38.60	25.18
07/07/94								
08/07/94								
09/07/94								
10/07/94	138.99	73.94	46.45	32.22	142.26	69.52	44.32	29.92
11/07/94								
12/07/94								
13/07/94	110.79	50.06	23.83	11.82	123.12	53.67	29.22	16.41
14/07/94								
16/07/94								
17/07/94	113.98	56.10	27.32	13.58	125.30	61.76	36.38	21.99
18/07/94								
19/07/94								
20/07/94	124.74	60.98	26.74	18.75	138.60	70.93	46.47	31.47
Average:	121.84	61.69	35.81	24.94	127.12	64.21	40.24	28.13
Count:	13	13	13	13	13	13	13	13
Maximum:	138.99	75.08	56.28	42.67	146.84	83.04	62.59	50.92
Minimum:	105.52	45.00	23.83	11.82	110.70	53.67	11.48	16.41
Standard Deviation:	10.84	9.83	9.75	9.02	11.74	9.55	12.64	10.06

■ERIOD 3.1.6
JMMARY DATA 8
=LUM TO R1; HIGH ACID DOSE

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
01/06/94	6.2	0.0	0.0	18.1	
02/06/94	6.2	0.0	0.0	18.7	
03/06/94	6.2	0.0	0.0	18.9	
04/06/94	6.2	0.0	0.0		
06/06/94	6.2	0.0	0.0		
07/06/94	6.2	0.0	0.0	18.5	
08/06/94	6.2	0.0	0.0	18.0	
09/06/94	6.2	0.0	0.0	20.3	
10/06/94	6.2	0.0	0.0	21.7	
12/06/94	6.2	0.0	0.0	21.1	
13/06/94	6.2	0.0	0.0	21.0	
14/06/94	6.2	0.0	0.0	19.8	
15/06/94	6.2	0.0	0.0	18.2	
16/06/94	6.2	0.0	0.0	20.6	
17/06/94	6.2	0.0	0.0	20.2	
18/06/94	6.2	0.0	0.0	20.5	
19/06/94	6.2	0.0	0.0	20.6	
20/06/94	6.2	0.0	0.0	20.0	
21/06/94	6.2	0.0	0.0	19.9	
22/06/94	6.2	0.0	0.0	20.0	
23/06/94	6.2	0.0	0.0	20.7	
24/06/94	6.2	0.0	0.0	21.3	
25/06/94	6.2	0.0	0.0		
26/06/94	6.2	0.0	0.0	20.5	
27/06/94	6.2	0.0	0.0	21.2	
28/06/94	6.2	0.0	0.0	19.8	
29/06/94	6.2	0.0	0.0	20.2	
30/06/94	6.2	0.0	0.0	21.1	
01/07/94	6.2	0.0	0.0	21.4	
02/07/94	6.2	0.0	0.0	21.4	
03/07/94	6.2	0.0	0.0	20.7	
04/07/94	6.2	0.0	0.0	20.8	
05/07/94	6.2	0.0	0.0	20.9	
06/07/94	6.2	0.0	0.0	20.8	
07/07/94	6.2	0.0	0.0	21.3	
08/07/94	6.2	0.0	0.0	20.8	
09/07/94	6.2	0.0	0.0	20.3	
10/07/94	6.2	0.0	0.0		
11/07/94	6.2	0.0	0.0	20.3	
12/07/94	6.2	0.0	0.0	20.9	
13/07/94	6.2	0.0	0.0	21.9	
14/07/94	6.2	0.0	0.0	21.2	
16/07/94	6.2	0.0	0.0	21.4	
17/07/94	6.2	0.0	0.0	21.2	
18/07/94	6.2	0.0	0.0	22.2	
19/07/94	6.2	0.0	0.0	21.5	
20/07/94	6.2	0.0	0.0	21.2	
Average:				20.5	0.0
Count:	47	47	47	43	0
Maximum:	6.2	0.0	0.0	22.2	
Minimum:	6.2	0.0	0.0	18.0	
Standard Deviation:				1.0	0.0

APPENDIX 5

PERIOD 3.2.1
SUMMARY DATA 1
ENHANCED CULTURE REDEVELOPED, NO ACID

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
19/08/94	150	35.5	34.8	16.90	15.40						
20/08/94	150	35.8	36.5	16.70	15.70						
21/08/94	150	35.5	35.5	16.60	14.60	348	24	26	42.9	1.91	2.00
22/08/94	150	34.8	34.8	16.10	15.80	226	24	25	40.9	2.35	1.90
23/08/94	150	34.8	34.8	16.80		288	21	23	42.0	3.23	2.01
24/08/94	150	34.6	37.4	16.00		305	29	34	44.5	2.64	4.20
25/08/94	150	34.1	33.4	16.20	14.00	273	21	23	44.9	2.76	2.74
26/08/94	150	34.1	34.3	16.70	17.60						
27/08/94	150	34.1	34.8	15.90	16.80						
28/08/94	150	35.0	35.0	16.10	16.40						
29/08/94	150	33.8	34.6	20.00	19.10						
30/08/94	150			22.80	22.70	503	22	27	54.3	1.59	2.24
31/08/94	150	35.5	36.5			335	22	24	44.2	1.55	2.58
Average:	150	34.8	35.2	17.23	16.81	325	23	26	44.8	2.29	2.52
Count:	13	12	12	12	10	7	7	7	7	7	7
Maximum:	150	35.8	37.4	22.80	22.70	503	29	34	54.3	3.23	4.20
Minimum:	150	33.8	33.4	15.90	14.00	226	21	23	40.9	1.55	1.90
Standard Deviation:	0	0.6	1.1	1.98	2.40	82	3	4	4.1	0.59	0.74

PERIOD 3.2.1
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
19/08/94							
20/08/94							
21/08/94	45.59	16.27	15.42	29.32	30.17	167.28	149.82
22/08/94	46.77	13.73	14.74	33.04	32.03	167.32	170.89
23/08/94	45.08	16.44	14.24	28.64	30.84	173.41	176.14
24/08/94	45.93	14.57	13.39	31.36	32.54	190.00	190.90
25/08/94	45.36	13.64	13.97	31.72	31.39	173.71	181.49
26/08/94							
27/08/94							
28/08/94							
29/08/94							
30/08/94	58.55	12.99	25.31	45.56	33.24	189.84	179.85
31/08/94	52.14	18.73	33.92	33.41	18.22	196.95	192.07
Average:	48.49	15.20	18.71	33.29	29.78	179.79	177.31
Count:	7	7	7	7	7	7	7
Maximum:	58.55	18.73	33.92	45.56	33.24	196.95	192.07
Minimum:	45.08	12.99	13.39	28.64	18.22	167.28	149.82
Standard Deviation:	4.69	1.89	7.29	5.27	4.81	11.27	13.23

PERIOD 3.2.1
SUMMARY DATA 3
ENHANCED CULTURE REDEVELOPED, NO ACID

	DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
	19/08/94										
	20/08/94										
	21/08/94	101.14	92.72	4340	2624	3637	2251	60.5	61.9	60	63
	22/08/94	100.51	103.19	4468	2684	3761	2271	60.1	60.4	58	61
	23/08/94	103.83	107.30	4456	2668	3838	2338	59.9	60.9	61	60
	24/08/94	112.67	113.63	4678	2774	4012	2388				
	25/08/94	101.25	106.86	4464	2602	3891	2291	58.3	58.9	63	62
	26/08/94										
	27/08/94										
	28/08/94										
	29/08/94										
	30/08/94	111.73	108.24	4878	2871	4443	2674	58.9	60.2		
	31/08/94	121.32	123.38	4729	2913	3761	2416	61.6	64.2	70	77
Average:		107.49	107.90	4573	2734	3906	2376	59.9	61.1	62	65
Count:		7	7	7	7	7	7	6	6	5	5
Maximum:		121.32	123.38	4878	2913	4443	2674	61.6	64.2	70	77
Minimum:		100.51	92.72	4340	2602	3637	2251	58.3	58.9	58	60
Standard Deviation:		7.34	8.67	177	113	245	134	1.1	1.7	4	6

PERIOD 3.2.1
SUMMARY DATA 4
ENHANCED CULTURE REDEVELOPED, NO ACID

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
19/08/94			7.05	7.02	7.15	7.08	0	0		
20/08/94			7.37	7.32	7.60	7.51	0	0		
21/08/94			7.33	7.27	7.57	7.50	0	0		
22/08/94			7.39	7.33	7.65	7.59	0	0		
23/08/94			7.35	7.36	7.63	7.59	0	0		
24/08/94			7.36	7.26	7.60	7.38	0	0		
25/08/94			7.35	7.47	7.58	7.87	0	0		
26/08/94			7.30	7.25	7.54	7.43	0	0		
27/08/94			7.29	7.23	7.51	7.43	0	0		
28/08/94			7.38	7.33	7.67	7.60	0	0		
29/08/94			7.26	7.30	7.42	7.55	0	0		
30/08/94			7.57	7.46	7.87	7.64	0	0		
31/08/94			7.44	7.33	7.68	7.57	0	0		
Average:	0.00	0.00	7.34	7.30	7.57	7.52	0	0	0.0	0.0
Count:	0	0	13	13	13	13	13	13	0	0
Maximum:			7.57	7.47	7.87	7.87	0	0		
Minimum:			7.05	7.02	7.15	7.08	0	0		
Standard Deviation:	0.00	0.00	0.11	0.11	0.16	0.17	0	0	0.0	0.0

PERIOD 3.2.1
SUMMARY DATA 5
ENHANCED CULTURE REDEVELOPED, NO ACID

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
19/08/94						
20/08/94						
21/08/94	0.21	0.11	7.53	9.24	14.67	13.76
22/08/94	0.18	0.18	6.26	8.18	12.17	13.83
23/08/94	0.20	0.12	5.82	6.25	13.64	9.55
24/08/94	0.23	0.14	6.65	9.88	14.35	
25/08/94	0.98	0.85	5.82	7.14	11.70	11.88
26/08/94						
27/08/94						
28/08/94						
29/08/94						
30/08/94	0.52	0.41	1.26	1.35	9.07	18.15
31/08/94	0.01	0.23	4.83	3.52		
Average:	0.33	0.29	5.45	6.51	12.60	13.43
Count:	7	7	7	7	6	5
Maximum:	0.98	0.85	7.53	9.88	14.67	18.15
Minimum:	0.01	0.11	1.26	1.35	9.07	9.55
Standard Deviation:	0.30	0.25	1.88	2.87	1.91	2.83

PERIOD 3.2.1
SUMMARY DATA 6
ENHANCED CULTURE REDEVELOPED, NO ACID

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
19/08/94								
20/08/94								
21/08/94	0.00	1.42	5.41	6.63	0.00	1.07	7.03	8.32
22/08/94								
23/08/94								
24/08/94	0.00	1.39	6.14	6.51	0.00	2.48	10.71	11.03
25/08/94								
26/08/94								
27/08/94								
28/08/94								
29/08/94								
30/08/94								
31/08/94	0.03	0.13	3.19	3.26	0.03	0.20	3.00	3.17
Average:	0.01	0.98	4.91	5.47	0.01	1.25	6.91	7.51
Count:	3	3	3	3	3	3	3	3
Maximum:	0.03	1.42	6.14	6.63	0.03	2.48	10.71	11.03
Minimum:	0.00	0.13	3.19	3.26	0.00	0.20	3.00	3.17
Standard Deviation:	0.01	0.60	1.25	1.56	0.01	0.94	3.15	3.26

PERIOD 3.2.1
SUMMARY DATA 7
ENHANCED CULTURE REDEVELOPED, NO ACID

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
19/08/94								
20/08/94								
21/08/94	111.85	54.91	33.39	17.12	100.83	62.36	34.40	15.59
22/08/94								
23/08/94								
24/08/94	105.07	46.43	26.78	14.24	93.21	49.99	27.28	17.12
25/08/94								
26/08/94								
27/08/94								
28/08/94								
29/08/94								
30/08/94								
31/08/94	135.54	68.40	53.32	26.83	132.46	77.62	41.51	43.54
Average:	117.49	56.58	37.83	19.40	108.83	63.32	34.40	25.42
Count:	3	3	3	3	3	3	3	3
Maximum:	135.54	68.40	53.32	26.83	132.46	77.62	41.51	43.54
Minimum:	105.07	46.43	26.78	14.24	93.21	49.99	27.28	15.59
Standard Deviation:	13.06	9.05	11.28	5.39	16.99	11.30	5.81	12.83

PERIOD 3.2.1
SUMMARY DATA 8
ENHANCED CULTURE REDEVELOPED, NO ACID

	ALUM R1	FERRIC R1	FERROUS R1	T1	T2
DATE	mmolAl/d	mmolFe/d	mmolFe/d	°C	°C
19/08/94	0.0	0.0	0.0	19.7	
20/08/94	0.0	0.0	0.0	18.2	
21/08/94	0.0	0.0	0.0	18.3	
22/08/94	0.0	0.0	0.0	18.8	
23/08/94	0.0	0.0	0.0	19.3	
24/08/94	0.0	0.0	0.0	19.3	
25/08/94	0.0	0.0	0.0	19.6	
26/08/94	0.0	0.0	0.0	20.6	
27/08/94	0.0	0.0	0.0	21.4	
28/08/94	0.0	0.0	0.0	18.8	
29/08/94	0.0	0.0	0.0	18.9	
30/08/94	0.0	0.0	0.0	21.1	
31/08/94	0.0	0.0	0.0	18.3	
Average:				19.4	0.0
Count:	13	13	13	13	0
Maximum:	0.0	0.0	0.0	21.4	
Minimum:	0.0	0.0	0.0	18.2	
Standard Deviation:				1.0	0.0

PERIOD 3.1.6
SUMMARY DATA 1
ALUM TO R1: HIGH ACID DOSE

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
01/06/94	250	32.6	30.2			457	20	19	68.5	2.30	0.94
02/06/94	250	33.1	30.7	17.60	20.70	391	20	18	69.7	3.40	3.90
03/06/94	250	34.1	30.5	20.00	24.40						
04/06/94	250	41.3	38.6								
06/06/94	250	32.9	29.8		21.70	386	13	14	36.6	2.24	
07/06/94	250	33.1		18.10	20.40	467	25	26	43.5		
08/06/94	250	25.4		11.50	11.40	445	18	24	49.7	1.98	2.20
09/06/94	250	29.0	31.2	15.70	15.10	437	25	22	52.5	2.10	1.90
10/06/94	250	31.7	29.8	17.40	18.10						
12/06/94	250	31.4	33.1	14.90	14.30	391	22	23	50.0	2.95	2.96
13/06/94	250	31.7	31.7	14.60	14.10	340	19	19	49.4		
14/06/94	250	30.7	28.6	12.20	12.20	367	12	7	42.2	1.80	1.80
15/06/94	250	30.5	27.1	11.90	12.40	267	16	17	41.8		
16/06/94	250	31.0	28.6	12.80	11.07	384	19	19			
17/06/94	250	31.7	29.0	12.40	12.10						
18/06/94	250	32.2	30.0	13.40	15.20						
19/06/94	250	31.9	32.9	14.03	15.30	439	21	22	56.0		
20/06/94	250	32.2	32.2	13.40	13.40	415	24	23	35.1		
21/06/94	250	31.2	30.5	13.80	14.80	457	20	20	54.2	1.80	2.30
22/06/94	250	30.2	30.2	12.80	13.30	354	16	16	63.9	2.40	2.20
23/06/94	250	32.2	32.9	14.90	16.50	396	23	22	60.2	2.30	2.40
24/06/94	250	31.0	31.0	15.20	13.40						
25/06/94	250	32.2	30.7								
26/06/94	250	15.6	32.6	14.90	18.20	451	18	18	55.1	2.10	2.60
27/06/94	250	34.8	32.6	16.90	20.70	417	21	23	42.9	2.50	2.60
28/06/94	250	32.9	32.6	14.30	16.10	374	19	22	49.2	1.60	
29/06/94	250	33.4	33.1	15.50	14.70	299	18	20	50.8	1.88	2.14
30/06/94	250	32.2	32.2	14.00	14.70	335	18	21	62.4	1.00	1.90
01/07/94	250	32.9	32.9	14.57	14.21						
02/07/94	250	33.1	32.6	14.57	14.30						
03/07/94	250	33.4	33.4	15.05	14.86	345	18	19	55.2	2.30	2.10
04/07/94	250	33.8	31.9	15.34	14.31	347	21	20	57.3	2.19	1.96
05/07/94	250	31.9	31.9	16.02	13.54	320	21	20	58.8	2.10	1.91
06/07/94	250	31.9	31.9	16.50	13.68	340	23	28	47.6	2.04	1.96
07/07/94	250	32.9	32.9	18.49	16.18	410	21	21	48.0	1.54	1.86
08/07/94	250	32.6	32.6	16.23	13.67						
09/07/94	250	33.4	32.4	15.95	13.26						
10/07/94	250	32.4	32.4			392	22	19	57.4	2.06	1.91
11/07/94	250	33.1	31.9	15.68	13.93	348	16	24	35.7	2.15	3.64
12/07/94	250	31.9	31.2	15.62	13.34	422	18	17	50.9	0.94	2.11
13/07/94	250	32.9	31.7	21.50	21.98	403	19	18	52.4	2.79	2.41
14/07/94	250	32.2	31.4	20.35	20.65	522	22	27	35.9	2.74	2.81
16/07/94	250	31.4	31.9	22.26	20.04						
17/07/94	250	33.1	32.9	20.89	19.82	496	85	57	36.1	1.06	5.95
18/07/94	250	31.4	29.8								
19/07/94	250	32.6	32.6			456	23	33	24.7	2.28	2.78
20/07/94	250	31.2	30.5			465	30	26			
Average:	250	31.9	31.6	15.67	15.80	398	22	22	49.8	2.09	2.45
Count:	47	47	45	39	40	34	34	34	32	27	25
Maximum:	250	41.3	38.6	22.26	24.40	522	85	57	69.7	3.40	5.95
Minimum:	250	15.6	27.1	11.50	11.07	267	12	7	24.7	0.94	0.94
Standard Deviation:	0	3.1	1.8	2.61	3.28	57	11	8	10.2	0.55	0.93

PERIOD 3.2.2
SUMMARY DATA 1
LOW ALUM TO R1, NO ACID

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	CORR COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
01/09/94	150	35.3	37.9	19.36	18.43	381	22	28	43.9	2.01	3.06
02/09/94	150			20.98	21.32						
03/09/94	150	35.3	35.0	20.54	23.35						
04/09/94	150	36.5	34.8	18.43	21.94	410	25	29	37.0	2.05	2.16
05/09/94	150	34.6	39.4	17.59	20.87	404	25	28	39.8	2.08	2.56
06/09/94	150			17.10	15.64	457	26	30	33.3	2.04	2.54
07/09/94	150	36.0				432	28	30	33.9	2.83	2.48
08/09/94	150	33.4	25.4	13.19	12.92	442	28	28	41.6	2.45	2.60
09/09/94	150			13.65							
10/09/94	150	34.8	21.8	16.17							
11/09/94	150	34.3	27.4	14.31	14.18	465	24	24	29.0	3.11	2.66
12/09/94	150	35.3	35.8	15.25	15.07	460	20	22	38.0	1.28	3.18
13/09/94	150	33.6	33.6	16.43	15.61	532	23	23	47.0	3.59	2.86
14/09/94	150	33.8	35.0	15.92		503	26	23	42.0	3.50	3.18
15/09/94	150	34.1	35.0	20.22	19.70	454	27	27	46.0	3.35	3.69
16/09/94	150	34.6	34.1	21.65	21.44						
17/09/94	150	34.8	36.2	15.68	28.37						
18/09/94	150	36.0	37.2	18.74	21.00	657	23	22	41.0	3.16	2.29
19/09/94	150	33.6	35.8	23.26	26.43	510	27	24	40.0	2.99	2.95
20/09/94	150	34.6	35.3	24.58	25.78	480	27	24	58.7	2.10	2.99
21/09/94	150	35.0	34.6	22.48	24.41	548	27	24	36.4	3.11	3.10
22/09/94	150	35.0	37.4	21.99	28.36	499	26	26	36.0	3.40	2.79
23/09/94	150	34.1	37.0	21.49	21.96						
24/09/94	150	35.8	37.2								
25/09/94	150	34.3	37.0	21.34	17.62	493	22	24	43.7	2.16	4.69
26/09/94	150	35.3	37.2	21.73	23.58	468	25	26	38.8	2.90	2.75
Average:	150	34.8	34.6	18.84	20.86	478	25	26	40.3	2.67	2.92
Count:	26	23	22	24	21	18	18	18	18	18	18
Maximum:	150	36.5	39.4	24.58	28.37	657	28	30	58.7	3.59	4.69
Minimum:	150	33.4	21.8	13.19	12.92	381	20	22	29.0	1.28	2.16
Standard Deviation:	0	0.8	4.2	3.18	4.42	61	2	3	6.3	0.64	0.56

PERIOD 3.2.2
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
01/09/94	50.63	19.95	41.08	30.68	9.55	179.15	159.96
02/09/94							
03/09/94							
04/09/94	53.82	17.94	31.35	35.88	22.47	197.74	164.75
05/09/94	55.33	26.99	32.86	28.34	22.47	180.20	152.90
06/09/94	51.81	26.66	33.53	25.15	18.28	172.36	159.93
07/09/94	50.97	20.62	30.85	30.35	20.12	194.45	173.35
08/09/94	58.59	27.18	42.48	31.41	16.11	182.29	144.48
09/09/94							
10/09/94							
11/09/94	51.26	28.97		22.29		170.49	
12/09/94	52.91	32.62	39.92	20.29	12.99	180.26	142.91
13/09/94	53.07	40.90	39.11	12.17	13.96	171.26	136.00
14/09/94	52.26	33.11	33.27	19.15	18.99	158.66	140.37
15/09/94	54.95	29.45	26.49	25.50	28.46	175.97	138.85
16/09/94							
17/09/94							
18/09/94	56.10	39.81	31.26	16.29	24.84	169.45	162.48
19/09/94	53.47	19.58	17.44	33.89	36.03	167.61	150.10
20/09/94	51.33	14.64	13.66	36.69	37.67	171.70	163.33
21/09/94	51.49	17.27	16.29	34.22	35.20	168.75	158.79
22/09/94	52.73	15.86	15.20	36.87	37.53	174.48	177.09
23/09/94							
24/09/94							
25/09/94	51.57	21.34	24.33	30.23	27.24	194.64	163.88
26/09/94	52.73	18.35	22.34	34.38	30.39	185.93	160.24
Average:	53.06	25.07	28.91	27.99	24.25	177.52	155.85
Count:	18	18	17	18	17	18	17
Maximum:	58.59	40.90	42.48	36.87	37.67	197.74	177.09
Minimum:	50.63	14.64	13.66	12.17	9.55	158.66	136.00
Standard Deviation:	2.01	7.73	9.11	7.20	8.68	10.15	11.69

PERIOD 3.2.2
SUMMARY DATA 3
LOW ALUM TO R1, NO ACID

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
01/09/94	108.24	102.15	4879	2948	4300	2746	60.4	63.9	70	67
02/09/94										
03/09/94										
04/09/94	119.95	106.59	4906	2976	4184	2707	60.7	64.7	71	76
05/09/94	106.03	95.28	5202	3061	4540	2829	58.8	62.3	73	75
06/09/94	101.91	100.63	5182	3064	4382	2757	59.1	62.9	75	78
07/09/94	112.27	105.43	5376	3104	4405	2679	57.7	60.8	74	79
08/09/94	105.56	90.41	5319	3080	4230	2647	57.9	62.6	79	85
09/09/94										
10/09/94										
11/09/94	102.83		5017	3026	3666	2404	60.3	65.6		
12/09/94	104.88	93.98	4859	2827	3730	2453	58.2	65.8	91	91
13/09/94	102.94	89.35	4966	2985	3796	2494	60.1	65.7	85	90
14/09/94	94.52	91.82	5031	2997	3871	2532	59.6	65.4	89	93
15/09/94	104.54	90.55	4863	2889	3852	2512	59.4	65.2	88	88
16/09/94										
17/09/94										
18/09/94	103.34	106.41	4983	3039	4190	2744	61.0	65.5	88	91
19/09/94	102.83	97.00	5040	3092	4274	2762	61.3	64.6	83	89
20/09/94	103.51	102.13	5245	3162	4446	2780	60.3	62.5	86	85
21/09/94	108.27	99.27	5151	3305	4458	2787	64.2	62.5	85	85
22/09/94	101.09	109.04	5183	3003	4455	2743	57.9	61.6	85	85
23/09/94										
24/09/94										
25/09/94	119.76	106.31	4999	3076	4538	2944	61.5	64.9	90	84
26/09/94	111.22	101.42	5159	3086	4675	2959	59.8	63.3	85	79
Average:	106.32	99.28	5076	3040	4222	2693	59.9	63.9	82	84
Count:	18	17	18	18	18	18	18	18	17	17
Maximum:	119.95	109.04	5376	3305	4675	2959	64.2	65.8	91	93
Minimum:	94.52	89.35	4859	2827	3666	2404	57.7	60.8	70	67
Standard Deviation:	6.14	6.27	153	101	301	154	1.6	1.5	7	7

PERIOD 3.2.2
SUMMARY DATA 4
LOW ALUM TO R1, NO ACID

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
01/09/94			7.28	7.18	7.47	7.31	0	0		
02/09/94			7.24	7.21	7.46	7.39	0	0		
03/09/94			7.20	7.22	7.45	7.41	0	0		
04/09/94			7.22	7.27	7.48	7.47	0	0		
05/09/94			7.24	7.25	7.48	7.46	0	0		
06/09/94			7.26	7.30	7.48	7.49	0	0		
07/09/94			7.28	7.30	7.52	7.50	0	0		
08/09/94			7.23	7.27	7.44	7.40	0	0		
09/09/94			7.48	7.36	7.47	7.40	0	0		
10/09/94			7.15	7.15	7.28	7.31	0	0		
11/09/94			7.20	7.16	7.37	7.25	0	0		
12/09/94			7.33	7.36	7.53	7.54	0	0		
13/09/94			7.34	7.34	7.52	7.52	0	0		
14/09/94			7.28	7.39	7.42	7.53	0	0		
15/09/94			7.27	7.34	7.43	7.50	0	0		
16/09/94			7.33	7.28	7.45	7.52	0	0		
17/09/94			7.27	7.28	7.58	7.57	0	0		
18/09/94			7.33	7.28	7.45	7.52	0	0		
19/09/94			7.33	7.28	7.55	7.62	0	0		
20/09/94			7.26	7.25	7.51	7.54	0	0		
21/09/94			7.27	7.28	7.52	7.53	0	0		
22/09/94			7.27	7.26	7.58	7.56	0	0		
23/09/94			7.27	7.24	7.51	7.51	0	0		
24/09/94			7.20	7.24	7.44	7.44	0	0		
25/09/94			7.43	7.48	7.71	7.84	0	0		
26/09/94			7.16	7.21	7.44	7.50	0	0		
Average:	0.00	0.00	7.27	7.28	7.48	7.49	0	0	0.0	0.0
Count:	0	0	26	26	26	26	26	26	0	0
Maximum:			7.48	7.48	7.71	7.84	0	0		
Minimum:			7.15	7.15	7.28	7.25	0	0		
Standard Deviation:	0.00	0.00	0.07	0.07	0.08	0.11	0	0	0.0	0.0

PERIOD 3.2.2
SUMMARY DATA 5
LOW ALUM TO R1, NO ACID

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
01/09/94	0.05	0.48	3.79	4.06	19.68	39.90
02/09/94						
03/09/94						
04/09/94	0.05	0.01	3.59	3.43	17.13	26.70
05/09/94	0.00	0.00	3.39	2.59	23.30	29.70
06/09/94	0.00	0.00	2.88	2.64	24.18	31.65
07/09/94	0.00	0.00	2.56	2.41	18.93	29.29
08/09/94	0.00	0.00	2.54	2.74	25.18	41.07
09/09/94						
10/09/94						
11/09/94	0.26	0.19	1.45	1.29	25.80	
12/09/94	0.64	0.53	1.17	0.83	27.03	32.36
13/09/94	0.73	0.54	3.20	2.63	38.13	37.96
14/09/94	0.49	0.53	2.80	1.95	31.11	32.84
15/09/94	0.52	0.36	4.18	3.84	26.91	24.98
16/09/94						
17/09/94						
18/09/94	0.38	0.38	2.08	1.11	38.53	30.79
19/09/94	0.37	0.30	1.83	1.02	17.40	15.96
20/09/94	0.45	0.32	3.19	2.89	12.58	11.84
21/09/94	0.49	0.30	3.27	3.43		
22/09/94	0.31	0.31	2.33	1.74	12.74	13.11
23/09/94						
24/09/94						
25/09/94	0.32	0.32	2.75	2.69	18.93	22.75
26/09/94	0.40	0.32	3.41	2.42	16.40	20.45
Average:	0.30	0.27	2.80	2.43	23.17	27.58
Count:	18	18	18	18	17	16
Maximum:	0.73	0.54	4.18	4.06	38.53	41.07
Minimum:	0.00	0.00	1.17	0.83	12.58	11.84
Standard Deviation:	0.23	0.19	0.78	0.93	7.47	8.66

PERIOD 3.2.2
SUMMARY DATA 6
LOW ALUM TO R1, NO ACID

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
01/09/94								
02/09/94								
03/09/94								
04/09/94	0.05	0.25	3.08	2.83	0.05	0.03	3.03	2.88
05/09/94								
06/09/94								
07/09/94	0.00	0.13	2.17	2.28	0.00	0.98	2.34	2.61
08/09/94								
09/09/94								
10/09/94								
11/09/94	0.00	0.24	1.75	1.68	0.04	0.14	1.55	1.31
12/09/94								
13/09/94								
14/09/94	0.03	1.88	6.78	3.60	0.05	2.64	7.52	2.60
15/09/94								
16/09/94								
17/09/94								
18/09/94	0.00	0.00	1.74	1.87	0.00	0.00	1.29	1.08
19/09/94								
20/09/94								
21/09/94	0.02	0.05	3.84	3.75	0.03	0.03	4.24	4.24
22/09/94								
23/09/94								
24/09/94								
25/09/94	0.00	0.35	1.63	1.64	0.00	0.43	1.73	1.74
26/09/94								
Average:	0.01	0.41	3.00	2.52	0.02	0.61	3.10	2.35
Count:	7	7	7	7	7	7	7	7
Maximum:	0.05	1.88	6.78	3.75	0.05	2.64	7.52	4.24
Minimum:	0.00	0.00	1.63	1.64	0.00	0.00	1.29	1.08
Standard Deviation:	0.02	0.61	1.72	0.82	0.02	0.89	2.03	1.00

PERIOD 3.2.2
SUMMARY DATA 7
LOW ALUM TO R1, NO ACID

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
01/09/94								
02/09/94								
03/09/94								
04/09/94	140.94	73.77	53.32	35.71	107.30	80.81	58.68	45.94
05/09/94								
06/09/94								
07/09/94	117.36	65.05	41.91	28.67	97.24	57.34	46.11	39.57
08/09/94								
09/09/94								
10/09/94								
11/09/94	119.71	60.10	47.36	34.50				
12/09/94								
13/09/94								
14/09/94	107.11	58.59	40.25	31.00	102.24	59.89	42.52	32.95
15/09/94								
16/09/94								
17/09/94								
18/09/94	120.92	70.09	48.04	35.87	111.87	64.99	43.93	30.11
19/09/94								
20/09/94								
21/09/94	127.68	66.23	39.98	26.32	125.03	65.64	41.13	25.99
22/09/94								
23/09/94								
24/09/94								
25/09/94	127.46	67.18	43.26	28.32	125.80	67.68	45.75	32.63
26/09/94								
Average:	123.03	65.86	44.87	31.48	111.58	66.06	46.35	34.53
Count:	7	7	7	7	6	6	6	6
Maximum:	140.94	73.77	53.32	35.87	125.80	80.81	58.68	45.94
Minimum:	107.11	58.59	39.98	26.32	97.24	57.34	41.13	25.99
Standard Deviation:	9.73	4.91	4.54	3.61	10.76	7.48	5.78	6.51

PERIOD 3.2.2
SUMMARY DATA 8
LOW ALUM TO R1, NO ACID

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
01/09/94	6.2	0.0	0.0	18.0	
02/09/94	6.2	0.0	0.0	18.7	
03/09/94	6.2	0.0	0.0	19.4	
04/09/94	6.2	0.0	0.0	19.1	
05/09/94	6.2	0.0	0.0	18.8	
06/09/94	6.2	0.0	0.0	17.9	
07/09/94	6.2	0.0	0.0		
08/09/94	6.2	0.0	0.0	17.0	
09/09/94	6.2	0.0	0.0	17.1	
10/09/94	6.2	0.0	0.0	16.5	
11/09/94	6.2	0.0	0.0	17.3	
12/09/94	6.2	0.0	0.0	17.9	
13/09/94	6.2	0.0	0.0	16.6	
14/09/94	6.2	0.0	0.0	16.3	
15/09/94	6.2	0.0	0.0	18.8	
16/09/94	6.2	0.0	0.0	18.9	
17/09/94	6.2	0.0	0.0	17.9	
18/09/94	6.2	0.0	0.0	17.6	
19/09/94	6.2	0.0	0.0	16.8	
20/09/94	6.2	0.0	0.0	19.8	
21/09/94	6.2	0.0	0.0	19.4	
22/09/94	6.2	0.0	0.0	20.9	
23/09/94	6.2	0.0	0.0	20.9	
24/09/94	6.2	0.0	0.0		
25/09/94	6.2	0.0	0.0	20.3	
26/09/94	6.2	0.0	0.0	20.5	
Average:				18.4	0.0
Count:	26	26	26	24	0
Maximum:	6.2	0.0	0.0	20.9	
Minimum:	6.2	0.0	0.0	16.3	
Standard Deviation:				1.4	0.0

PERIOD 3.2.3
SUMMARY DATA 1
LOW ALUM TO R1 AEROBIC, WITH ACID

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	CORR COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
27/09/94	150	34.3	35.8	17.97	18.17	447	24	25	41.7	2.83	2.95
28/09/94	150	34.6	37.0	16.22	16.82	410	20	21	43.2	2.01	3.51
29/09/94	150	34.8	36.2	16.55	18.14	417	24	22	40.7	2.39	2.56
30/09/94	150	34.8	36.2	17.69	18.59						
01/10/94	150	36.0	37.4	17.49	21.35						
02/10/94	150	36.0	37.2	17.83	18.08	349	25	23	23.5	3.00	2.39
03/10/94	150			16.31	17.57	395	26	22	52.4	2.83	3.99
04/10/94	150	35.0	36.2	16.63	16.59	461	25	21	50.9	3.61	3.31
05/10/94	150	34.6	36.7	17.16	18.67	503	27	25	45.9	1.11	2.53
06/10/94	150	35.8	37.7	18.42	19.26	507	30	27	35.5	3.33	3.89
07/10/94	150	34.6	36.0	18.26	19.84						
08/10/94	150	36.0	37.4	19.20	20.95						
09/10/94	150	36.0	37.0	18.69	20.80						
10/10/94	150	36.0	37.2	14.40	14.46	329	25	23	26.4	2.16	2.00
12/10/94	150	35.3	36.0	15.78	17.26	326	21	22	25.1	3.80	2.59
13/10/94	150	36.0	37.2	14.21	14.93	323	21	20	28.0	2.83	2.74
14/10/94	150	35.5	36.2	14.54	15.48						
15/10/94	150	36.7	37.2	14.83							
16/10/94	150	35.5	36.7	14.41	14.90	310	21	21	36.0	2.75	3.20
17/10/94	150	36.7	37.2	14.01	14.42	295	25	24	53.5	5.74	5.29
18/10/94	150	36.7	37.9	15.44	16.82	412	24	23	67.3	4.95	6.46
20/10/94	150	34.1	35.8	19.80	19.06	402	29	37	45.0	2.75	4.63
21/10/94	150	35.3	35.3	16.52	17.43						
22/10/94	150	35.8	34.3	16.32	16.13						
23/10/94	150	35.5	34.6	16.47	16.07	377	24	26	28.5	3.29	3.55
24/10/94	150	35.8	34.3	17.31	17.09	385	25	23	25.0	2.60	1.63
25/10/94	150	35.5	36.2	16.36	16.51	371	19	22	30.8	2.40	2.91
26/10/94	150	34.8	36.0	15.31	16.65	396	19	20	26.1	2.83	2.20
27/10/94	150	36.0	37.4	15.43	15.70	375	18	19	46.5	6.03	7.81
28/10/94	150	35.8	36.5	13.92	13.70						
29/10/94	150	37.0	37.0	15.53	14.45						
30/10/94	150	36.0	37.2	13.56	13.44	317	18	16	33.5	6.56	
31/10/94	250	35.5	36.0			313	19	14	22.0	3.10	1.68
01/11/94	150	36.0	36.7	13.30	13.20	366	18	19	28.1	7.01	10.41
02/11/94	150	36.5	36.7	13.00	13.90	320	20	17	59.4	6.64	2.84
03/11/94	150	35.5	37.0	11.60	13.80	352	24	23	37.0	8.19	2.50
04/11/94	150	36.2	37.0	15.50	13.90						
05/11/94	150	35.5	36.7	17.20	14.90						
06/11/94	150	35.5	36.7	16.50	15.40	347	26	22	26.0	2.15	6.09
07/11/94	150	36.0	36.7	17.80	16.20	418	23	22	55.8	5.80	1.95
Average:	153	35.6	36.5	16.09	16.60	379	23	22	38.3	3.80	3.68
Count:	40	39	39	39	38	27	27	27	27	27	26
Maximum:	250	37.0	37.9	19.80	21.35	507	30	37	67.3	8.19	10.41
Minimum:	150	34.1	34.3	11.60	13.20	295	18	14	22.0	1.11	1.63
Standard Deviation:	16	0.7	0.8	1.81	2.17	56	3	4	12.3	1.81	2.02

PERIOD 3.2.3
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
27/09/94	52.40	31.80	35.62	20.60	16.78	191.07	170.77
28/09/94	52.56	47.08	47.91	5.48	4.65	189.52	169.78
29/09/94	54.23	28.78	31.44	25.45	22.79	169.02	157.39
30/09/94							
01/10/94							
02/10/94	47.91	7.65	9.32	40.26	38.59	191.14	177.75
03/10/94	50.24	13.14	17.47	37.10	32.77	203.42	151.05
04/10/94	51.24	14.14	18.13	37.10	33.11	193.05	180.87
05/10/94	50.41	22.13	24.95	28.28	25.46	207.68	184.59
06/10/94	52.57	22.18	23.99	30.39	28.58	196.61	187.79
07/10/94							
08/10/94							
09/10/94							
10/10/94	46.99	22.51	26.29	24.48	20.70	188.79	178.10
12/10/94	46.99	28.91	13.80	18.08	33.19	247.36	170.28
13/10/94	50.14	31.40	21.37	18.74	28.77	201.40	173.81
14/10/94							
15/10/94							
16/10/94	46.52	28.93	32.88	17.59	13.64	234.77	185.59
17/10/94	47.67	37.81	35.67	9.86	12.00	204.80	169.87
18/10/94	51.95	31.89	35.67	20.06	16.28	188.67	176.54
20/10/94	51.96	11.21	22.83	40.75	29.13	223.35	134.66
21/10/94							
22/10/94							
23/10/94	50.65	13.66	16.12	36.99	34.53	220.67	186.38
24/10/94	49.67	13.17	18.90	36.50	30.77	210.35	189.03
25/10/94	49.01	16.94	22.34	32.07	26.67	216.08	190.98
26/10/94	51.96	25.77	29.70	26.19	22.26	245.34	210.69
27/10/94	52.69	21.93	23.07	30.76	29.62	205.71	188.77
28/10/94							
29/10/94							
30/10/94	45.66	12.76	16.04	32.90	29.62	219.05	185.81
31/10/94	45.49	18.82	22.09	26.67	23.40	241.59	189.78
01/11/94	48.44	26.84	32.24	21.60	16.20	229.19	200.71
02/11/94	46.80	20.62	24.38	26.18	22.42	268.12	218.68
03/11/94	49.34	24.43	29.02	24.91	20.32	239.09	214.11
04/11/94							
05/11/94							
06/11/94	49.34	22.79	25.90	26.55	23.44	258.95	244.86
07/11/94	48.36	19.18	25.57	29.18	22.79	241.80	209.23
Average:	49.67	22.83	25.29	26.84	24.39	215.80	185.11
Count:	27	27	27	27	27	27	27
Maximum:	54.23	47.08	47.91	40.75	38.59	268.12	244.86
Minimum:	45.49	7.65	9.32	5.48	4.65	169.02	134.66
Standard Deviation:	2.37	8.76	8.10	8.56	7.66	24.43	21.77

PERIOD 3.2.3
SUMMARY DATA 3
LOW ALUM TO R1 AEROBIC, WITH ACID

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
27/09/94	115.38	108.81	4930	2977	4388	2796	60.4	63.7	89	84
28/09/94	116.23	110.40	4908	3010	4415	2871	61.3	65.0	88	86
29/09/94	102.54	100.74	5062	3071	4492	2875	60.7	64.0	89	82
30/09/94										
01/10/94										
02/10/94	111.20	110.56	5356	3116	4815	2995	58.2	62.2	80	75
03/10/94	105.01	90.17	5418	2797	4741	2830	51.6	59.7	79	76
04/10/94	110.14	106.73	5332	3042	4879	2879	57.1	59.0	79	74
05/10/94	117.20	108.80	5394	3044	4832	2848	56.4	58.9	78	77
06/10/94	112.61	114.67	5325	3050	4900	2992	57.3	61.1	77	76
07/10/94										
08/10/94										
09/10/94										
10/10/94	113.24	101.81	5165	3098	5390	3081	60.0	57.2	77	67
12/10/94	145.63	96.19	4693	2763	5192	2933	58.9	56.5	87	75
13/10/94	112.13	103.65	5234	2914	4774	2847	55.7	59.6	78	80
14/10/94										
15/10/94										
16/10/94	134.84	115.33	4950	2843	4419	2746	57.4	62.1	77	81
17/10/94	116.87	103.79	4642	2649	4419	2700	57.1	61.1		
18/10/94	105.46	102.50	5113	2858	4571	2654	55.9	58.1	70	83
20/10/94	135.66	75.90	3673	2231	4797	2704	60.7	56.4	103	79
21/10/94										
22/10/94										
23/10/94	122.46	109.66	4804	2666	4514	2656	55.5	58.8	77	86
24/10/94	113.32	109.70	4917	2649	4632	2688	53.9	58.0	73	78
25/10/94	117.91	113.03	4781	2609	4481	2652	54.6	59.2	75	85
26/10/94	132.87	125.39	4982	2698	4535	2699	54.2	59.5	74	82
27/10/94	112.35	110.48	4865	2657	4562	2670	54.6	58.5	74	79
28/10/94										
29/10/94										
30/10/94	113.61	105.97	5171	2682	4648	2651	51.9	57.0		
31/10/94	128.36	110.69	4730	2513	4583	2673	53.1	58.3	76	79
01/11/94	118.81	114.39	4917	2549	4578	2609	51.8	57.0	71	79
02/11/94	137.71	123.99	5181	2661	4725	2679	51.4	56.7	66	76
03/11/94	120.66	117.30	4918	2482	4514	2473	50.5	54.8	73	75
04/11/94										
05/11/94										
06/11/94	137.52	143.83	4363	2317	4183	2457	53.1	58.7	83	86
07/11/94	125.78	117.81	4731	2461	4550	2562	52.0	56.3	72	75
Average:	119.83	109.34	4946	2756	4649	2749	55.8	59.2	79	79
Count:	27	27	27	27	27	27	27	27	25	25
Maximum:	145.63	143.83	5418	3116	5390	3081	61.3	65.0	103	86
Minimum:	102.54	75.90	3673	2231	4183	2457	50.5	54.8	66	67
Standard Deviation:	11.05	11.90	356	241	248	152	3.2	2.5	8	5

PERIOD 3.2.3
SUMMARY DATA 4
LOW ALUM TO R1 AEROBIC, WITH ACID

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
27/09/94			7.24	7.24	7.48	7.42	10	10		
28/09/94			7.18	7.20	7.38	7.47	10	10		
29/09/94			7.19	7.18	7.41	7.44	10	10		
30/09/94			7.30	7.25	7.54	7.55	10	10		
01/10/94			7.34	7.37	7.58	7.63	10	10		
02/10/94			7.40	7.37	7.65	7.65	10	10		
03/10/94			7.55	7.57	7.79	7.90	10	10		
04/10/94			7.45	7.44	7.67	7.70	10	10		
05/10/94			7.42	7.45	7.63	7.71	10	10		
06/10/94			7.34	7.32	7.59	7.62	10	10		
07/10/94			7.34	7.34	7.58	7.63	10	10		
08/10/94			7.39	7.40	7.65	7.64	10	10		
09/10/94			7.49	7.44	7.71	7.71	10	10		
10/10/94			7.38	7.31	7.61	7.61	10	10		
12/10/94			7.59	6.90	7.83	6.97	10	10		
13/10/94			7.32	7.30	7.52	7.59	10	10		
14/10/94			7.28	7.31	7.46	7.54	10	10		
15/10/94			7.41	7.34	7.59	7.60	10	10		
16/10/94			7.39	7.32	7.57	7.53	10	10		
17/10/94			7.38	7.27	7.55	7.54	10	10		
18/10/94			7.27	7.23	7.43	7.46	10	10		
20/10/94			7.01	7.04	7.03	7.05	10	10		
21/10/94			7.43	7.33	7.61	7.63	10	10		
22/10/94			7.44	7.43	7.68	7.74	10	10		
23/10/94			7.45	7.43	7.69	7.74	10	10		
24/10/94			7.36	7.30	7.56	7.60	10	10		
25/10/94			7.40	7.33	7.61	7.62	10	10		
26/10/94			7.36	7.28	7.56	7.58	10	10		
27/10/94			7.32	7.32	7.55	7.61	10	10		
28/10/94			7.37	7.37	7.56	7.65	10	10		
29/10/94			7.44	7.44	7.64	7.68	10	10		
30/10/94			7.42	7.41	7.66	7.68	10	10		
31/10/94			7.45	7.40	7.65	7.68	10	10		
01/11/94			7.39	7.39	7.52	7.64	10	10		
02/11/94			7.34	7.33	7.55	7.61	10	10		
03/11/94			7.38	7.35	7.59	7.62	10	10		
04/11/94			7.38	7.31	7.61	7.61	10	10		
05/11/94			7.40	7.38	7.55	7.61	10	10		
06/11/94			7.35	7.29	7.56	7.60	10	10		
07/11/94			7.34	7.30	7.56	7.63	10	10		
Average:	0.00	0.00	7.37	7.32	7.57	7.59	10	10	0.0	0.0
Count:	0	0	40	40	40	40	40	40	0	0
Maximum:			7.59	7.57	7.83	7.90	10	10		
Minimum:			7.01	6.90	7.03	6.97	10	10		
Standard Deviation:	0.00	0.00	0.10	0.11	0.12	0.16	0	0	0.0	0.0

PERIOD 3.2.3
SUMMARY DATA 5
LOW ALUM TO R1 AEROBIC, WITH ACID

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
27/09/94	0.57	0.39	4.23	3.27	30.29	33.88
28/09/94	0.56	0.38	8.71	8.46	46.03	47.51
29/09/94	0.34	0.21	7.97	7.39	25.52	29.27
30/09/94						
01/10/94						
02/10/94	0.40	0.28	7.41	5.89	6.62	8.65
03/10/94	0.41	0.30	8.62	7.72	10.83	16.54
04/10/94	0.40	0.30	9.43	8.47	13.45	17.59
05/10/94	0.45	0.30	9.66	7.80	20.75	23.50
06/10/94	0.35	0.34	7.61	6.51	18.59	21.43
07/10/94						
08/10/94						
09/10/94						
10/10/94	0.72	0.56	8.92	7.24	20.82	24.47
12/10/94	0.50	0.31	8.56	6.38	27.65	12.81
13/10/94	0.48	0.25	8.57	4.84	29.92	19.77
14/10/94						
15/10/94						
16/10/94	0.52	0.37	8.48	5.65		31.81
17/10/94	0.48	0.35	7.56	5.39	34.17	33.83
18/10/94	0.54	0.37	10.49	7.72	30.00	34.20
20/10/94	0.51	0.94	12.15	6.75	8.57	19.46
21/10/94						
22/10/94						
23/10/94	0.31	0.30	9.20	6.67	11.79	13.93
24/10/94	0.47	0.36	8.81	6.87	9.71	13.78
25/10/94	0.35	0.38	10.07	8.13	13.69	18.50
26/10/94	0.89	0.61	8.43	6.01	24.16	27.69
27/10/94	0.81	0.53	6.03	3.09	19.84	
28/10/94						
29/10/94						
30/10/94	0.81	0.49	4.03	2.92	11.20	14.90
31/10/94	0.66	0.40	5.64	3.88	16.67	21.47
01/11/94	0.67	0.45	4.27	3.64	19.00	22.96
02/11/94	0.72	0.34	2.95	2.95	17.68	20.90
03/11/94	1.01	0.68	5.44	3.09	20.95	24.79
04/11/94						
05/11/94						
06/11/94	1.10	0.83	5.90	3.50	21.61	25.60
07/11/94	0.46	0.39	6.80	5.91	17.83	21.48
Average:	0.57	0.42	7.63	5.78	20.28	23.10
Count:	27	27	27	27	26	26
Maximum:	1.10	0.94	12.15	8.47	46.03	47.51
Minimum:	0.31	0.21	2.95	2.92	6.62	8.65
Standard Deviation:	0.20	0.17	2.16	1.84	8.86	8.28

PERIOD 3.2.3
SUMMARY DATA 6
LOW ALUM TO R1 AEROBIC, WITH ACID

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
27/09/94								
28/09/94	0.09	3.62	8.03	8.16	0.04	3.31	7.94	8.03
29/09/94								
30/09/94								
01/10/94								
02/10/94	0.05	2.92	7.59	7.86	0.09	2.41	7.05	8.04
03/10/94								
04/10/94								
05/10/94	0.05	3.58	8.95	9.13	0.07	2.48	7.45	7.53
06/10/94								
07/10/94								
08/10/94								
09/10/94								
10/10/94								
12/10/94	0.06	3.67	8.44	8.81	0.04	1.06	4.44	4.44
13/10/94								
14/10/94								
15/10/94								
16/10/94	0.08	4.06	8.39	8.65	0.07	2.35	5.83	6.09
17/10/94								
18/10/94								
20/10/94								
21/10/94								
22/10/94								
23/10/94	0.10	3.60	9.20	9.29	0.05	2.49	7.09	6.75
24/10/94								
25/10/94								
26/10/94	0.03	1.92	6.39	6.55	0.06	1.04	3.64	3.81
27/10/94								
28/10/94								
29/10/94								
30/10/94								
31/10/94								
01/11/94								
02/11/94	0.03	0.73	2.63	2.63	0.03	0.63	2.45	2.47
03/11/94								
04/11/94								
05/11/94								
06/11/94								
07/11/94	0.12	1.63	6.80	7.69	0.13	1.34	6.44	7.07
Average:	0.07	2.86	7.38	7.64	0.06	1.90	5.81	6.03
Count:	9	9	9	9	9	9	9	9
Maximum:	0.12	4.06	9.20	9.29	0.13	3.31	7.94	8.04
Minimum:	0.03	0.73	2.63	2.63	0.03	0.63	2.45	2.47
Standard Deviation:	0.03	1.09	1.89	1.94	0.03	0.85	1.78	1.89

PERIOD 3.2.3
SUMMARY DATA 7
LOW ALUM TO R1 AEROBIC, WITH ACID

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
27/09/94								
28/09/94	119.16	67.61	49.41	37.45	116.67	69.00	50.90	39.11
29/09/94								
30/09/94								
01/10/94								
02/10/94	101.50	42.76	19.63	7.49	102.31	46.91	22.96	10.81
03/10/94								
04/10/94								
05/10/94	133.92	69.87	44.75	29.45	133.92	71.70	48.25	32.61
06/10/94								
07/10/94								
08/10/94								
09/10/94								
10/10/94								
12/10/94	110.07	61.12	41.07	31.05	101.86	49.62	26.94	14.62
13/10/94								
14/10/94								
15/10/94								
16/10/94	101.93	58.85	39.13	29.59	128.23	65.59	45.54	31.89
17/10/94								
18/10/94								
20/10/94								
21/10/94								
22/10/94								
23/10/94	104.32	47.87	25.45	13.50	106.78	49.83	28.88	16.28
24/10/94								
25/10/94								
26/10/94	124.78	62.10	37.72	26.76	125.60	65.21	41.81	29.86
27/10/94								
28/10/94								
29/10/94								
30/10/94								
31/10/94								
01/11/94								
02/11/94	99.82	45.82	26.35	16.69	99.82	53.02	32.73	23.89
03/11/94								
04/11/94								
05/11/94								
06/11/94								
07/11/94	131.96	60.82	34.10	17.87	118.85	61.97	36.56	22.29
Average:	114.16	57.42	35.29	23.32	114.89	59.21	37.17	24.60
Count:	9	9	9	9	9	9	9	9
Maximum:	133.92	69.87	49.41	37.45	133.92	71.70	50.90	39.11
Minimum:	99.82	42.76	19.63	7.49	99.82	46.91	22.96	10.81
Standard Deviation:	12.80	9.12	9.23	9.24	11.99	8.86	9.42	8.95

PERIOD 3.2.3
SUMMARY DATA 8
LOW ALUM TO R1 AEROBIC, WITH ACID

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
27/09/94	6.2	0.0	0.0	21.6	
28/09/94	6.2	0.0	0.0	16.9	
29/09/94	6.2	0.0	0.0	16.4	
30/09/94	6.2	0.0	0.0	17.6	
01/10/94	6.2	0.0	0.0	17.2	
02/10/94	6.2	0.0	0.0	18.1	
03/10/94	6.2	0.0	0.0	17.7	
04/10/94	6.2	0.0	0.0	17.6	
05/10/94	6.2	0.0	0.0	18.4	
06/10/94	6.2	0.0	0.0	17.9	
07/10/94	6.2	0.0	0.0	17.5	
08/10/94	6.2	0.0	0.0	18.0	
09/10/94	6.2	0.0	0.0	18.8	
10/10/94	6.2	0.0	0.0	16.4	
12/10/94	6.2	0.0	0.0	18.5	
13/10/94	6.2	0.0	0.0	18.1	
14/10/94	6.2	0.0	0.0	18.4	
15/10/94	6.2	0.0	0.0	18.4	
16/10/94	6.2	0.0	0.0	18.4	
17/10/94	6.2	0.0	0.0	18.8	
18/10/94	6.2	0.0	0.0	18.3	
20/10/94	6.2	0.0	0.0	18.2	
21/10/94	6.2	0.0	0.0	18.4	
22/10/94	6.2	0.0	0.0	18.0	
23/10/94	6.2	0.0	0.0	18.0	
24/10/94	6.2	0.0	0.0	18.4	
25/10/94	6.2	0.0	0.0	18.8	
26/10/94	6.2	0.0	0.0	19.0	
27/10/94	6.2	0.0	0.0	18.5	
28/10/94	6.2	0.0	0.0	18.0	
29/10/94	6.2	0.0	0.0	18.5	
30/10/94	6.2	0.0	0.0	18.5	
31/10/94	6.2	0.0	0.0		
01/11/94	6.2	0.0	0.0	18.1	
02/11/94	6.2	0.0	0.0	17.8	
03/11/94	6.2	0.0	0.0	18.3	
04/11/94	6.2	0.0	0.0	18.6	
05/11/94	6.2	0.0	0.0	18.2	
06/11/94	6.2	0.0	0.0	18.5	
07/11/94	6.2	0.0	0.0	18.8	
Average:				18.2	0.0
Count:	40	40	40	39	0
Maximum:	6.2	0.0	0.0	21.6	
Minimum:	6.2	0.0	0.0	16.4	
Standard Deviation:				0.8	0.0

PERIOD 3.2.4
SUMMARY DATA 1
LOW ALUM TO R1 ANAEROBIC, WITH ACID

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	CORR COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
08/11/94	150	37.4	37.9	15.80	15.00	399	24	21	39.0	2.94	2.39
09/11/94	150	35.5	35.5	16.40	16.20	344	21	19	32.5	3.88	8.98
10/11/94	150	36.0	36.5	16.20	16.10	333	26	23	31.5	1.69	7.71
11/11/94	150	36.5	36.5	16.70	18.00						
12/11/94	150	36.2	36.2	17.20	16.40						
13/11/94	150	36.2	37.0	12.70	16.80	307	41	23	22.8	8.65	7.81
14/11/94	150	36.5	36.5	16.40	12.70	290	23	19			
15/11/94	150	35.5	36.2	16.50	15.50	375	21	19			
16/11/94	150	35.8	36.5	16.40	15.90	342	24	21			
17/11/94	150	35.8	35.8			330	22	22			
18/11/94	150	20.2	20.2	14.60	16.00						
19/11/94	150	36.7	37.9	15.60	15.40						
20/11/94	150	36.7	37.2	15.40	15.10	326	23	18			
21/11/94	150	36.5	36.5	13.90	15.40	338	24	19			
22/11/94	150	36.2	36.2	13.90	13.50	309	25	19	25.1	1.33	1.26
23/11/94	150	35.8	35.8	18.90	14.70	360	22	22	29.1	1.07	1.12
24/11/94	150	36.0	36.0	15.00	14.40	335	26	21	28.8	1.54	1.07
25/11/94	150	35.8	36.0	16.20	15.80						
26/11/94	150	36.0	36.7	16.60	15.90						
27/11/94	150	35.8	35.8	15.50	15.60	363	25	21	35.3	1.44	0.99
28/11/94	150	34.6	35.8	14.10	16.40	361	26	23	31.9	1.22	1.51
29/11/94	150	36.5	36.0	17.90	20.00	495	23	25	36.1	1.24	1.32
30/11/94	150	36.7	36.7	18.80	21.60	447	25	16	34.3	1.60	1.64
01/12/94	150	35.5	36.2	21.00	19.20	512	28	24	38.2	1.56	1.85
02/12/94	150	36.5	37.0	18.60	19.40						
03/12/94	150		36.7								
04/12/94	150	36.5	36.5	22.00	18.40	354	22	22	23.5	1.61	1.86
05/12/94	150	35.8	36.2	21.70	18.70	359	21	19	32.8	1.94	0.89
06/12/94	150		36.7	17.40	15.20	334	20	21	35.4	0.49	0.64
07/12/94	150	35.8	35.8	15.50	16.60	429	17	19	28.1	1.13	0.98
08/12/94	150	36.7	36.7	17.20	15.90	390	23	20	42.6	3.45	1.93
09/12/94	150	36.0	36.0	16.60	15.60						
10/12/94	150	36.5	36.5	15.90	14.60						
11/12/94	150	35.8	35.3	14.10	13.20	292	20	20	48.8	2.66	2.41
12/12/94	150	36.2	36.0	13.00	12.70	268	16	18	53.2	2.66	0.98
13/12/94	150	36.0	36.0	13.70	15.10	357	17	18	42.7	2.36	2.13
14/12/94	150	35.8	37.2	14.80	14.20	341	20	20	47.0	2.44	2.28
15/12/94	150	35.3	36.0	15.20	14.90						
16/12/94	150	36.5	36.5	15.00	14.60						
17/12/94	150	35.3	35.3	14.00	14.00						
18/12/94	150	35.8	35.5	13.80	13.30	286	21	19	45.6	2.36	1.64
19/12/94	150	35.5	36.2	13.20	12.90	311	20	20	47.6	2.90	2.51
20/12/94	150	36.0	36.0	11.80	12.00	257	20	16	36.4	2.16	2.60
21/12/94	150	36.0		13.10	12.50	318	18	21	55.4	2.68	2.34
22/12/94	150	35.8	35.8	13.40	13.70	318	22	17	55.4	2.86	1.75
23/12/94	150	35.8	35.8	16.50	14.80						
24/12/94	150	36.0	36.0	14.50	13.60						
25/12/94	150	36.2	36.2	14.50	13.90	310	19	20	46.1	2.41	2.61
26/12/94	150	35.5	35.5	13.00	13.50	267	17	22	48.4	2.60	3.06
Average:	150	35.7	35.9	15.75	15.42	346	22	20	38.3	2.32	2.44
Count:	49	47	48	47	47	34	34	34	28	28	28
Maximum:	150	37.4	37.9	22.00	21.60	512	41	25	55.4	8.65	8.98
Minimum:	150	20.2	20.2	11.80	12.00	257	16	16	22.8	0.49	0.64
Standard Deviation:	0	2.3	2.4	2.24	2.05	57	4	2	9.3	1.45	2.09

APPENDIX 5

PERIOD 3.2.4
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
08/11/94	50.00	14.59	18.52	35.41	31.48	258.37	204.20
09/11/94	47.21	11.48	18.20	35.73	29.01	255.17	216.25
10/11/94	47.02	13.09	19.87	33.93	27.15	249.49	214.80
11/11/94							
12/11/94							
13/11/94	48.31		15.83		32.48		211.93
14/11/94	48.15		23.91		24.24	228.88	203.66
15/11/94	46.69	18.90	26.82	27.79	19.87	231.73	202.93
16/11/94	45.24	19.55	17.45	25.69	27.79	220.39	209.63
17/11/94	49.75	23.31	17.73	26.44	32.02	240.18	218.01
18/11/94							
19/11/94							
20/11/94	48.60	23.48	18.22	25.12	30.38	236.54	200.33
21/11/94	48.93	22.82	19.37	26.11	29.56	242.48	231.47
22/11/94	47.45	22.99	20.69	24.46	26.76	244.98	235.73
23/11/94	50.40	29.22	27.91	21.18	22.49	250.37	217.24
24/11/94	50.98	24.75	23.44	26.23	27.54	286.04	227.76
25/11/94							
26/11/94							
27/11/94	50.82	24.10	22.79	26.72	28.03	263.86	228.81
28/11/94	49.01	25.08	26.39	23.93	22.62	192.74	268.06
29/11/94	58.80	26.09	27.40	32.71	31.40	235.97	268.86
30/11/94	53.24	21.84	25.43	31.40	27.81	240.35	219.71
01/12/94	50.13	21.51	19.22	28.62	30.91	231.90	205.26
02/12/94							
03/12/94							
04/12/94	52.30	21.90	26.36	30.40	25.94	243.75	207.89
05/12/94	44.54	28.18	32.14	16.36	12.40	237.29	200.15
06/12/94	48.66	30.26	33.08	18.40	15.58	217.16	210.92
07/12/94	48.16	32.91	28.93	15.25	19.23	227.34	201.46
08/12/94	43.02	20.48	28.93	22.54	14.09	239.12	213.26
09/12/94							
10/12/94							
11/12/94	49.49	12.85	19.81	36.64	29.68	248.87	214.96
12/12/94	48.00	16.99	22.96	31.01	25.04	272.32	222.57
13/12/94	47.24	20.98	26.26	26.26	20.98	219.67	210.00
14/12/94	46.12	22.42	24.34	23.70	21.78	233.28	210.61
15/12/94							
16/12/94							
17/12/94							
18/12/94	53.51	24.85	23.86	28.66	29.65	239.11	231.90
19/12/94	49.04	27.00	28.33	22.04	20.71	240.39	238.17
20/12/94	48.38	25.02	26.34	23.36	22.04	246.33	240.73
21/12/94	49.20	29.49	30.32	19.71	18.88	260.79	244.74
22/12/94	49.20	25.35	22.70	23.85	26.50	243.55	241.00
23/12/94							
24/12/94							
25/12/94	49.54	22.70	21.70	26.84	27.84	255.20	269.38
26/12/94	48.87	21.37	21.21	27.50	27.66	252.80	257.67
Average:	49.00	22.67	23.72	26.37	25.28	242.01	223.53
Count:	34	32	34	32	34	33	34
Maximum:	58.80	32.91	33.08	36.64	32.48	286.04	269.38
Minimum:	43.02	11.48	15.83	15.25	12.40	192.74	200.15
Standard Deviation:	2.75	4.97	4.42	5.23	5.19	16.90	19.91

PERIOD 3.2.4
SUMMARY DATA 3
LOW ALUM TO R1 ANAEROBIC, WITH ACID

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
08/11/94	131.59	115.66	4734	2411	4592	2601	50.9	56.6	72	76
09/11/94	135.36	127.95	4711	2499	4369	2585	53.0	59.2	72	82
10/11/94	126.96	120.06	4785	2435	4589	2565	50.9	55.9	71	78
11/11/94										
12/11/94										
13/11/94		119.25			4756	2676		56.3		78
14/11/94	118.26	116.05	5069	2619	3982	2269	51.7	57.0	43	93
15/11/94	118.14	112.82	4992	2545	4139	2301	51.0	55.6	72	80
16/11/94	112.15	116.85	4913	2500	4162	2320	50.9	55.7	71	79
17/11/94	123.11	120.55	5041	2584	4181	2312	51.3	55.3	67	79
18/11/94										
19/11/94										
20/11/94	119.55	108.91	4903	2478	4387	2385	50.5	54.4	65	75
21/11/94	123.54	127.98	4758	2424	4272	2362	50.9	55.3	69	80
22/11/94	129.23	136.62	4561	2406	4110	2382	52.8	58.0	72	88
23/11/94	127.51	117.27	4571	2328	4242	2290	50.9	54.0	65	70
24/11/94	146.50	126.54	4563	2337	4262	2368	51.2	55.6	72	80
25/11/94										
26/11/94										
27/11/94	135.72	125.68	4940	2541	4761	2615	51.4	54.9	71	74
28/11/94	100.48	148.50	4617	2407	4493	2489	52.1	55.4	74	78
29/11/94	125.80	153.86	4843	2582	4587	2625	53.3	57.2	70	76
30/11/94	125.68	122.66	5173	2705	4487	2505	52.3	55.8	66	80
01/12/94	125.07	115.49	4819	2599	4525	2546	53.9	56.3	77	82
02/12/94										
03/12/94										
04/12/94	129.73	119.86	4656	2478	4612	2659	53.2	57.7	71	79
05/12/94	124.42	110.98	5054	2650	4698	2605	52.4	55.4	67	81
06/12/94	117.58	119.25	3899	2111	4192	2370	54.1	56.5	88	93
07/12/94	125.12	115.46	3823	2104	4746	2720	55.0	57.3	73	76
08/12/94	127.76	118.60	3614	1931	4089	2274	53.4	55.6	75	98
09/12/94										
10/12/94										
11/12/94	132.87	118.32	4486	2395	4393	2418	53.4	55.0	63	87
12/12/94	144.44	125.81	4425	2347	4329	2447	53.0	56.5	68	88
13/12/94	115.80	113.29	4729	2493	4297	2318	52.7	53.9	63	84
14/12/94	119.43	113.73	4840	2478	4435	2395	51.2	54.0	62	83
15/12/94										
16/12/94										
17/12/94										
18/12/94	123.98	123.94	4677	2425	4264	2279	51.8	53.4	64	91
19/12/94	123.66	125.80	4582	2357	4188	2212	51.4	52.8	65	91
20/12/94	129.00	128.73	4495	2354	4041	2161	52.4	53.5	67	94
21/12/94	133.32	126.62	4511	2306	3742	1936	51.1	51.7	64	102
22/12/94	123.08	124.92	4563	2306	3899	2021	50.5	51.8	64	85
23/12/94										
24/12/94										
25/12/94	131.85	138.79	4649	2402	3975	2048	51.7	51.5	0	0
26/12/94	131.89	132.75	4585	2392	3981	2051	52.2	51.5	65	93
Average:	126.02	123.22	4654	2422	4317	2386	52.1	55.2	66	81
Count:	33	34	33	33	34	34	33	34	33	34
Maximum:	146.50	153.86	5173	2705	4761	2720	55.0	59.2	88	102
Minimum:	100.48	108.91	3614	1931	3742	1936	50.5	51.5	0	0
Standard Deviation:	8.61	9.81	336	157	260	197	1.1	1.9	14	16

APPENDIX 5

PERIOD 3.2.4
SUMMARY DATA 4
LOW ALUM TO R1 ANAEROBIC, WITH ACID

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
08/11/94			7.34	7.30	7.56	7.63	10	10		
09/11/94			7.23	7.34	7.53	7.65	10	10		
10/11/94			7.41	7.30	7.62	7.62	10	10		
11/11/94			7.43	7.46	7.68	7.76	10	10		
12/11/94			7.52	7.48	7.78	7.81	10	10		
13/11/94			7.38	7.37	7.61	7.67	10	10		
14/11/94				7.31	7.56	7.60	10	10		
15/11/94			7.25	7.32	7.40	7.59	10	10		
16/11/94			7.33	7.33	7.55	6.86	10	10		
17/11/94			7.34	7.35	7.53	7.65	10	10		
18/11/94			6.96	6.93	7.03	7.00	10	10		
19/11/94	7.00	6.91	7.44	7.36	7.62	7.75	10	10		
20/11/94	6.92	6.87	7.33	7.33	7.50	7.64	10	10		
21/11/94	6.88	6.91	7.38	7.44	7.59	7.72	10	10		
22/11/94	6.88	6.80	7.27	7.34	7.48	7.59	10	10		
23/11/94	7.12	7.04	7.49	7.48	7.65	7.74	10	10		
24/11/94	7.04	7.02	7.45	7.43	7.61	7.70	10	10		
25/11/94	7.11	7.06	7.47	7.51	7.65	7.76	10	10		
26/11/94	7.08	7.03	7.43	7.45	7.62	7.71	10	10		
27/11/94	6.98	6.98	7.31	7.28	7.48	7.57	10	10		
28/11/94	7.21	7.24	7.50	7.39	7.60	7.74	10	10		
29/11/94	7.01	7.00	7.28	7.38	7.48	7.58	10	10		
30/11/94	7.12	7.11	7.32	7.37	7.55	7.61	10	10		
01/12/94	6.58	6.88	7.35	7.29	7.52	7.56	10	10		
02/12/94	6.89	6.86	7.33	7.33	7.56	7.66	10	10		
03/12/94		6.84		7.32		7.62	10	10		
04/12/94	6.87	6.85	7.29	7.27	7.53	7.58	10	10		
05/12/94	6.96	6.97	7.30	7.34	7.49	7.61	10	10		
06/12/94	7.07	6.95	7.32	7.31	7.56	7.57	10	10		
07/12/94	7.07	7.03	7.31	7.27	7.45	7.49	10	10		
08/12/94	6.95	6.91	7.37	7.41	7.59	7.67	10	10		
09/12/94	7.02	6.94	7.38	7.43	7.62	7.66	10	10		
10/12/94	6.92	6.91	7.00	7.38	7.63	7.67	10	10		
11/12/94	6.98	6.91	7.31	7.31	7.51	7.58	10	10		
12/12/94	6.96	6.96	7.30	7.34	7.52	7.59	10	10		
13/12/94	7.04	7.02	7.29	7.38	7.58	7.46	10	10		
14/12/94	6.93	6.87	7.28	7.39	7.51	7.67	10	10		
15/12/94	6.96	6.92	7.32	7.35	7.51	7.60	10	10		
16/12/94	6.93	6.92	7.48	7.47	7.68	7.70	10	10		
17/12/94	6.96	6.93	7.28	7.32	7.48	7.58	10	10		
18/12/94										
19/12/94	6.97	6.94	7.34	7.33	7.51	7.56	10	10		
20/12/94	6.94	6.93	7.29	7.36	7.47	7.60	10	10		
21/12/94	7.01	6.99	7.32	7.33	7.48	7.56	10	10		
22/12/94	6.96	6.93	7.30	7.37	7.49	7.62	10	10		
23/12/94	6.95	6.93	7.31	7.37	7.49	7.60	10	10		
24/12/94	6.93	6.89	7.32	7.33	7.53	7.62	10	10		
25/12/94	6.94	6.92	7.36	7.44	7.55	7.69	10	10		
26/12/94	6.94	6.90	7.30	7.37	7.50	7.66	10	10		
Average:	6.97	6.95	7.33	7.36	7.54	7.61	10	10	0.0	0.0
Count:	36	37	46	48	47	48	48	48	0	0
Maximum:	7.21	7.24	7.52	7.51	7.78	7.81	10	10		
Minimum:	6.58	6.80	6.96	6.93	7.03	6.86	10	10		
Standard Deviation:	0.10	0.08	0.10	0.09	0.10	0.16	0	0	0.0	0.0

APPENDIX 5

PERIOD 3.2.4
SUMMARY DATA 5
LOW ALUM TO R1 ANAEROBIC, WITH ACID

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
08/11/94	0.35	0.43	7.42	5.50	12.46	15.76
09/11/94	0.39	0.35	10.26	6.84		
10/11/94	0.27	0.30	8.07	4.06	10.48	17.68
11/11/94						
12/11/94						
13/11/94	4.83	0.22	2.09	2.88		15.16
14/11/94	0.57	0.41	7.37	4.23		22.75
15/11/94	0.38	0.31	7.13	3.46	17.74	24.96
16/11/94	0.11	0.24	7.26	3.01	17.74	17.24
17/11/94	0.76	0.62	4.89	2.84	21.72	16.91
18/11/94						
19/11/94						
20/11/94	0.23	0.24	2.77	1.50	21.72	17.38
21/11/94	0.61	0.46	7.36	3.66	19.83	18.24
22/11/94	0.91	0.63	4.69	2.87	20.85	19.62
23/11/94	0.67	0.73	4.03	2.64	27.84	26.60
24/11/94	0.51	0.29	2.82	1.15	21.49	21.49
25/11/94						
26/11/94						
27/11/94	0.51	0.47	3.32	2.34	22.18	22.47
28/11/94	0.47	0.47	2.73	1.70	23.25	25.77
29/11/94	1.32	0.94	3.69	2.34	24.52	28.85
30/11/94	0.40	0.38	2.44	2.02	20.46	24.14
01/12/94	0.38	0.41	2.30	1.78	20.87	20.25
02/12/94						
03/12/94						
04/12/94	0.72	0.43	3.97	2.68	18.00	25.60
05/12/94	0.90	0.47	7.52	2.96	25.39	29.97
06/12/94	0.85	0.44	8.81	4.13	30.03	32.54
07/12/94	0.45	0.52	2.96	2.77	32.15	28.30
08/12/94	0.69	0.39	2.51	2.54	19.33	25.71
09/12/94						
10/12/94						
11/12/94	0.51	0.51	2.44	2.88	11.83	19.08
12/12/94	0.87	0.51	3.84	3.66	15.84	22.02
13/12/94	5.21	4.17	4.82	3.18		25.09
14/12/94	3.79	3.79	4.40	4.36	15.05	18.40
15/12/94						
16/12/94						
17/12/94						
18/12/94	3.98	4.17	5.11	5.70	13.71	14.72
19/12/94	0.98	0.53	4.73	3.54	24.55	30.89
20/12/94	0.53	0.53	3.24	3.11	26.54	26.93
21/12/94	0.72	0.56	2.96	2.79	27.13	28.12
22/12/94	0.97	0.58	3.50	3.26	21.67	20.30
23/12/94						
24/12/94						
25/12/94	0.83	0.47	5.63	5.83	20.35	19.58
26/12/94	0.60	0.74	3.05	3.17	20.40	19.71
Average:	1.07	0.79	4.71	3.28	20.84	22.49
Count:	34	34	34	34	30	33
Maximum:	5.21	4.17	10.26	6.84	32.15	32.54
Minimum:	0.11	0.22	2.09	1.15	10.48	14.72
Standard Deviation:	1.28	1.03	2.16	1.24	5.13	4.82

APPENDIX 5

PERIOD 3.2.4
SUMMARY DATA 6
LOW ALUM TO R1 ANAEROBIC, WITH ACID

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
08/11/94	0.13	2.67	7.58	7.75	0.11	1.13	5.17	5.25
09/11/94	0.12	3.44	10.51	12.14	0.11	1.35	7.01	6.32
10/11/94								
11/11/94								
12/11/94								
13/11/94					0.08	1.20	3.79	3.77
14/11/94								
15/11/94								
16/11/94								
17/11/94								
18/11/94								
19/11/94								
20/11/94	0.00	0.79	2.69	2.70	0.00	0.33	1.69	1.61
21/11/94	0.00	1.04	4.03	3.89	0.00	0.38	2.38	2.52
22/11/94								
23/11/94	0.04	0.58	1.79	1.73	0.00	0.29	1.35	1.37
24/11/94								
25/11/94								
26/11/94								
27/11/94	0.00	0.69	2.14	2.26	0.00	0.45	1.77	1.87
28/11/94	0.00	0.64	2.21	2.05	0.00	0.54	1.73	1.62
29/11/94								
30/11/94	0.00	0.00	1.59	1.38	0.00	0.00	1.86	1.62
01/12/94								
02/12/94								
03/12/94								
04/12/94	0.00	0.24	2.03	2.11	0.00	0.00	1.91	1.95
05/12/94								
06/12/94								
07/12/94	0.03	0.14	1.39	1.39	0.02	0.19	1.39	1.59
08/12/94								
09/12/94								
10/12/94								
11/12/94	0.04	0.75	2.33	2.41	0.04	1.17	2.80	2.86
12/12/94	0.02	1.10	3.04	2.96	0.00	1.46	3.20	3.16
13/12/94								
14/12/94	0.02	0.88	2.42	2.58	0.02	0.88	2.47	2.68
15/12/94								
16/12/94								
17/12/94								
18/12/94								
19/12/94	0.00	0.88	2.18	2.25	0.00	0.94	2.29	2.40
20/12/94								
21/12/94								
22/12/94								
23/12/94								
24/12/94								
25/12/94								
26/12/94	0.00	0.95	2.25	2.47	0.00	0.99	2.26	2.43
Average:	0.03	0.99	3.21	3.34	0.02	0.71	2.69	2.69
Count:	15	15	15	15	16	16	16	16
Maximum:	0.13	3.44	10.51	12.14	0.11	1.46	7.01	6.32
Minimum:	0.00	0.00	1.39	1.38	0.00	0.00	1.35	1.37
Standard Deviation:	0.04	0.88	2.43	2.78	0.04	0.47	1.46	1.35

PERIOD 3.2.4
SUMMARY DATA 7
LOW ALUM TO R1 ANAEROBIC, WITH ACID

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
08/11/94	102.46	43.77	23.11	11.64	96.72	50.68	29.18	16.88
09/11/94	122.95	51.64	26.39	13.61	112.29	58.03	34.43	20.16
10/11/94								
11/11/94								
12/11/94								
13/11/94					113.10	56.39	32.48	21.17
14/11/94								
15/11/94								
16/11/94								
17/11/94								
18/11/94								
19/11/94								
20/11/94	94.41	50.40	29.88	20.85	128.88	55.33	27.42	16.91
21/11/94	110.00	53.85	30.70	22.00	126.42	60.58	35.63	21.02
22/11/94								
23/11/94	111.65	60.91	41.87	30.70	123.14	66.82	43.02	31.69
24/11/94								
25/11/94								
26/11/94								
27/11/94	100.82	54.92	36.23	27.70	112.29	63.77	41.15	27.38
28/11/94	83.83	50.30	34.59	26.91	101.82	56.51	40.15	28.21
29/11/94								
30/11/94	91.19	70.25	39.66	30.01	111.63	75.48	45.55	27.23
01/12/94								
02/12/94								
03/12/94								
04/12/94	94.61	52.97	33.13	22.06	106.18	74.28	43.55	28.18
05/12/94								
06/12/94								
07/12/94	95.75	60.10	38.05	23.79	97.41	56.79	33.41	23.96
08/12/94								
09/12/94								
10/12/94								
11/12/94	89.12	47.33	28.77	18.49	104.87	53.80	35.89	25.45
12/12/94	81.65	44.68	30.92	22.13	92.43	50.82	36.72	28.10
13/12/94								
14/12/94	80.86	43.55	26.90	21.30	91.27	45.96	31.87	21.94
15/12/94								
16/12/94								
17/12/94								
18/12/94								
19/12/94	98.57	51.03	33.80	25.02	102.72	55.00	35.12	26.01
20/12/94								
21/12/94								
22/12/94								
23/12/94								
24/12/94								
25/12/94								
26/12/94	84.49	41.91	25.18	15.57	95.26	48.04	29.66	21.54
Average:	96.16	51.84	31.95	22.12	107.28	58.02	35.95	24.11
Count:	15	15	15	15	16	16	16	16
Maximum:	122.95	70.25	41.87	30.70	128.88	75.48	45.55	31.69
Minimum:	80.86	41.91	23.11	11.64	91.27	45.96	27.42	16.88
Standard Deviation:	11.63	7.36	5.31	5.43	11.39	8.21	5.25	4.20

APPENDIX 5

PERIOD 3.2.4
SUMMARY DATA 8
LOW ALUM TO R1 ANAEROBIC, WITH ACID

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
08/11/94	6.2	0.0	0.0	17.7	
09/11/94	6.2	0.0	0.0	18.5	
10/11/94	6.2	0.0	0.0	18.6	
11/11/94	6.2	0.0	0.0	18.6	
12/11/94	6.2	0.0	0.0	18.0	
13/11/94	6.2	0.0	0.0	18.8	
14/11/94	6.2	0.0	0.0	18.6	
15/11/94	6.2	0.0	0.0	18.9	
16/11/94	6.2	0.0	0.0	18.5	
17/11/94	6.2	0.0	0.0		
18/11/94	6.2	0.0	0.0	18.2	
19/11/94	6.2	0.0	0.0	18.7	
20/11/94	6.2	0.0	0.0	18.4	
21/11/94	6.2	0.0	0.0	18.8	
22/11/94	6.2	0.0	0.0	18.8	
23/11/94	6.2	0.0	0.0	18.1	
24/11/94	6.2	0.0	0.0	17.9	
25/11/94	6.2	0.0	0.0	17.8	
26/11/94	6.2	0.0	0.0	17.8	
27/11/94	6.2	0.0	0.0	18.5	
28/11/94	6.2	0.0	0.0	17.7	
29/11/94	6.2	0.0	0.0	18.7	
30/11/94	6.2	0.0	0.0	18.3	
01/12/94	6.2	0.0	0.0	18.6	
02/12/94	6.2	0.0	0.0	19.1	
03/12/94	6.2	0.0	0.0		
04/12/94	6.2	0.0	0.0	18.6	
05/12/94	6.2	0.0	0.0	18.5	
06/12/94	6.2	0.0	0.0	19.7	
07/12/94	6.2	0.0	0.0	19.0	
08/12/94	6.2	0.0	0.0	19.1	
09/12/94	6.2	0.0	0.0	19.1	
10/12/94	6.2	0.0	0.0	18.2	
11/12/94	6.2	0.0	0.0	18.0	
12/12/94	6.2	0.0	0.0	17.9	
13/12/94	6.2	0.0	0.0	18.7	
14/12/94	6.2	0.0	0.0	19.1	
15/12/94	6.2	0.0	0.0	19.3	
16/12/94	6.2	0.0	0.0	18.5	
17/12/94	6.2	0.0	0.0	18.8	
18/12/94	6.2	0.0	0.0	19.1	
19/12/94	6.2	0.0	0.0	18.7	
20/12/94	6.2	0.0	0.0	18.6	
21/12/94	6.2	0.0	0.0	18.7	
22/12/94	6.2	0.0	0.0	19.0	
23/12/94	6.2	0.0	0.0	18.9	
24/12/94	6.2	0.0	0.0	18.8	
25/12/94	6.2	0.0	0.0	19.0	
26/12/94	6.2	0.0	0.0	19.0	
Average:				18.6	0.0
Count:	49	49	49	47	0
Maximum:	6.2	0.0	0.0	19.7	
Minimum:	6.2	0.0	0.0	17.7	
Standard Deviation:				0.4	0.0

APPENDIX 5

PERIOD 3.2.5
SUMMARY DATA 1
HIGH ALUM TO ANAEROBIC, WITH ACID

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	CORR COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
27/12/94	150	36.7	35.8	10.90	11.20	247	21	19	43.7	1.60	2.95
28/12/94	150	36.7	36.0	10.30	10.00	196	17	17	31.2	2.95	2.83
29/12/94	150	36.0	36.0	9.80	9.50	223	19	17	10.4	1.93	1.86
30/12/94	150	35.8	36.5	9.70	9.70						
31/12/94	150	35.8	36.2	11.00	10.90	288	19	14	34.0	1.58	1.53
01/01/95	150	36.0	36.0	10.40	19.20						
02/01/95	150	36.2	36.2	11.50	19.40	286	17	17	32.3	1.98	1.60
03/01/95	150	36.5	36.5	10.70	11.10	264	19	18	38.9	1.69	1.56
04/01/95	150	36.0	36.0	12.00	12.20	298	17	19	40.6	2.78	2.60
05/01/95	150	36.5	36.5	11.00	11.40	263	16	17	32.6	2.39	2.34
06/01/95	150	36.2	36.2	10.70	10.60						
07/01/95	150	36.0	36.0	10.80	11.00						
08/01/95	150	36.0	36.0	11.10	11.44	236	20	13	26.6	1.65	0.20
09/01/95	150	36.0	36.0	11.20	11.80	213	16	11	28.8	2.36	1.78
Average:	150	36.2	36.1	10.79	12.10	251	18	16	31.9	2.09	1.93
Count:	14	14	14	14	14	10	10	10	10	10	10
Maximum:	150	36.7	36.5	12.00	19.40	298	21	19	43.7	2.95	2.95
Minimum:	150	35.8	35.8	9.70	9.50	196	16	11	10.4	1.58	0.20
Standard Deviation:	0	0.3	0.2	0.59	3.03	33	2	3	8.8	0.48	0.77

PERIOD 3.2.5
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
27/12/94	45.39	20.87	25.35	24.52	20.04	259.48	261.29
28/12/94						272.27	240.75
29/12/94	44.26	30.53	35.70	13.73	8.56	264.67	261.62
30/12/94							
31/12/94	52.59	31.58	36.21	21.01	16.38	256.01	250.85
01/01/95							
02/01/95	50.72	30.69	35.05	20.03	15.67	266.09	231.86
03/01/95	47.81	23.26	29.56	24.55	18.25	262.96	239.97
04/01/95	45.71	24.55	30.69	21.16	15.02	261.43	232.13
05/01/95	45.23	19.06	25.85	26.17	19.38	275.10	246.23
06/01/95							
07/01/95							
08/01/95	44.65	17.69	24.14	26.96	20.51	279.88	250.15
09/01/95	43.99	19.02	25.14	24.97	18.85	275.88	241.30
Average:	46.71	24.14	29.74	22.57	16.96	267.38	245.62
Count:	9	9	9	9	9	10	10
Maximum:	52.59	31.58	36.21	26.96	20.51	279.88	261.62
Minimum:	43.99	17.69	24.14	13.73	8.56	256.01	231.86
Standard Deviation:	2.88	5.21	4.64	3.87	3.49	7.53	9.98

PERIOD 3.2.5
SUMMARY DATA 3
HIGH ALUM TO R1 ANAERROBIC, WITH ACID

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
27/12/94	133.27	138.27	4587	2356	3906	2067	51.4	52.9	68	100
28/12/94	139.48	129.43	4482	2296	3869	2080	51.2	53.8	67	97
29/12/94	131.11	132.75	4423	2191	3772	1914	49.5	50.7	70	101
30/12/94										
31/12/94	130.15	135.48	4231	2151	3503	1892	50.8	54.0	69	103
01/01/95										
02/01/95	134.88	123.56	3904	1979	3556	1895	50.7	53.3	79	104
03/01/95	134.12	125.77	3878	1978	3442	1804	51.0	52.4	75	102
04/01/95	133.33	125.81	3998	2039	3428	1858	51.0	54.2	73	96
05/01/95	135.27	131.01	4096	2014	3477	1850	49.2	53.2	68	95
06/01/95										
07/01/95										
08/01/95	135.70	128.35	4253	2062	3672	1884	48.5	51.3	68	93
09/01/95	136.20	126.24	4128	2038	3563	1864	49.4	52.3		
Average:	134.35	129.67	4198	2110	3619	1911	50.3	52.8	71	99
Count:	10	10	10	10	10	10	10	10	9	9
Maximum:	139.48	138.27	4587	2356	3906	2080	51.4	54.2	79	104
Minimum:	130.15	123.56	3878	1978	3428	1804	48.5	50.7	67	93
Standard Deviation:	2.51	4.47	230	126	167	86	1.0	1.1	4	4

PERIOD 3.2.5
SUMMARY DATA 4
HIGH ALUM TO R1 ANAEROBIC, WITH ACID

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
27/12/94	6.91	7.02	7.33	7.42	7.49	7.70	10	10		
28/12/94	6.83	6.97	7.19	7.35	7.34	7.49	10	10		
29/12/94	7.09	7.17	7.27	7.35	7.31	7.49	10	10		
30/12/94	6.94	6.97	7.33	7.46	7.44	7.62	10	10		
31/12/94	7.08	7.08	7.29	7.40	7.39	7.55	10	10		
01/01/95	7.18	7.00	7.42	7.37	7.48	7.63	10	10		
02/01/95		7.09		7.34		7.57	10	10		
03/01/95	6.97	7.00	7.33	7.44	7.50	7.65	10	10		
04/01/95	6.98	7.04	7.32	7.39	7.49	7.58	10	10		
05/01/95	6.94	6.96	7.39	7.45	7.55	7.67	10	10		
06/01/95	7.09	7.09	7.42	7.47	7.58	7.69	10	10		
07/01/95	6.98	6.97	7.39	7.52						
08/01/95										
09/01/95										
Average:	7.00	7.03	7.33	7.41	7.46	7.60	10	10	0.0	0.0
Count:	11	12	11	12	10	11	11	11	0	0
Maximum:	7.18	7.17	7.42	7.52	7.58	7.70	10	10		
Minimum:	6.83	6.96	7.19	7.34	7.31	7.49	10	10		
Standard Deviation:	0.10	0.06	0.07	0.05	0.08	0.07	0	0	0.0	0.0

PERIOD 3.2.5
SUMMARY DATA 5
HIGH ALUM TO R1 ANAEROBIC, WITH ACID

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
27/12/94	0.68	0.72	3.20	3.09	19.13	21.47
28/12/94	0.68	0.46	6.03	7.03	22.65	34.17
29/12/94	0.42	0.46	7.33	7.23	30.72	36.09
30/12/94						
31/12/94	0.46	0.44	7.13	7.74	27.65	36.86
01/01/95						
02/01/95	0.44	0.46	6.83	7.03	25.34	30.33
03/01/95	0.48	0.33	7.32	7.45	21.11	27.45
04/01/95	0.30	0.27	5.85	6.24	22.67	29.30
05/01/95	0.30	0.36	5.20	5.47	17.64	24.02
06/01/95						
07/01/95						
08/01/95	0.75	0.60	3.97	4.32	15.02	22.93
09/01/95	0.09	0.19	5.58	4.72	22.72	29.17
Average:	0.46	0.43	5.84	6.03	22.47	29.18
Count:	10	10	10	10	10	10
Maximum:	0.75	0.72	7.33	7.74	30.72	36.86
Minimum:	0.09	0.19	3.20	3.09	15.02	21.47
Standard Deviation:	0.19	0.15	1.34	1.48	4.42	5.11

PERIOD 3.2.5
SUMMARY DATA 6
HIGH ALUM TO R1 ANAEROBIC, WITH ACID

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
27/12/94								
28/12/94	0.06	3.48	6.03	6.23	0.04	3.54	7.03	6.43
29/12/94	0.04	3.24	6.63	7.03	0.03	3.13	5.83	7.03
30/12/94								
31/12/94								
01/01/95								
02/01/95	0.05	2.83	6.63	6.63	0.06	3.15	6.63	6.73
03/01/95	0.05	2.73	6.63	6.90	0.06	3.40	6.90	7.11
04/01/95	0.08	1.55	5.12	5.25	0.08	2.33	5.47	5.60
05/01/95	0.06	1.53	4.96	5.08	0.04	2.18	5.22	5.27
06/01/95								
07/01/95								
08/01/95								
09/01/95	0.04	2.00	3.38	4.65	0.05	2.61	3.64	4.73
Average:	0.05	2.48	5.63	5.97	0.05	2.91	5.82	6.13
Count:	7	7	7	7	7	7	7	7
Maximum:	0.08	3.48	6.63	7.03	0.08	3.54	7.03	7.11
Minimum:	0.04	1.53	3.38	4.65	0.03	2.18	3.64	4.73
Standard Deviation:	0.01	0.73	1.13	0.89	0.02	0.49	1.10	0.86

PERIOD 3.2.5
SUMMARY DATA 7
HIGH ALUM TO R1 ANAEROBIC, WITH ACID

	DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
	27/12/94								
	28/12/94	47.65	32.47	28.27	25.68	58.96	40.38	34.24	30.04
	29/12/94	75.92	44.74	34.08	28.91	90.46	55.24	40.71	34.24
	30/12/94								
	31/12/94								
	01/01/95								
	02/01/95	82.38	47.01	31.50	23.91	96.11	55.73	38.77	31.18
	03/01/95	67.04	39.58	28.11	21.97	82.38	49.11	35.54	29.40
	04/01/95	84.80	49.59	31.18	22.78	102.57	57.99	38.44	29.72
	05/01/95	71.07	39.41	23.91	16.80	86.42	47.01	30.85	23.91
	06/01/95								
	07/01/95								
	08/01/95								
	09/01/95	65.32	36.55	24.80	19.18	78.55	42.83	31.42	26.46
Average:		70.60	41.34	28.84	22.75	85.06	49.76	35.71	29.28
Count:		7	7	7	7	7	7	7	7
Maximum:		84.80	49.59	34.08	28.91	102.57	57.99	40.71	34.24
Minimum:		47.65	32.47	23.91	16.80	58.96	40.38	30.85	23.91
Standard Deviation:		11.56	5.61	3.41	3.72	13.04	6.30	3.51	3.07

PERIOD 3.2.5
SUMMARY DATA 8
HIGH ALUM TO R1 ANAEROBIC, WITH ACID

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
27/12/94	12.4	0.0	0.0	19.0	
28/12/94	12.4	0.0	0.0	19.0	
29/12/94	12.4	0.0	0.0	19.4	
30/12/94	12.4	0.0	0.0	18.9	
31/12/94	12.4	0.0	0.0	18.5	
01/01/95	12.4	0.0	0.0	19.1	
02/01/95	12.4	0.0	0.0	18.9	
03/01/95	12.4	0.0	0.0	18.7	
04/01/95	12.4	0.0	0.0	19.7	
05/01/95	12.4	0.0	0.0	18.6	
06/01/95	12.4	0.0	0.0	18.9	
07/01/95	12.4	0.0	0.0	18.6	
08/01/95	12.4	0.0	0.0	19.0	
09/01/95	12.4	0.0	0.0	19.0	
Average:				19.0	0.0
Count:	14	14	14	14	0
Maximum:	12.4	0.0	0.0	19.7	
Minimum:	12.4	0.0	0.0	18.5	
Standard Deviation:				0.3	0.0

PERIOD 3.2.6
SUMMARY DATA 1
HIGH ALUM TO R1 AEROBIC, WITH ACID

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	CORR COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
10/01/95	150	36.0	36.0	11.90	12.90	240	18	15	23.6	1.69	2.83
11/01/95	150	35.8	35.8	12.00	12.80	221	18	13	18.1	1.76	1.48
12/01/95	150	36.0	36.0	11.54	12.20	228	17	15	20.9	2.69	2.09
13/01/95	150	35.0	35.0	11.00	11.50						
14/01/95	150	35.3	35.3	13.80	13.90						
15/01/95	150	36.2	36.2	14.10	15.90	323	22	18			
16/01/95	150	35.5	35.5	16.10	17.50	368	22	19			
17/01/95	150	35.8	35.0	14.50	14.50	343	23	21			
18/01/95	150	34.6	34.8	12.50	13.90	370	23	23			
19/01/95	150	36.7	37.4	12.40	13.90	322	19	19			
20/01/95	150	35.5	35.5	13.30	14.70						
21/01/95	150	36.0	36.0	13.20	15.00						
22/01/95	150	36.2	36.7	14.70	14.80	366	18	20			
23/01/95	150	37.0	36.5	13.70	14.90	340	21	21			
Average:	150	35.8	35.8	13.20	14.17	312	20	18	20.9	2.05	2.13
Count:	14	14	14	14	14	10	10	10	3	3	3
Maximum:	150	37.0	37.4	16.10	17.50	370	23	23	23.6	2.69	2.83
Minimum:	150	34.6	34.8	11.00	11.50	221	17	13	18.1	1.69	1.48
Standard Deviation:	0	0.6	0.7	1.35	1.48	56	2	3	2.2	0.46	0.55

PERIOD 3.2.6
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
10/01/95	44.32	22.99	29.93	21.33	14.39	282.79	248.31
11/01/95	44.81	22.16	28.44	22.65	16.37	289.61	254.05
12/01/95	43.82	21.99	29.77	21.83	14.05	271.38	241.24
13/01/95							
14/01/95							
15/01/95	49.00	15.73	22.84	33.27	26.16	287.73	228.33
16/01/95	48.67	12.42	18.54	36.25	30.13	265.32	243.22
17/01/95	48.50	9.44	15.23	39.06	33.27	268.24	251.59
18/01/95	46.53	12.09	20.04	34.44	26.49	261.52	248.50
19/01/95	45.02	9.93	14.90	35.09	30.12	282.57	243.12
20/01/95							
21/01/95							
22/01/95	48.68	11.59	17.88	37.09	30.80	237.91	251.14
23/01/95	48.35	13.91	21.36	34.44	26.99	279.78	241.24
Average:	46.77	15.23	21.89	31.55	24.88	272.69	245.07
Count:	10	10	10	10	10	10	10
Maximum:	49.00	22.99	29.93	39.06	33.27	289.61	254.05
Minimum:	43.82	9.44	14.90	21.33	14.05	237.91	228.33
Standard Deviation:	1.98	4.99	5.43	6.48	6.85	14.74	7.06

PERIOD 3.2.6
SUMMARY DATA 3
HIGH ALUM TO R1 AEROBIC, WITH ACID

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
10/01/95	137.54	131.69	4184	2035	3541	1878	48.6	53.0	67	99
11/01/95	137.49	133.24	3981	1890	3413	1790	47.5	52.4	70	100
12/01/95	129.00	124.64	4115	1956	3476	1796	47.5	51.7	70	98
13/01/95										
14/01/95										
15/01/95	132.97	122.91	3934	1818	3394	1827	46.2	53.8	71	106
16/01/95	128.04	128.82	4163	2009	3444	1824	48.3	53.0	72	107
17/01/95	131.50	135.69	4041	1981	3367	1816	49.0	53.9	74	110
18/01/95	127.40	132.30	4315	2102	3567	1899	48.7	53.2	70	104
19/01/95	136.00	128.00	4517	2174	3829	2016	48.1	52.7	66	97
20/01/95										
21/01/95										
22/01/95	137.47	132.15	4794	2770	3972	2090	57.8	52.6	67	98
23/01/95	131.43	126.80	4926	2314	4022	2114	47.0	52.6	65	92
Average:	132.88	129.62	4297	2105	3603	1905	48.9	52.9	69	101
Count:	10	10	10	10	10	10	10	10	10	10
Maximum:	137.54	135.69	4926	2770	4022	2114	57.8	53.9	74	110
Minimum:	127.40	122.91	3934	1818	3367	1790	46.2	51.7	65	92
Standard Deviation:	3.82	3.86	324	259	233	117	3.1	0.6	3	5

PERIOD 3.2.6
SUMMARY DATA 4
HIGH ALUM TO R1 AEROBIC, WITH ACID

	DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
	10/01/95										
	11/01/95	7.09	7.03	7.47	7.53	7.52	7.61	10	10		
	12/01/95	7.21	7.10	7.54	7.65	7.57	7.69	10	10		
	13/01/95	7.17	7.11	7.53	7.62	7.59	7.68	10	10		
	14/01/95	7.24	7.13	7.55	7.63	7.58	7.68	10	10		
	15/01/95	7.14	6.94	7.62	7.62	7.68	7.72	10	10		
	16/01/95	7.08	7.02	7.62	7.65	7.70	7.72	10	10		
	17/01/95	7.10	7.02	7.63	7.59	7.66	7.70	10	10		
	18/01/95	7.12	7.04	7.50	7.53	7.62	7.66	10	10		
	19/01/95	7.11	7.05	7.64	7.70	7.76	7.86	10	10		
	20/01/95	7.06	6.97	7.56	7.60	7.65	7.75	10	10		
	21/01/95	7.04	6.94	7.58	7.57	7.67	7.73	10	10		
	22/01/95	7.16	6.94	7.67	7.59	7.76	7.69	10	10		
	23/01/95	7.04	6.98	7.63	7.60	7.64	7.71	10	10		
Average:		7.12	7.02	7.58	7.61	7.65	7.71	10	10	0.0	0.0
Count:		13	13	13	13	13	13	13	13	0	0
Maximum:		7.24	7.13	7.67	7.70	7.76	7.86	10	10		
Minimum:		7.04	6.94	7.47	7.53	7.52	7.61	10	10		
Standard Deviation:		0.06	0.06	0.06	0.05	0.07	0.06	0	0	0.0	0.0

PERIOD 3.2.6
SUMMARY DATA 5
HIGH ALUM TO R1 AEROBIC, WITH ACID

	DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
	10/01/95	0.26	0.24	4.62	4.90	26.24	28.10
	11/01/95	1.37	1.32	4.70	4.40	25.82	30.01
	12/01/95	0.64	0.47	4.44	4.60	22.72	27.86
	13/01/95						
	14/01/95						
	15/01/95			3.20	3.55	21.04	27.80
	16/01/95	1.99	1.61	5.04	7.80	16.98	22.96
	17/01/95	0.06	0.00	5.58	6.73	5.89	12.03
	18/01/95	0.00	0.00	3.66	4.64	6.63	14.98
	19/01/95	0.00	0.00	3.01	3.72	4.91	9.45
	20/01/95						
	21/01/95						
	22/01/95	0.74	0.50	3.71	4.49	6.38	12.52
	23/01/95	1.02	0.24	4.53	6.01	8.84	16.94
Average:		0.68	0.49	4.25	5.08	14.55	20.27
Count:		9	9	10	10	10	10
Maximum:		1.99	1.61	5.58	7.80	26.24	30.01
Minimum:		0.00	0.00	3.01	3.55	4.91	9.45
Standard Deviation:		0.65	0.56	0.78	1.28	8.42	7.50

PERIOD 3.2.6
SUMMARY DATA 6
HIGH ALUM TO R1 AEROBIC, WITH ACID

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
10/01/95	0.04	1.84	3.24	4.27	0.04	2.38	3.33	4.63
11/01/95	0.04	1.86	2.93	4.35	0.04	2.37	3.16	4.07
12/01/95	0.04	1.35	2.55	3.87	0.03	2.29	3.10	3.62
13/01/95								
14/01/95								
15/01/95	0.04	0.98	2.38	3.66	0.05	2.03	2.80	3.51
16/01/95	0.05	1.41	3.33	4.93	0.06	2.74	4.68	5.97
17/01/95	0.27	1.58	3.90	4.61	0.04	3.16	4.74	5.61
18/01/95	0.02	0.56	2.24	2.58	0.03	1.16	2.91	3.07
19/01/95	0.02	0.56	2.24	2.58	0.03	1.16	2.91	3.07
20/01/95								
21/01/95								
22/01/95								
23/01/95	0.04	1.36	3.01	4.51	0.04	2.53	4.49	5.89
Average:	0.06	1.28	2.87	3.93	0.04	2.20	3.57	4.38
Count:	9	9	9	9	9	9	9	9
Maximum:	0.27	1.86	3.90	4.93	0.06	3.16	4.74	5.97
Minimum:	0.02	0.56	2.24	2.58	0.03	1.16	2.80	3.07
Standard Deviation:	0.07	0.46	0.53	0.80	0.01	0.63	0.77	1.12

PERIOD 3.2.6
SUMMARY DATA 7
HIGH ALUM TO R1 AEROBIC, WITH ACID

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
10/01/95	89.30	49.11	32.58	23.48	98.39	52.09	36.88	30.01
11/01/95	76.07	41.84	27.29	19.84	87.64	29.77	33.57	27.78
12/01/95	87.64	46.30	28.44	20.01	97.57	51.92	36.21	29.27
13/01/95								
14/01/95								
15/01/95	92.60	45.48	21.17	12.40	102.53	48.29	30.43	20.51
16/01/95	84.42	44.36	20.20	9.27	93.53	42.54	27.48	17.05
17/01/95	81.11	36.75	17.38	10.26	93.53	43.37	26.49	18.21
18/01/95	89.41	39.24	17.72	8.94	96.04	45.70	24.84	15.40
19/01/95	89.41	39.24	17.72	8.94	96.04	45.70	24.84	15.40
20/01/95								
21/01/95								
22/01/95								
23/01/95	84.45	41.73	22.02	13.91	93.55	48.51	30.30	22.85
Average:	86.05	42.67	22.72	14.12	95.42	45.32	30.12	21.83
Count:	9	9	9	9	9	9	9	9
Maximum:	92.60	49.11	32.58	23.48	102.53	52.09	36.88	30.01
Minimum:	76.07	36.75	17.38	8.94	87.64	29.77	24.84	15.40
Standard Deviation:	4.81	3.73	5.15	5.27	3.89	6.34	4.36	5.57

PERIOD 3.2.6
SUMMARY DATA 8
HIGH ALUM TO R1 AEROBIC, WITH ACID

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
10/01/95	12.4	0.0	0.0	19.4	
11/01/95	12.4	0.0	0.0	18.8	
12/01/95	12.4	0.0	0.0	18.6	
13/01/95	12.4	0.0	0.0	18.4	
14/01/95	12.4	0.0	0.0	18.8	
15/01/95	12.4	0.0	0.0	18.7	
16/01/95	12.4	0.0	0.0	18.5	
17/01/95	12.4	0.0	0.0	18.8	
18/01/95	12.4	0.0	0.0	18.9	
19/01/95	12.4	0.0	0.0	19.3	
20/01/95	12.4	0.0	0.0	19.4	
21/01/95	12.4	0.0	0.0	18.9	
22/01/95	12.4	0.0	0.0	18.5	
23/01/95	12.4	0.0	0.0	18.8	
Average:				18.8	0.0
Count:	14	14	14	14	0
Maximum:	12.4	0.0	0.0	19.4	
Minimum:	12.4	0.0	0.0	18.4	
Standard Deviation:				0.3	0.0

PERIOD 3.2.7
SUMMARY DATA 1
HIGH ALUM TO R1 AEROBIC, WITH BICARB.

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
20/02/95	150			12.00	13.30	403	19	21			2.09
21/02/95	150	37.0	37.0	13.10	14.60	396	27	25		3.39	0.81
22/02/95	150	36.0	36.0	12.40	14.90	354	20	21			
23/02/95	150	37.2	39.4	12.90	16.00	370	18	17	69.0	3.29	2.45
24/02/95	150	36.5	37.2	10.80	12.50						
25/02/95	150	36.7	37.2								
26/02/95	150	35.8	37.4	10.60	8.80	324	17	16	46.7		
27/02/95	150	36.2	37.9			323	14	19	14.3		
28/02/95	150	36.2	37.9	9.60	11.40	304	11	17	14.0		
01/03/95	150	37.0	37.0								
02/03/95	150					249	11	17			
03/03/95	150	37.9	36.7	8.20							
04/03/95	150			8.00	7.90						
05/03/95	150	36.7	36.7	8.70	9.60	223	14	16			
06/03/95	150	36.2	37.4	9.30	12.30	167	15	16		1.05	2.58
07/03/95	150	36.7	37.9	9.60	10.70	398	15	16	11.0	0.91	2.21
08/03/95	150	36.7	37.9	9.20	8.70	363	13	20			
09/03/95	150	36.5	36.5	9.70	7.50	336	17	21			
10/03/95	150	37.0		8.90	10.30						
11/03/95	150	36.2	36.2	9.20	9.70						
12/03/95	150	35.3	35.3	9.00	6.30	281	21	15			
13/03/95	150	36.2	36.2	10.00	11.70	339	14	17			
14/03/95	150	36.7	36.7	10.00	10.70	304	13	15			
15/03/95	150	36.0	35.3	10.50	12.50	445	16	23			
16/03/95	150	35.3		12.30	13.30	433	11	10			
17/03/95	150	36.2	35.8	11.80	12.50						
18/03/95	150	36.5	35.8	11.80	12.00						
19/03/95	150	36.0	34.1	12.80	8.50	447	16	20			
20/03/95	150	36.2	35.3	13.40	14.00	417	17	20			
21/03/95	150	36.2		13.40	13.20	469	18	19			
22/03/95	150	37.0	36.0	13.40	12.60	358	17	16			
Average:	150	36.4	36.7	10.76	11.37	350	16	18	31.0	2.16	2.03
Count:	31	28	25	27	26	22	22	22	5	4	5
Maximum:	150	37.9	39.4	13.40	16.00	469	27	25	69.0	3.39	2.58
Minimum:	150	35.3	34.1	8.00	6.30	167	11	10	11.0	0.91	0.81
Standard Deviation:	0	0.5	1.1	1.73	2.41	75	4	3	23.1	1.18	0.63

APPENDIX 5

PERIOD 3.2.7
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
20/02/95	50.11	11.43	16.81	38.68	33.30	95.37	89.89
21/02/95	48.97	25.79	31.99	23.18	16.98	96.48	89.09
22/02/95	44.89	20.73	29.71	24.16	15.18	108.10	97.22
23/02/95	45.38	16.32	24.16	29.06	21.22	115.46	101.09
24/02/95							
25/02/95							
26/02/95	45.38	32.32		13.06		137.65	
27/02/95	45.83	25.63	29.90	20.20	15.93	125.50	97.49
28/02/95	44.35	19.55	26.94	24.80	17.41	129.76	104.67
01/03/95							
02/03/95	44.03	24.15	34.17	19.88	9.86	151.23	110.95
03/03/95							
04/03/95							
05/03/95	44.85	26.94	38.11	17.91	6.74	166.48	115.25
06/03/95	56.62	23.89	29.62	32.73	27.00	158.37	112.83
07/03/95	51.39	18.16	29.78	33.23	21.61	168.25	122.65
08/03/95	50.24	20.62	35.68	29.62	14.56	170.64	124.16
09/03/95	45.98		20.78		25.20	176.20	119.91
10/03/95							
11/03/95							
12/03/95	43.86	22.42		21.44		178.18	129.19
13/03/95	47.51	21.52	26.98	25.99	20.53	209.52	126.29
14/03/95	46.02	20.53	27.98	25.49	18.04	184.20	129.01
15/03/95	48.51	27.65	37.91	20.86	10.60	186.50	124.77
16/03/95	46.52	25.83	34.77	20.69	11.75	204.83	122.63
17/03/95							
18/03/95							
19/03/95	47.18	17.88		29.30		208.40	123.41
20/03/95	47.73	16.13	19.38	31.60	28.35	194.53	121.95
21/03/95	45.61	16.13	20.52	29.48	25.09	203.08	133.52
22/03/95	43.42	15.89	22.02	27.53	21.40	202.87	134.28
Average:	47.02	21.41	28.27	25.66	18.99	162.35	115.73
Count:	22	21	19	21	19	22	21
Maximum:	56.62	32.32	38.11	38.68	33.30	209.52	134.28
Minimum:	43.42	11.43	16.81	13.06	6.74	95.37	89.09
Standard Deviation:	3.00	4.88	6.20	5.89	6.73	36.46	13.65

PERIOD 3.2.7
SUMMARY DATA 3
HIGH ALUM TO R1 AEROBIC, WITH ACID, WITH BICARB.

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
20/02/95	61.91	60.52	3164	2054	2886	1943	64.9	67.3		
21/02/95	61.49	58.51	3265	2081	3041	1997	63.7	65.7	67	72
22/02/95	68.28	63.44	3347	2114	3062	1998	63.2	65.3	66	72
23/02/95	70.03	58.92	3380	2050	3380	1970	60.7	58.3	59	59
24/02/95										
25/02/95										
26/02/95	84.73		3410	2099			61.6		59	
27/02/95	76.42	65.39	3375	2055	2864	1921	60.9	67.1	53	45
28/02/95	75.78	66.32	3512	2051	2923	1852	58.4	63.4	51	58
01/03/95										
02/03/95	86.22	70.73	3182	1814	2764	1762	57.0	63.7		
03/03/95										
04/03/95										
05/03/95	93.35	74.84	3449	1934	2678	1739	56.1	64.9	52	60
06/03/95	78.30	63.22	4013	1984	3184	1784	49.4	56.0	47	53
07/03/95	80.29	68.82	4097	1955	3258	1828	47.7	56.1	46	46
08/03/95	84.70	70.44	4386	2177	3090	1753	49.6	56.7	46	52
09/03/95	87.01	68.85	4119	2034	2971	1706	49.4	57.4	51	54
10/03/95										
11/03/95										
12/03/95	87.73	75.02	4141	2039	2814	1634	49.2	58.1	51	60
13/03/95	100.30	73.77	4176	1999	3097	1809	47.9	58.4	50	52
14/03/95	90.17	75.60	4480	2193	3394	1989	49.0	58.6	49	53
15/03/95	94.70	75.73	4248	2157	3170	1924	50.8	60.7	49	60
16/03/95	102.44	72.43	4315	2158	3017	1782	50.0	59.1	51	63
17/03/95										
18/03/95										
19/03/95	103.72	77.74	4533	2256	3237	2039	49.8	63.0	48	56
20/03/95	98.95	77.64	4494	2286	3399	2164	50.9	63.7	49	50
21/03/95	101.99	80.03	4520	2270	3460	2074	50.2	59.9	49	52
22/03/95	101.33	80.80	4673	2334	3485	2097	49.9	60.2	47	55
Average:	85.90	70.42	3922	2095	3104	1894	54.1	61.1	52	56
Count:	22	21	22	22	21	21	22	21	20	19
Maximum:	103.72	80.80	4673	2334	3485	2164	64.9	67.3	67	72
Minimum:	61.49	58.51	3164	1814	2678	1634	47.7	56.0	46	45
Standard Deviation:	12.86	6.68	510	123	231	140	5.8	3.6	6	7

PERIOD 3.2.7
SUMMARY DATA 4
HIGH ALUM TO R1 AEROBIC, WITH ACID, WITH BICARB.

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk R1	H2CO3* Alk R2
20/02/95										
21/02/95			7.09	7.15	7.18	7.24	10	10		
22/02/95			7.18	7.15	7.29	7.30	10	10		
23/02/95	7.30	7.33	7.51	7.50	7.65	7.65	10	10		
24/02/95	7.34	7.25	7.39	7.37		7.53	10	10		
25/02/95	7.36	7.36	7.43	7.41	7.55	7.57	10	10		
26/02/95	7.66	7.45	7.71	7.72	7.87	7.95	10	10		
27/02/95	7.19	7.14	7.41	7.39	7.56	7.58	10	10		
28/02/95	7.34	7.30	7.71	7.81	7.93	8.02	10	10		
01/03/95	7.19	7.07	7.37	7.32	7.55	7.51	10	10		
02/03/95										
03/03/95	7.32	7.31	7.82	7.80	7.90	8.02	10	10		
04/03/95	7.30	7.42	7.63	7.71	7.72	7.79	10	10		
05/03/95	7.20	7.22	7.40	7.40	7.48	7.57	10	10		
06/03/95	7.28	7.26	7.33	7.34	7.45	7.50	10	10		
07/03/95	9.49	9.88	8.51	8.71	8.40	8.45	10	10		
08/03/95	7.37	7.35	7.60	7.57	7.72	7.72	10	10		
09/03/95	7.37	7.33	7.53	7.68	7.38	7.85	10	10		
10/03/95	7.27	7.33	7.55	7.61	7.57	7.49	10	10		
11/03/95	7.40	7.38	7.52	7.49	7.60	7.61	10	10		
12/03/95	7.19	7.42	7.58	7.51	7.68	7.67	10	10	275.4	325.1
13/03/95	7.33	7.32	7.47	7.50	7.62	7.60	10	10	267.9	315.2
14/03/95	7.27	7.29	7.46	7.53	7.60	7.68	10	10	265.3	302.6
15/03/95	7.46	7.58	7.56	7.59	7.64	7.72	10	10	271.3	312.4
16/03/95	7.26	7.24	7.54	7.44	7.68	7.63	10	10	293.0	322.2
17/03/95	7.25	7.22	7.52	7.48	7.66	7.69	10	10		
18/03/95	7.22	7.24	7.45	7.48	7.63	7.69	10	10		
19/03/95	7.09	7.16	7.41	7.36	7.56	7.57	10	10	300.5	325.2
20/03/95	7.14	7.13	7.42	7.52	7.61	7.78	10	10	283.5	324.2
21/03/95	7.25	7.17	7.53	7.50	7.69	7.75	10	10	284.4	325.9
22/03/95	7.09	7.04	7.46	7.42	7.62	7.63	10	10	285.5	320.1
Average:	7.37	7.38	7.52	7.53	7.64	7.68	10	10	280.8	319.2
Count:	27	27	29	29	28	29	29	29	9	9
Maximum:	9.49	9.88	8.51	8.71	8.40	8.45	10	10	300.5	325.9
Minimum:	7.09	7.04	7.09	7.15	7.18	7.24	10	10	265.3	302.6
Standard Deviation:	0.43	0.50	0.24	0.27	0.22	0.23	0	0	11.1	7.4

PERIOD 3.2.7
SUMMARY DATA 5
HIGH ALUM TO R1 AEROBIC, WITH ACID, WITH BICARB.

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
20/02/95	0.00	0.00	5.42	5.42	12.57	19.39
21/02/95	0.00	0.00	7.90	7.45	31.24	37.70
22/02/95	0.00	0.00	5.42	4.29	24.41	33.03
23/02/95	0.00	0.00	5.50	4.62	18.24	29.25
24/02/95						
25/02/95						
26/02/95	0.00	0.00	5.10	3.80		
27/02/95	0.00	0.00	3.07	2.65	30.58	35.18
28/02/95	0.00	0.00	3.10	2.87	24.33	31.57
01/03/95						
02/03/95	0.00	0.00	4.41	5.21	30.70	38.37
03/03/95						
04/03/95						
05/03/95	0.00	0.00	5.50	7.30	31.10	44.93
06/03/95	0.00	0.00	4.30	5.50	26.35	32.40
07/03/95	0.00	0.00	3.30	4.40	20.74	38.88
08/03/95	0.00	0.00	3.60	2.30	24.19	42.34
09/03/95		0.00	0.69	4.71		23.38
10/03/95						
11/03/95						
12/03/95	0.00		5.68	1.80	25.59	
13/03/95	0.00	0.04	7.07	5.94	24.55	27.97
14/03/95	0.00	0.00	6.50	5.70	22.12	31.33
15/03/95	0.00	0.00	6.50	5.70	31.33	42.85
16/03/95	0.00	0.00	5.74	4.76	25.04	32.80
17/03/95						
18/03/95						
19/03/95	0.00	0.00	5.49	1.95	17.02	
20/03/95	0.00	0.00	4.80	3.21	15.77	19.39
21/03/95	0.00	0.00	3.56	2.89	15.76	20.17
22/03/95	0.00	0.00	2.88	2.72	15.77	22.36
Average:	0.00	0.00	4.80	4.33	23.37	31.75
Count:	21	21	22	22	20	19
Maximum:	0.00	0.04	7.90	7.45	31.33	44.93
Minimum:	0.00	0.00	0.69	1.80	12.57	19.39
Standard Deviation:	0.00	0.01	1.60	1.60	5.82	7.86

PERIOD 3.2.7
SUMMARY DATA 6
HIGH ALUM TO R1 AEROBIC, WITH ACID, WITH BICARB.

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAR1	NO3 R1 fAR2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAR1	NO3 R2 fAR2
20/02/95								
21/02/95								
22/02/95								
23/02/95								
24/02/95								
25/02/95								
26/02/95	0.06	0.54	2.88	2.79	0.10	0.03	1.70	1.18
27/02/95	0.00	1.97	4.18	4.03	0.00	1.79	3.94	4.06
28/02/95								
01/03/95								
02/03/95								
03/03/95								
04/03/95								
05/03/95	0.00	2.68	5.00	5.20	0.00	3.50	6.29	6.59
06/03/95	0.09	1.73	3.76	3.70				
07/03/95								
08/03/95	0.00	1.97	4.35	4.23	0.00	0.09	2.53	2.70
09/03/95								
10/03/95								
11/03/95								
12/03/95	0.02	2.74	11.35	12.10	0.06	4.71	12.09	11.72
13/03/95	0.05	3.22	6.49	7.16	0.05	2.51	6.08	5.94
14/03/95								
15/03/95	0.03	3.08	6.35	5.43	0.08	1.78	4.86	5.30
16/03/95								
17/03/95								
18/03/95								
19/03/95	0.01	1.57	4.89	3.66	0.04	0.05	4.89	3.31
20/03/95								
21/03/95	0.03	0.13	2.84	2.79	0.01	0.05	2.84	2.79
22/03/95								
Average:	0.03	1.96	5.21	5.11	0.04	1.61	5.02	4.84
Count:	10	10	10	10	9	9	9	9
Maximum:	0.09	3.22	11.35	12.10	0.10	4.71	12.09	11.72
Minimum:	0.00	0.13	2.84	2.79	0.00	0.03	1.70	1.18
Standard Deviation:	0.03	0.98	2.36	2.65	0.04	1.62	2.90	2.92

PERIOD 3.2.7
SUMMARY DATA 7
HIGH ALUM TO R1 AEROBIC, WITH ACID, WITH BICARB.

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
20/02/95								
21/02/95								
22/02/95								
23/02/95								
24/02/95								
25/02/95								
26/02/95	66.93	42.22	33.46	27.42				
27/02/95	64.89	39.26	29.24	23.98	69.00	43.70	35.81	30.23
28/02/95								
01/03/95								
02/03/95								
03/03/95								
04/03/95								
05/03/95	55.03	35.65	27.60	23.98	67.35	47.97	41.23	35.98
06/03/95								
07/03/95								
08/03/95	65.46	36.33	25.86	20.62	73.64	46.15	38.78	32.24
09/03/95								
10/03/95								
11/03/95								
12/03/95	60.55	34.69	24.87	19.80	58.91	29.95	24.22	23.07
13/03/95	72.84	39.73	27.65	20.53	71.19	45.20	33.77	26.98
14/03/95								
15/03/95	86.09	51.65	39.24	31.29	81.95	55.79	44.53	37.91
16/03/95								
17/03/95								
18/03/95								
19/03/95	84.43	41.55	23.18	16.89	94.36	61.75	41.39	31.79
20/03/95								
21/03/95	87.96	43.66	25.74	17.10	88.78	50.33	32.42	22.15
22/03/95								
Average:	71.58	40.53	28.54	22.40	75.65	47.61	36.52	30.04
Count:	9	9	9	9	8	8	8	8
Maximum:	87.96	51.65	39.24	31.29	94.36	61.75	44.53	37.91
Minimum:	55.03	34.69	23.18	16.89	58.91	29.95	24.22	22.15
Standard Deviation:	11.28	4.89	4.69	4.49	11.06	8.73	6.03	5.31

PERIOD 3.2.7
SUMMARY DATA 8
HIGH ALUM TO R1 AEROBIC, WITH ACID, WITH BICARB.

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
20/02/95				20.6	
21/02/95				17.2	
22/02/95				18.7	
23/02/95				21.7	
24/02/95				18.7	
25/02/95					
26/02/95				18.8	
27/02/95					
28/02/95				18.7	
01/03/95					
02/03/95					
03/03/95				19.8	
04/03/95				19.9	
05/03/95				18.6	
06/03/95				19.0	
07/03/95				19.3	
08/03/95				19.0	
09/03/95				19.9	
10/03/95				20.0	
11/03/95				19.2	
12/03/95				18.8	
13/03/95				19.4	
14/03/95				19.8	
15/03/95				19.6	
16/03/95				19.9	
17/03/95				18.7	
18/03/95				18.7	
19/03/95				19.1	
20/03/95				19.4	
21/03/95				19.8	
22/03/95				19.7	
Average:				19.3	0.0
Count:	0	0	0	27	0
Maximum:				21.7	
Minimum:				17.2	
Standard Deviation:				0.8	0.0

PERIOD 3.2.8(A)
SUMMARY DATA 1
HIGH ALUM TO R1 AEROBIC, NO BICARB.

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
23/03/95	150	34.6	34.6	12.50	12.20	377	16	15			
24/03/95	150	36.0	36.0	12.30	12.10						
25/03/95	150	35.8	35.8	9.10	8.90						
26/03/95	150	36.0	35.0	6.70	7.60	171	10	9			
27/03/95	150	35.0	35.0	10.20	10.70	373	11	13	22.6	2.29	4.07
28/03/95	150	36.0	36.0			288	18	18			
29/03/95	150	36.0	35.3	13.70	17.00	296	14	16		3.67	
30/03/95	150	36.0	35.0	10.90	11.70	253	17	13			
31/03/95	150	36.5	35.3	10.20	10.90						
01/04/95	150	36.7	36.7	9.90	10.70						
02/04/95	150	36.7	35.5	9.90	8.00	303	14	14	16.8	2.00	2.00
03/04/95	150	36.0	36.0	9.10	10.00	243	11	17			
04/04/95	150	37.2	37.9	9.20	9.30	271	13	15	16.7	2.00	2.00
05/04/95	150	36.5	36.5	9.20	9.20	254	11	13			
06/04/95	150	36.5	36.5	10.60	12.30	483	27	32	14.5	2.00	2.00
07/04/95	150	37.7	38.4	11.70	12.10						
08/04/95	150	36.0	34.1	12.10	12.20						
09/04/95	150	36.0	36.0	11.70	10.50	349	18	18	24.6	2.00	2.00
10/04/95	150	36.2	37.0	10.90	10.70	428	15	18			
11/04/95	150	37.2	37.2	10.80	11.10	310	13	13	15.8	2.00	2.00
12/04/95	150	36.5	36.7	12.10	12.50	395	16	15			
13/04/95	150	37.0	38.2	12.10	12.40	278	21	17	22.1	2.00	2.00
14/04/95	150	39.6	39.6	11.50							
15/04/95	150	36.5	37.7	11.30	21.20						
16/04/95	150	37.2		9.00	12.40	275	20	16	21.8	3.33	5.56
17/04/95	150	36.7	37.7	9.10	10.00	235	21	16			
18/04/95	150	37.2	37.7	9.30	11.00	346	20	13	30.6	3.70	3.98
19/04/95	150	37.2	37.4	10.60	12.40	342	21	17			
20/04/95	150	37.0	37.0	10.50	12.70	329	19	17	30.2	4.33	3.54
21/04/95	150	37.2	37.9	12.80	11.40						
22/04/95	150	36.7	34.8	11.80	10.90						
23/04/95	150	35.8	33.6	11.10		289	19	17	23.7	3.85	3.21
24/04/95	150	36.5		9.70	9.60	305	17	15			
25/04/95	150	37.0	37.0	10.00	9.70	286	19	15	20.1	3.12	2.00
Average:	150	36.6	36.4	10.65	11.40	312	17	16	21.6	2.79	2.86
Count:	34	34	32	33	31	24	24	24	12	13	12
Maximum:	150	39.6	39.6	13.70	21.20	483	27	32	30.6	4.33	5.56
Minimum:	150	34.6	33.6	6.70	7.60	171	10	9	14.5	2.00	2.00
Standard Deviation:	0	0.8	1.4	1.41	2.48	66	4	4	5.0	0.85	1.15

APPENDIX 5

PERIOD 3.2.8(A)
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
23/03/95	43.89	16.52	23.28	27.37	20.61	206.20	131.95
24/03/95							
25/03/95							
26/03/95	38.70	24.38	28.79	14.32	9.91	225.47	163.43
27/03/95	44.20						146.84
28/03/95	42.00						
29/03/95	42.63	19.82	26.59	22.81	16.04		146.52
30/03/95	41.69	14.47	22.50	27.22	19.19	212.06	155.64
31/03/95							
01/04/95							
02/04/95	46.15	24.70		21.45		231.23	
03/04/95	44.85	23.40	32.83	21.45	12.02	250.91	162.07
04/04/95	47.29	25.84	33.64	21.45	13.65	246.52	168.77
05/04/95	45.67	24.70	34.45	20.97	11.22	259.99	169.52
06/04/95	49.08	28.77	39.17	20.31	9.91	236.86	199.24
07/04/95							
08/04/95							
09/04/95	49.23	11.41	21.19	37.82	28.04	247.02	173.11
10/04/95	47.92	13.20	21.52	34.72	26.40	257.97	176.74
11/04/95	46.62	12.71	18.58	33.91	28.04	255.55	170.99
12/04/95	47.11	16.46	22.66	30.65	24.45	288.35	206.00
13/04/95	47.95	18.39	22.50	29.56	25.45	270.72	199.70
Average:	45.31	19.63	26.75	26.00	18.84	245.30	169.32
Count:	16	14	13	14	13	13	14
Maximum:	49.23	28.77	39.17	37.82	28.04	288.35	206.00
Minimum:	38.70	11.41	18.58	14.32	9.91	206.20	131.95
Standard Deviation:	2.87	5.44	6.15	6.45	6.81	22.04	20.58

PERIOD 3.2.8(A)
SUMMARY DATA 3
HIGH ALUM TO R1 AEROBIC, WITH ACID, NO BICARB.

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
23/03/95	102.03	80.82	4533	2243	3484	2134	49.5	61.3	51	55
24/03/95										
25/03/95										
26/03/95	109.16	94.62	4410	2135	3242	1877	48.4	57.9	48	59
27/03/95		86.21	4370	2145	3376	1982	49.1	58.7	50	53
28/03/95			4207	2196	3173	2053	52.2	64.7	52	57
29/03/95		88.16	4424	2193	3319	1997	49.6	60.2	50	54
30/03/95	105.30	93.18	4213	2092	3140	1880	49.7	59.9	52	57
31/03/95										
01/04/95										
02/04/95	112.98		4085	1996			48.9		51	
03/04/95	117.38	96.03	4209	1969	3080	1825	46.8	59.3	52	55
04/04/95	116.31	99.37	4080	1925	2911	1714	47.2	58.9	54	58
05/04/95	122.61	99.59	4016	1894	2921	1716	47.2	58.7	55	58
06/04/95	111.71	116.74	4088	1928	2840	1664	47.2	58.6	54	60
07/04/95										
08/04/95										
09/04/95	116.43	100.70	4396	2072	3189	1855	47.1	58.2	52	53
10/04/95	121.33	101.41	4299	2022	3247	1863	47.0	57.4	54	55
11/04/95	121.56	100.16	4358	2073	3206	1878	47.6	58.6	50	53
12/04/95	134.98	115.37	4456	2086	3405	1907	46.8	56.0	52	50
13/04/95	130.11	117.57	4455	2141	3268	1924	48.1	58.9	52	52
14/04/95										
15/04/95										
16/04/95	127.43	109.64	4381	2106	3205	1835	48.1	57.3		
17/04/95	134.76	119.72	4301	2005	3278	1820	46.6	55.5	53	55
18/04/95	158.82	102.19	4301	2005	3278	1820	46.6	55.5	51	55
19/04/95	127.53	121.50	4249	2041	3203	1827	48.0	57.0		56
20/04/95	129.81	117.29	4172	1971	3055	1746	47.2	57.2	55	62
21/04/95										
22/04/95										
23/04/95	125.86	112.74	4056	1938	3280	1878	47.8	57.3	58	60
24/04/95	122.20	111.27	4057	1966	3235	1835	48.5	56.7	57	62
25/04/95	118.79	128.34	4201	2018	3200	1778	48.0	55.6	52	66
Average:	122.24	105.12	4263	2048	3197	1861	48.1	58.2	53	57
Count:	21	22	24	24	23	23	24	23	22	22
Maximum:	158.82	128.34	4533	2243	3484	2134	52.2	64.7	58	66
Minimum:	102.03	80.82	4016	1894	2840	1664	46.6	55.5	48	50
Standard Deviation:	11.98	12.40	146	93	151	106	1.3	2.0	2	4

PERIOD 3.2.8 (A)
SUMMARY DATA 4
HIGH ALUM TO R1 AEROBIC, WITH ACID, NO BICARB.

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk R1	H2CO3* Alk R2
23/03/95	7.11	7.05	7.40	7.41	7.59	7.63	10	10	228.6	264.7
24/03/95	6.98	6.97	7.31	7.31	7.44	7.50	10	10		
25/03/95	6.96	6.92	7.19	7.20	7.33	7.39	10	10		
26/03/95	7.18	7.12	7.35	7.40	7.40	7.47	10	10	162.4	200.7
27/03/95	7.09	6.99	7.20	7.20	7.23	7.29	10	10		
28/03/95	7.01	6.95	7.07	7.11	7.17	7.28	10	10	109.5	145.2
29/03/95	6.75	6.86	6.87	6.99	6.81	7.01	10	10	135.2	165.6
30/03/95	6.98	6.98	7.03	7.08	7.16	7.29	10	10	145.6	177.9
31/03/95	6.99	6.93	7.09	7.07	7.19	7.23	10	10		
01/04/95	6.88	6.80	6.96	7.06	7.08	7.21	10	10		
02/04/95	7.02	6.99	7.24	7.17	7.28	7.26	10	10	133.5	159.0
03/04/95	6.97	6.95	7.08	7.19	7.20	7.22	10	10	131.9	164.4
04/04/95	7.06	7.07	7.25	7.12	7.28	7.23	10	10	131.8	168.5
05/04/95	7.08	6.99	7.18	7.20	7.32	7.38	10	10	135.8	168.1
06/04/95	7.09	7.02	7.25	7.20	7.31	7.34	10	10	126.5	167.3
07/04/95	6.98	6.95	7.12	7.21	7.20	7.39	10	10		
08/04/95	7.00	6.89	7.34	7.35	7.49	7.55	10	10		
09/04/95	6.97	6.80	7.25	7.14	7.39	7.35	10	10	150.0	165.8
10/04/95	7.26	7.24	7.53	7.60	7.67	7.80	10	10	144.9	181.8
11/04/95	7.00	6.94	7.30	7.26	7.45	7.50	10	10	150.1	187.2
12/04/95	7.00	6.93	7.29	7.26	7.42	7.50	10	10	136.6	179.4
13/04/95	6.98	6.91	7.26	7.22	7.39	7.45	10	10	142.0	179.8
14/04/95	6.92	7.01	7.17	7.12	7.28	7.27	10	10		
15/04/95										
16/04/95	6.86	7.19	7.06	7.34	7.19	7.54	10	10	117.4	174.8
17/04/95	6.98	6.88	7.16	7.13	7.08	7.33	10	10	100.5	144.3
18/04/95	6.98	6.94	7.13	7.09	7.18	7.25	10	10	91.8	131.8
19/04/95	7.02	6.93	7.15	7.06	6.98	7.24	10	10	105.1	145.1
20/04/95	7.03	6.95	7.07	7.07	7.18	7.27	10	10	100.8	142.7
21/04/95	7.03	6.96	7.04	7.12	7.15	7.28	10	10		
22/04/95	7.05	7.02	6.95	7.08	7.11	7.25	10	10		
23/04/95	6.77	6.76	6.90	7.04	7.06	7.23	10	10	130.3	157.9
24/04/95	7.01	7.01	7.05	7.58	7.24	7.88	10	10	131.2	174.1
25/04/95	7.00	6.85	7.14	7.25	7.29	7.46	10	10	135.8	181.8
Average:	7.00	6.96	7.16	7.20	7.26	7.37	10	10	133.8	170.8
Count:	33	33	33	33	33	33	33	33	23	23
Maximum:	7.26	7.24	7.53	7.60	7.67	7.88	10	10	228.6	264.7
Minimum:	6.75	6.76	6.87	6.99	6.81	7.01	10	10	91.8	131.8
Standard Deviation:	0.10	0.10	0.14	0.14	0.17	0.17	0	0	26.7	25.7

PERIOD 3.2.8(A)
SUMMARY DATA 5
HIGH ALUM TO R1 AEROBIC, WITH ACID, NO BICARB.

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
23/03/95	0.00	0.00	3.14	2.68	16.11	23.39
24/03/95						
25/03/95						
26/03/95	0.00	0.00	1.65	1.11	22.35	27.67
27/03/95	0.00	0.00	5.35	4.74		
28/03/95						
29/03/95	0.71	0.43	6.06	5.72	20.10	25.94
30/03/95	0.38	0.33	5.52	4.59	14.03	22.42
31/03/95						
01/04/95						
02/04/95	0.33	0.33	4.94	3.52	23.31	
03/04/95	0.43	0.33	5.08	3.55	21.64	31.26
04/04/95	0.53	0.19	5.01	4.85	24.85	32.48
05/04/95	0.86	0.56	5.09	4.73	23.42	32.70
06/04/95	0.76	0.60	5.10	4.32	27.62	37.56
07/04/95						
08/04/95						
09/04/95	0.39	0.21	2.19	2.22	10.49	20.21
10/04/95	0.32	0.20	3.14	2.40	12.10	20.17
11/04/95	0.18	0.19	2.88	2.36	11.60	17.27
12/04/95	0.53	0.31	4.89	3.86	15.37	21.87
13/04/95	0.19	0.09	5.21	3.67	17.78	22.31
14/04/95						
15/04/95						
16/04/95	0.14	0.14	5.81	4.62	22.53	16.35
17/04/95	0.14	0.87	6.54	5.42	25.07	23.53
18/04/95	0.14	0.12	7.26	6.29	35.71	30.84
19/04/95	0.24	0.24	8.72	7.02	23.81	30.30
20/04/95	0.00	0.00	10.40	6.55	26.18	32.36
21/04/95						
22/04/95						
23/04/95	0.00	0.00	4.84	4.59	24.85	29.38
24/04/95	0.00	0.00	4.59	3.35	23.31	25.74
25/04/95	0.24	0.19	4.13	2.05	19.88	18.78
Average:	0.28	0.23	5.11	4.10	21.01	25.83
Count:	23	23	23	23	22	21
Maximum:	0.86	0.87	10.40	7.02	35.71	37.56
Minimum:	0.00	0.00	1.65	1.11	10.49	16.35
Standard Deviation:	0.25	0.22	1.91	1.50	5.87	5.73

PERIOD 3.2.8(A)
SUMMARY DATA 6
HIGH ALUM TO R1 AEROBIC, WITH ACID, NO BICARB.

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
23/03/95								
24/03/95								
25/03/95								
26/03/95								
27/03/95								
28/03/95								
29/03/95								
30/03/95								
31/03/95								
01/04/95								
02/04/95								
03/04/95	0.00	2.68	4.57	4.79	0.00	1.44	3.64	3.84
04/04/95								
05/04/95								
06/04/95								
07/04/95								
08/04/95								
09/04/95	0.00	0.40	2.22	2.19	0.00	0.11	2.23	2.23
10/04/95	0.00	0.97	2.96	2.91	0.00	0.24	2.63	2.34
11/04/95								
12/04/95	0.02	2.14	5.00	5.18	0.00	0.79	3.99	3.92
13/04/95								
14/04/95								
15/04/95								
16/04/95								
17/04/95	0.00	4.43	6.90	7.99	0.00	2.90	5.32	5.32
18/04/95	0.00	4.21	7.99	7.51	0.00	3.48	7.51	7.26
19/04/95								
20/04/95								
21/04/95								
22/04/95								
23/04/95								
24/04/95	0.00	2.02	4.65	3.94	0.00	0.59	2.69	2.55
25/04/95								
Average:	0.00	2.41	4.90	4.93	0.00	1.36	4.00	3.92
Count:	7	7	7	7	7	7	7	7
Maximum:	0.02	4.43	7.99	7.99	0.00	3.48	7.51	7.26
Minimum:	0.00	0.40	2.22	2.19	0.00	0.11	2.23	2.23
Standard Deviation:	0.01	1.40	1.88	2.02	0.00	1.23	1.73	1.71

PERIOD 3.2.8(A)
SUMMARY DATA 7
HIGH ALUM TO R1 AEROBIC, WITH ACID, NO BICARB.

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
23/03/95								
24/03/95								
25/03/95								
26/03/95	49.55	44.83	34.14	28.79	52.70	39.64	33.66	30.68
27/03/95								
28/03/95								
29/03/95								
30/03/95								
31/03/95								
01/04/95								
02/04/95								
03/04/95	68.26	34.78	28.28	21.94	73.94	46.32	35.59	29.42
04/04/95								
05/04/95								
06/04/95								
07/04/95								
08/04/95								
09/04/95	77.43	34.56	18.75	10.11	86.39	48.74	30.16	19.89
10/04/95	86.39	40.43	22.98	13.53	92.91	52.49	33.93	21.19
11/04/95								
12/04/95	87.85	42.69	27.09	17.24	96.06	56.81	34.48	22.66
13/04/95								
14/04/95								
15/04/95								
16/04/95								
17/04/95	64.04	37.77	29.39	25.12	69.78	43.35	33.99	27.75
18/04/95	90.31	56.81	40.06	35.96	94.41	58.78	44.17	35.30
19/04/95								
20/04/95	80.17	47.94	35.83	28.80	92.44	56.45	41.56	33.54
21/04/95								
22/04/95								
23/04/95								
24/04/95	89.17	48.59	34.69	26.67	103.08	56.28	37.80	27.49
25/04/95								
Average:	77.02	43.16	30.13	23.13	84.63	50.98	36.15	27.55
Count:	9	9	9	9	9	9	9	9
Maximum:	90.31	56.81	40.06	35.96	103.08	58.78	44.17	35.30
Minimum:	49.55	34.56	18.75	10.11	52.70	39.64	30.16	19.89
Standard Deviation:	13.08	6.85	6.34	7.77	15.11	6.40	4.10	5.08

PERIOD 3.2.8(A)
SUMMARY DATA 8
HIGH ALUM TO R1 AEROBIC, WITH ACID, NO BICARB.

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
23/03/95	12.4	0.0	0.0	19.8	
24/03/95	12.4	0.0	0.0	19.8	
25/03/95	12.4	0.0	0.0	19.8	
26/03/95	12.4	0.0	0.0	19.2	
27/03/95	12.4	0.0	0.0	19.9	
28/03/95	12.4	0.0	0.0		
29/03/95	12.4	0.0	0.0	19.5	
30/03/95	12.4	0.0	0.0	19.5	
31/03/95	12.4	0.0	0.0	19.6	
01/04/95	12.4	0.0	0.0	19.4	
02/04/95	12.4	0.0	0.0	19.7	
03/04/95	12.4	0.0	0.0	19.7	
04/04/95	12.4	0.0	0.0	19.8	
05/04/95	12.4	0.0	0.0	19.7	
06/04/95	12.4	0.0	0.0	19.6	
07/04/95	12.4	0.0	0.0	19.5	
08/04/95	12.4	0.0	0.0	19.4	
09/04/95	12.4	0.0	0.0	19.4	
10/04/95	12.4	0.0	0.0	19.0	
11/04/95	12.4	0.0	0.0	19.1	
12/04/95	12.4	0.0	0.0	19.5	
13/04/95	12.4	0.0	0.0	19.4	
14/04/95	12.4	0.0	0.0	18.9	
15/04/95	12.4	0.0	0.0	19.5	
16/04/95	12.4	0.0	0.0	20.0	
17/04/95	12.4	0.0	0.0	19.5	
18/04/95	12.4	0.0	0.0	19.7	
19/04/95	12.4	0.0	0.0	19.4	
20/04/95	12.4	0.0	0.0	19.6	
21/04/95	12.4	0.0	0.0	19.9	
22/04/95	12.4	0.0	0.0	19.7	
23/04/95	12.4	0.0	0.0	19.7	
24/04/95	12.4	0.0	0.0	19.6	
25/04/95	12.4	0.0	0.0	19.6	
Average:				19.6	0.0
Count:	34	34	34	33	0
Maximum:	12.4	0.0	0.0	20.0	
Minimum:	12.4	0.0	0.0	18.9	
Standard Deviation:				0.2	0.0

PERIOD 3.2.8(B)
SUMMARY DATA 1
HIGH ALUM TO R1 AEROBIC, NO BICARB.

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
16/04/95	150	37.2		9.00	12.40	275	20	16	21.8	3.33	5.56
17/04/95	150	36.7	37.7	9.10	10.00	235	21	16			
18/04/95	150	37.2	37.7	9.30	11.00	346	20	13	30.6	3.70	3.98
19/04/95	150	37.2	37.4	10.60	12.40	342	21	17			
20/04/95	150	37.0	37.0	10.50	12.70	329	19	17	30.2	4.33	3.54
21/04/95	150	37.2	37.9	12.80	11.40						
22/04/95	150	36.7	34.8	11.80	10.90						
23/04/95	150	35.8	33.6	11.10		289	19	17	23.7	3.85	3.21
24/04/95	150	36.5		9.70	9.60	305	17	15			
25/04/95	150	37.0	37.0	10.00	9.70	286	19	15	20.1	3.12	2.00
Average:	150	36.9	36.6	10.39	11.12	301	20	16	25.3	3.67	3.66
Count:	10	10	8	10	9	8	8	8	5	5	5
Maximum:	150	37.2	37.9	12.80	12.70	346	21	17	30.6	4.33	5.56
Minimum:	150	35.8	33.6	9.00	9.60	235	17	13	20.1	3.12	2.00
Standard Deviation:	0	0.4	1.5	1.17	1.13	35	1	1	4.3	0.42	1.16

PERIOD 3.2.8(B)
SUMMARY DATA 2

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R2 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
16/04/95	43.51	22.99	16.42	20.52	27.09	265.09	191.49
17/04/95	42.69	26.27	24.30	16.42	18.39	289.09	215.63
18/04/95	47.29	35.63	34.32	11.66	12.97	340.68	184.05
19/04/95	46.47	27.09	31.85	19.38	14.62	265.49	213.00
20/04/95	49.58	28.80	33.87	20.78	15.71	274.77	205.23
21/04/95							
22/04/95							
23/04/95	45.32	26.67	31.25	18.65	14.07	263.41	196.90
24/04/95	45.81	25.36	26.99	20.45	18.82	252.17	196.16
25/04/95	45.65	21.60	20.29	24.05	25.36	247.29	230.98
Average:	45.79	26.80	27.41	18.99	18.38	274.75	204.18
Count:	8	8	8	8	8	8	8
Maximum:	49.58	35.63	34.32	24.05	27.09	340.68	230.98
Minimum:	42.69	21.60	16.42	11.66	12.97	247.29	184.05
Standard Deviation:	2.00	3.97	6.18	3.43	4.92	27.67	14.19

PERIOD 3.2.8(B)
SUMMARY DATA 3

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
16/04/95	127.43	109.64	4381	2106	3205	1835	48.1	57.3		
17/04/95	134.76	119.72	4301	2005	3278	1820	46.6	55.5	53	55
18/04/95	158.82	102.19	4301	2005	3278	1820	46.6	55.5	51	55
19/04/95	127.53	121.50	4249	2041	3203	1827	48.0	57.0		56
20/04/95	129.81	117.29	4172	1971	3055	1746	47.2	57.2	55	62
21/04/95										
22/04/95										
23/04/95	125.86	112.74	4056	1938	3280	1878	47.8	57.3	58	60
24/04/95	122.20	111.27	4057	1966	3235	1835	48.5	56.7	57	62
25/04/95	118.79	128.34	4201	2018	3200	1778	48.0	55.6	52	66
Average:	130.65	115.34	4215	2006	3217	1817	47.6	56.5	54	59
Count:	8	8	8	8	8	8	8	8	6	7
Maximum:	158.82	128.34	4381	2106	3280	1878	48.5	57.3	58	66
Minimum:	118.79	102.19	4056	1938	3055	1746	46.6	55.5	51	55
Standard Deviation:	11.54	7.57	109	49	69	37	0.7	0.8	3	4

PERIOD 3.2.8(B)
SUMMARY DATA 4

	DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
	16/04/95	6.86	7.19	7.06	7.34	7.19	7.54	10	10	117.4	174.8
	17/04/95	6.98	6.88	7.16	7.13	7.08	7.33	10	10	100.5	144.3
	18/04/95	6.98	6.94	7.13	7.09	7.18	7.25	10	10	91.8	131.8
	19/04/95	7.02	6.93	7.15	7.06	6.98	7.24	10	10	105.1	145.1
	20/04/95	7.03	6.95	7.07	7.07	7.18	7.27	10	10	100.8	142.7
	21/04/95	7.03	6.96	7.04	7.12	7.15	7.28	10	10		
	22/04/95	7.05	7.02	6.95	7.08	7.11	7.25	10	10		
	23/04/95	6.77	6.76	6.90	7.04	7.06	7.23	10	10	130.3	157.9
	24/04/95	7.01	7.01	7.05	7.58	7.24	7.88	10	10	131.2	174.1
	25/04/95	7.00	6.85	7.14	7.25	7.29	7.46	10	10	135.8	181.8
Average:		6.97	6.95	7.07	7.18	7.15	7.37	10	10	114.1	156.6
Count:		10	10	10	10	10	10	10	10	8	8
Maximum:		7.05	7.19	7.16	7.58	7.29	7.88	10	10	135.8	181.8
Minimum:		6.77	6.76	6.90	7.04	6.98	7.23	10	10	91.8	131.8
Standard Deviation:		0.08	0.11	0.08	0.16	0.09	0.20	0	0	15.7	17.2

PERIOD 3.2.8(B)
SUMMARY DATA 5

	DATE	NH3 fR1	NH3 fR2	NO3 fR1	NO3 fR2	SRP fR1	SRP fR2
	16/04/95	0.14	0.14	5.81	4.62	22.53	16.35
	17/04/95	0.14	0.87	6.54	5.42	25.07	23.53
	18/04/95	0.14	0.12	7.26	6.29	35.71	30.84
	19/04/95	0.24	0.24	8.72	7.02	23.81	30.30
	20/04/95	0.00	0.00	10.40	6.55	26.18	32.36
	21/04/95						
	22/04/95						
	23/04/95	0.00	0.00	4.84	4.59	24.85	29.38
	24/04/95	0.00	0.00	4.59	3.35	23.31	25.74
	25/04/95	0.24	0.19	4.13	2.05	19.88	18.78
Average:		0.11	0.20	6.54	4.99	25.17	25.91
Count:		8	8	8	8	8	8
Maximum:		0.24	0.87	10.40	7.02	35.71	32.36
Minimum:		0.00	0.00	4.13	2.05	19.88	16.35
Standard Deviation:		0.10	0.27	2.04	1.58	4.37	5.54

PERIOD 3.2.8(B)
SUMMARY DATA 6

	DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
	16/04/95								
	17/04/95	0.00	4.43	6.90	7.99	0.00	2.90	5.32	5.32
	18/04/95	0.00	4.21	7.99	7.51	0.00	3.48	7.51	7.26
	19/04/95								
	20/04/95								
	21/04/95								
	22/04/95								
	23/04/95								
	24/04/95	0.00	2.02	4.65	3.94	0.00	0.59	2.69	2.55
	25/04/95								
Average:		0.00	3.55	6.51	6.48	0.00	2.32	5.17	5.04
Count:		3	3	3	3	3	3	3	3
Maximum:		0.00	4.43	7.99	7.99	0.00	3.48	7.51	7.26
Minimum:		0.00	2.02	4.65	3.94	0.00	0.59	2.69	2.55
Standard Deviation:		0.00	1.09	1.39	1.81	0.00	1.25	1.97	1.93

PERIOD 3.2.8(B)
SUMMARY DATA 7

	DATE	TP R1 fAN	TP R1 fAX	TP R1 fAB1	TP R1 fAB2	TP R2 fAN	TP R2 fAX	TP R2 fAB1	TP R2 fAB2
	16/04/95								
	17/04/95	64.04	37.77	29.39	25.12	69.78	43.35	33.99	27.75
	18/04/95	90.31	56.81	40.06	35.96	94.41	58.78	44.17	35.30
	19/04/95								
	20/04/95	80.17	47.94	35.83	28.80	92.44	56.45	41.56	33.54
	21/04/95								
	22/04/95								
	23/04/95								
	24/04/95	89.17	48.59	34.69	26.67	103.08	56.28	37.80	27.49
	25/04/95								
Average:		80.92	47.78	34.99	29.14	89.93	53.72	39.38	31.02
Count:		4	4	4	4	4	4	4	4
Maximum:		90.31	56.81	40.06	35.96	103.08	58.78	44.17	35.30
Minimum:		64.04	37.77	29.39	25.12	69.78	43.35	33.99	27.49
Standard Deviation:		10.51	6.75	3.80	4.15	12.30	6.07	3.85	3.46

PERIOD 3.3.1
SUMMARY DATA 1
LOW FERRIC TO R1 AEROBIC

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
16/05/95	150	38.6	37.4	15.60	11.10	474	19	15	40.5	3.56	2.00
17/05/95	150	36.2	35.5	18.10	16.10	415	19	17			
18/05/95	150	36.5	36.5	13.70	17.00	397	16	16	16.0	3.61	2.00
19/05/95	150	36.2	36.2	12.80	17.30						
20/05/95	150	36.7	35.3	14.30	17.30						
21/05/95	150	36.5	36.2	14.40	15.30	352	20	19	23.3	5.26	3.58
22/05/95	150	35.8	35.8	16.00	16.70	604	21	18			
23/05/95	150	37.0	36.0	17.20	18.10	573	23	21	59.7	3.54	2.00
24/05/95	150	36.0	35.8	20.60	20.80	489	34	20	52.9		
25/05/95	150	37.7	36.5	19.90	22.00	514	35	28	53.4	4.79	3.65
26/05/95	150	36.0	35.5	20.00	21.30						
27/05/95	150	36.5	36.5	18.40	19.00						
28/05/95	150	36.5		16.90	20.40	475	26	25	40.5	3.01	2.00
29/05/95	150	36.2	37.2	16.90	21.00	521	22	23			
30/05/95	150	36.2	37.0	18.20	23.30	527	26	24	39.3	3.30	2.00
31/05/95	150	37.2	37.2	17.30	20.10	489	22	27			
01/06/95	150	36.5	36.5	17.30	22.60	559			36.9	2.00	2.00
02/06/95	150	37.2	36.5	17.60	19.70						
03/06/95	150	36.0	37.4	17.40	21.70						
04/06/95	150	34.8		16.20	12.59	481	28	26	17.9	2.00	2.00
05/06/95	150	35.8	37.4	17.10	23.30	637	25	24			
06/06/95	150	35.5	35.5	18.50	26.10	578	21	23	29.0	4.46	2.00
07/06/95	150	35.3	35.8	20.30	21.70	436	21	23			
08/06/95	150	34.8	34.8	18.60	20.40	392	17	14	32.3	3.39	2.00
09/06/95	150	36.0	36.0	17.90	24.40						
10/06/95	150	37.0	37.0	18.40	25.60						
11/06/95	150	35.5	36.2	16.10		436	20	23			
12/06/95	150	36.5	37.2	18.10	17.30	404	25	25			
13/06/95	150	36.7	36.7	19.70	17.90	508	21	21	12.0	2.00	3.80
14/06/95	150	37.0	37.0	19.00	19.60	393	19	20			
15/06/95	150	36.7	37.7	17.70	20.10						
16/06/95	150	35.8	38.4	17.60	21.00						
17/06/95	150	35.5	37.0	17.80							
18/06/95	150	36.7	37.2	16.20		278	18	19	27.6	2.00	2.00
19/06/95	150	36.2	36.2	15.50	19.80	374	20	19			
20/06/95	150	37.2	37.2	14.30	15.30	338	19	17	36.4	2.00	2.00
21/06/95	150		37.0	17.30	16.30	329	16	16			
22/06/95	150	31.7	36.2	15.40	13.00	290	16	16	10.8	2.00	2.00
23/06/95	150			15.10	13.00						
24/06/95	150	38.6	26.6	17.30	16.30						
25/06/95	150	38.4	39.4	16.20	15.10	406	18	14	13.7	2.00	2.00
26/06/95	150	34.8	35.8	15.80	15.70	445	19	20			
27/06/95	150	34.8	34.8	15.50	17.10	376	21	20	33.4	3.92	2.00
28/06/95	150	36.5	36.5	15.70	19.40	333	16	18			
29/06/95	150	34.3	35.8	16.00	14.90	406	19	17	34.9	2.00	2.00
30/06/95	150	34.8	34.8	17.70	15.30						
01/07/95	150	35.0	35.0	17.50	15.00						
02/07/95	150	35.3	35.3	16.10	14.20	349	17	16	29.7	2.00	2.00
03/07/95	150	35.3	34.8	15.70	15.40	478	18	15			
04/07/95	150	35.5	35.5	15.70	16.20	387	17	17	19.1	2.00	2.00
05/07/95	150	34.1	35.3	17.10	15.70	428	14	17			
06/07/95	150	34.8		15.60	14.90	362	16	14	13.2	2.00	2.00
07/07/95	150	34.8	35.5	12.50	15.30						
08/07/95	150	35.8	35.8	12.60	14.30						
09/07/95	150	36.0	36.0	15.10	16.00	460	23	19	25.9	2.00	2.00
10/07/95	150			13.60	16.60	449	29	13			
11/07/95	150		36.5	18.10	19.90	522	26	24	41.8	2.00	2.00

PERIOD 3.3.1
SUMMARY DATA 1
LOW FERRIC TO R1 AEROBIC

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
12/07/95	150	37.0	37.0	17.10	17.30	486	25	26			
13/07/95	150	36.7	36.7	18.20	17.50	451	26	25	33.0	3.35	4.44
14/07/95	150	36.7	36.7	17.10	17.20						
15/07/95	150	36.7	37.2	17.00	17.50						
16/07/95	150	34.1	36.0	17.20	15.60	420	26	27	40.2	3.42	4.00
Average:	150	36.0	36.2	16.77	17.98	442	21	20	31.3	2.86	2.38
Count:	62	58	57	62	59	43	42	42	26	25	25
Maximum:	150	38.6	39.4	20.60	26.10	637	35	28	59.7	5.26	4.44
Minimum:	150	31.7	26.6	12.50	11.10	278	14	13	10.8	2.00	2.00
Standard Deviation:	0	1.2	1.6	1.80	3.26	82	5	4	13.0	1.01	0.77

PERIOD 3.3.1
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
16/05/95	53.77	33.15	35.95	20.62	17.82	204.65	185.40
17/05/95	52.99	22.36	27.23	30.63	25.76	193.07	184.54
18/05/95	50.40	20.26	28.52	30.14	21.88	204.74	185.47
19/05/95							
20/05/95							
21/05/95	49.59	23.98	28.36	25.61	21.23	219.13	198.98
22/05/95	50.46	27.36	30.80	23.10	19.66	197.80	180.58
23/05/95	48.49	20.15	23.76	28.34	24.73	186.21	177.05
24/05/95	49.64	14.25	17.86	35.39	31.78	180.45	177.30
25/05/95	50.46	17.86	14.42	32.60	36.04	192.46	175.87
26/05/95							
27/05/95							
28/05/95	51.11	27.69	28.67	23.42	22.44	187.96	185.23
29/05/95	51.55	22.75	24.22	28.80	27.33	191.66	170.65
30/05/95	52.53	18.16	21.11	34.37	31.42	180.52	168.41
31/05/95	51.38	18.16	21.11	33.22	30.27	185.29	182.12
01/06/95	50.89	15.87	19.31	35.02	31.58	196.83	180.04
02/06/95							
03/06/95							
04/06/95	47.62	18.98	21.60	28.64	26.02	194.06	190.55
05/06/95	52.88	23.74	24.07	29.14	28.81	195.38	183.40
06/06/95	50.42	24.88	27.83	25.54	22.59	184.90	171.77
07/06/95	48.79	24.72	26.03	24.07	22.76	190.84	184.72
08/06/95	47.97	28.81	29.96	19.16	18.01	198.75	177.35
09/06/95							
10/06/95							
11/06/95	50.42	31.76	31.92	18.66	18.50	197.18	190.15
12/06/95	51.39	33.83	33.50	17.56	17.89	191.24	181.89
13/06/95	53.04	30.54	34.32	22.50	18.72	191.04	181.88
14/06/95	51.89	23.97	27.75	27.92	24.14	194.91	173.23
15/06/95							
16/06/95							
17/06/95							
18/06/95	50.08	27.42	29.39	22.66	20.69	202.14	185.07
19/06/95	49.26	34.97	36.29	14.29	12.97	208.36	184.05
20/06/95	46.63	33.00	36.29	13.63	10.34	186.38	175.36
21/06/95	47.13	31.03	35.80	16.10	11.33	208.13	176.88
22/06/95	46.80	31.69	35.96	15.11	10.84	193.43	177.84
23/06/95							
24/06/95							
25/06/95	49.26	26.11	33.00	23.15	16.26	202.62	178.83
26/06/95	49.34	22.95	26.88	26.39	22.46	203.67	179.67
27/06/95	49.50	22.95	28.52	26.55	20.98	192.27	185.31
28/06/95	50.32	22.29	26.88	28.03	23.44	213.37	183.66
29/06/95	49.83	24.59	29.01	25.24	20.82	218.36	181.07
30/06/95							
01/07/95							
02/07/95	47.54	19.83	25.08	27.71	22.46	208.38	175.60
03/07/95	47.93	19.37	25.44	28.56	22.49	223.46	186.43
04/07/95	45.31	17.89	22.32	27.42	22.99	188.01	185.26
05/07/95	45.96	17.73	22.98	28.23	22.98	234.40	197.26
06/07/95	55.32	15.43	19.04	39.89	36.28	224.26	192.21
07/07/95							
08/07/95							
09/07/95	49.74	19.04	29.71	30.70	20.03	233.23	200.33
10/07/95	48.10	11.65	24.29	36.45	23.81	224.83	183.37
11/07/95	52.70	18.81	25.78	33.89	26.92	231.06	198.13

PERIOD 3.3.1
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

	DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
	12/07/95	48.06	14.61	26.79	33.45	21.27	222.44	185.06
	13/07/95	47.09	10.72	21.27	36.37	25.82	224.97	190.22
	14/07/95							
	15/07/95							
	16/07/95	50.17	12.18	19.97	37.99	30.20	243.23	200.23
Average:		49.85	22.73	26.95	27.12	22.90	203.40	183.45
Count:		43	43	43	43	43	43	43
Maximum:		55.32	34.97	36.29	39.89	36.28	243.23	200.33
Minimum:		45.31	10.72	14.42	13.63	10.34	180.45	168.41
Standard Deviation:		2.18	6.32	5.38	6.52	5.94	16.11	7.69

PERIOD 3.3.1
SUMMARY DATA 3
LOW FERRIC TO R1 AEROBIC

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
16/05/95	110.73	110.15	2532	1370	2725	1619	54.1	59.4	55	70
17/05/95	104.13	106.57	2926	1578	2722	1572	53.9	57.8	51	71
18/05/95	107.39	105.81	2852	1496	2864	1634	52.5	57.1	63	70
19/05/95										
20/05/95										
21/05/95	112.75	113.15	3162	1627	2979	1694	51.5	56.9	57	74
22/05/95	106.11	106.02	3335	1789	3214	1887	53.6	58.7	54	68
23/05/95	102.05	104.90	3580	1962	3389	2008	54.8	59.3	56	68
24/05/95	99.63	105.33	3749	2070	3562	2116	55.2	59.4	53	65
25/05/95	103.83	104.51	3203	1728	3778	2245	53.9	59.4	62	66
26/05/95										
27/05/95										
28/05/95	103.99	109.63	4049	2240	3945	2335	55.3	59.2	57	67
29/05/95	103.67	101.25	4167	2254	4089	2426	54.1	59.3	55	68
30/05/95	100.58	100.13	4523	2520	4380	2604	55.7	59.5	53	66
31/05/95	100.30	106.82	4356	2358	4182	2453	54.1	58.7	55	69
01/06/95	105.43	103.21	4501	2411	4455	2554	53.6	57.3	56	65
02/06/95										
03/06/95										
04/06/95	105.07	109.16	4719	2555	4542	2602	54.1	57.3	57	64
05/06/95	102.91	105.23	4868	2564	4636	2660	52.7	57.4	58	65
06/06/95	101.33	99.61	4976	2727	4799	2783	54.8	58.0	56	65
07/06/95	105.00	112.07	4693	2582	4470	2712	55.0	60.7	64	69
08/06/95	106.15	102.74	4750	2537	4621	2677	53.4	57.9	59	67
09/06/95										
10/06/95										
11/06/95	105.25	110.43	4682	2499	4403	2557	53.4	58.1	62	70
12/06/95	106.50	107.10	4471	2490	4431	2609	55.7	58.9	63	72
13/06/95	101.27	104.56	4767	2527	4460	2564	53.0	57.5	61	70
14/06/95	108.10	105.20	4724	2620	4339	2635	55.5	60.7	66	76
15/06/95										
16/06/95										
17/06/95										
18/06/95	105.35	105.94	4816	2510	4495	2573	52.1	57.2	64	69
19/06/95	108.26	106.08	4702	2443	4334	2498	52.0	57.6		
20/06/95	98.69	101.51	4725	2502	4319	2500	53.0	57.9	68	74
21/06/95	109.33	107.76	3935	2067	4038	2460	52.5	60.9	79	77
22/06/95	101.48	106.17	4401	2309	4052	2419	52.5	59.7	59	79
23/06/95										
24/06/95										
25/06/95	106.02	103.04	4631	2423	4207	2424	52.3	57.6	69	76
26/06/95	101.96	103.46	4678	2342	4246	2445	50.1	57.6	71	78
27/06/95	98.19	106.56	4674	2387	4184	2406	51.1	57.5	73	81
28/06/95	108.56	107.50	4560	2320	4071	2383	50.9	58.5	75	81
29/06/95	106.14	104.94	4633	2252	4155	2408	48.6	58.0	73	79
30/06/95										
01/07/95										
02/07/95	109.37	108.14	4586	2407	4123	2539	52.5	61.6	76	82
03/07/95	117.12	114.22	4415	2314	3981	2439	52.4	61.3	77	85
04/07/95	102.07	105.57	5082	2759	4245	2419	54.3	57.0	67	78
05/07/95	116.30	113.18	4432	2199	4235	2430	49.6	57.4	77	83
06/07/95	111.94	108.17	4634	2313	4325	2434	49.9	56.3	69	79
07/07/95										
08/07/95										
09/07/95	119.29	119.15	4307	2203	4257	2532	51.1	59.5	79	85

PERIOD 3.3.1
SUMMARY DATA 3
LOW FERRIC TO R1 AEROBIC

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
10/07/95	112.39	108.12	3783	1891	4418	2605	50.0	59.0	90	81
11/07/95	113.01	110.82	3889	1902	4507	2521	48.9	55.9	77	82
12/07/95	109.30	104.79	4011	1971	4602	2606	49.1	56.6	75	80
13/07/95	109.87	106.45	4212	2057	4637	2595	48.8	56.0	71	82
14/07/95										
15/07/95										
16/07/95	118.46	111.24	4441	2163	4788	2660	48.7	55.6	77	79
Average:	106.63	106.89	4259	2238	4121	2401	52.6	58.3	65	74
Count:	43	43	43	43	43	43	43	43	42	42
Maximum:	119.29	119.15	5082	2759	4799	2783	55.7	61.6	90	85
Minimum:	98.19	99.61	2532	1370	2722	1572	48.6	55.6	51	64
Standard Deviation:	5.20	3.86	611	333	527	299	2.1	1.4	9	6

PERIOD 3.3.1
SUMMARY DATA 4
LOW FERRIC TO R1 AEROBIC

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
16/05/95	7.29	7.12	7.19	7.19	7.32	7.32	10	10		
17/05/95	7.13	7.02	7.22	7.26	7.41	7.51	10	10		
18/05/95	7.11	6.98	7.47	7.28	7.61	7.50	10	10		
19/05/95	7.17	7.05	7.35	7.35	7.54	7.52	10	10		
20/05/95	7.19	7.02	7.41	7.28	7.60	7.45	10	10		
21/05/95	7.17	7.03	7.31	7.33	7.60	7.66	10	10	220.0	240.8
22/05/95	7.20	7.08	7.26	7.27	7.46	7.50	10	10		
23/05/95	7.11	7.03	7.21	7.21	7.41	7.44	10	10	207.1	231.3
24/05/95	7.05	6.95	7.20	7.17	7.40	7.41	10	10		
25/05/95	7.10	6.98	7.36	7.33	7.61	7.66	10	10		
26/05/95	7.10	6.93	7.33	7.29	7.51	7.50	10	10		
27/05/95	7.01	6.84	7.33	7.26	7.56	7.57	10	10		
28/05/95	7.21	7.12	7.45	7.43	7.62	7.76	10	10		
29/05/95	7.06	6.99	7.30	7.29	7.55	7.52	10	10		
30/05/95	7.06	6.96	7.29	7.26	7.52	7.48	10	10		
31/05/95	7.02	6.90	7.42	7.33	7.62	7.64	10	10		
01/06/95	6.98	6.89	7.29	7.22	7.43	7.52	10	10		
02/06/95	6.98	6.87	7.34	7.28	7.56	7.59	10	10		
03/06/95	7.11	6.96	7.36	7.33	7.57	7.63	10	10		
04/06/95	7.07	7.07	7.21	7.34	7.42	7.55	10	10		
05/06/95	7.09	6.96	7.35	7.27	7.52	7.47	10	10		
06/06/95	6.99	6.88	7.19	7.23	7.46	7.46	10	10		
07/06/95	7.02	6.88	7.23	7.21	7.42	7.36	10	10		
08/06/95	7.01	6.90	7.30	7.24	7.48	7.51	10	10	199.6	231.5
09/06/95	7.02	6.90	7.27	7.18	7.42	7.40	10	10		
10/06/95	6.96	6.85	7.26	7.20	7.48	7.44	10	10		
11/06/95	7.21	7.03	7.47	7.37	7.61	7.47	10	10		
12/06/95	7.07	7.03	7.34	7.50	7.54	7.86	10	10		
13/06/95	6.70	6.59	6.89	6.90	7.15	7.20	10	10	213.1	229.1
14/06/95	6.98	6.89	7.33	7.29	7.58	7.62	10	10		
15/06/95	7.00	6.92	7.31	7.28	7.56	7.59	10	10		
16/06/95	7.00	6.98	7.26	7.18	7.40	7.42	10	10		
17/06/95	7.02	6.86	7.29	7.00	7.51	7.09	10	10		
18/06/95	7.02	6.96	7.30	7.52	7.49	7.88	10	10	203.4	230.3
19/06/95	7.08	7.00	7.37	7.33	7.53	7.58	10	10		
20/06/95	7.04	6.93	7.24	7.12	7.41	7.32	10	10		
21/06/95	7.19	7.07	7.30	7.21	7.46	7.43	10	10	208.6	228.3
22/06/95	7.14	7.05	7.32	7.25	7.46	7.42	10	10		
23/06/95	7.21	7.16	7.38	7.27	7.53	7.46	10	10		
24/06/95	7.11	7.03	7.31	7.16	7.49	7.38	10	10		
25/06/95	7.12	7.23	7.07	7.20	7.32	7.41	10	10	212.5	240.4
26/06/95	7.20	7.19	7.42	7.30	7.60	7.63	10	10		
27/06/95	7.25	7.22	7.39	7.41	7.59	7.62	10	10		
28/06/95	7.24	7.25	7.48	7.44	7.67	7.65	10	10	259.3	276.8
29/06/95	7.31	7.24	7.49	7.44	7.67	7.58	10	10		
30/06/95	7.19	7.23	7.42	7.46	7.64	7.73	10	10		
01/07/95	7.21	7.25	7.43	7.46	7.62	7.72	10	10		
02/07/95	7.18	7.18	7.43	7.43	7.64	7.70	10	10		
03/07/95	7.27	7.22	7.47	7.44	7.66	7.76	10	10	201.3	179.2
04/07/95	6.97	7.19	7.34	7.42	7.76	7.68	10	10		
05/07/95	7.19	7.22	7.55	7.44	7.69	7.71	10	10		
06/07/95	7.06	6.98	7.42	7.38	7.61	7.64	10	10	184.4	209.9
07/07/95	7.10	7.02	7.50	7.39	7.66	7.63	10	10		
08/07/95	7.08	6.99	7.38	7.33	7.63	7.58	10	10		
09/07/95	7.07	6.98	7.48	7.35	7.68	7.56	10	10		

PERIOD 3.3.1
SUMMARY DATA 4
LOW FERRIC TO R1 AEROBIC

	DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk R1	H2CO3* Alk R2
	10/07/95	7.07	6.97	7.35	7.28	7.62	7.59	10	10		
	11/07/95	7.24	6.99	7.51	7.33	7.52	7.60	10	10		
	12/07/95	7.05	6.92	7.33	7.30	7.59	7.61	10	10		
	13/07/95	7.05	6.82	7.39	7.30	7.64	7.60	10	10		
	14/07/95	7.06	6.96	7.41	7.39	7.66	7.67	10	10		
	15/07/95	7.16	6.95	7.47	7.28	7.71	7.53	10	10		
	16/07/95	6.86	6.85	7.46	7.42	7.72	7.72	10	10		
Average:		7.10	7.01	7.34	7.30	7.54	7.55	10	10	210.9	229.8
Count:		62	62	62	62	62	62	62	62	10	10
Maximum:		7.31	7.25	7.55	7.52	7.76	7.88	10	10	259.3	276.8
Minimum:		6.70	6.59	6.89	6.90	7.15	7.09	10	10	184.4	179.2
Standard Deviation:		0.11	0.13	0.11	0.11	0.11	0.14	0	0	18.5	23.3

PERIOD 3.3.1
SUMMARY DATA 5
LOW FERRIC TO R1 AEROBIC

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
16/05/95	0.50	0.25	9.64	8.64	30.48	35.35
17/05/95	0.20	0.20	9.13	5.98	21.28	24.73
18/05/95	0.31	0.31	7.99	7.98	18.40	28.18
19/05/95						
20/05/95						
21/05/95	0.37	0.23	9.23	7.12	23.09	22.99
22/05/95	0.28	0.28	9.89	10.04	27.17	29.23
23/05/95	0.40	0.32	8.70	7.38	17.01	20.60
24/05/95	0.18	0.11	8.43	8.13	12.07	18.78
25/05/95	0.18	0.17	9.90	7.90	15.37	12.65
26/05/95						
27/05/95						
28/05/95	0.14	0.15	9.31	4.98	28.39	25.78
29/05/95	0.17	0.13	7.20	5.30	20.07	21.35
30/05/95	0.13	0.14	5.30	3.09	16.19	20.65
31/05/95	0.18	0.13	5.07	2.85	15.61	18.57
01/06/95	0.10	0.09	7.01	3.56	16.71	16.94
02/06/95						
03/06/95						
04/06/95	0.25	0.10	6.42	3.33	15.52	18.62
05/06/95	0.05	0.08	7.02	4.40	19.44	21.98
06/06/95	0.14	0.09	5.92	3.49	22.59	25.21
07/06/95	0.18	0.09	5.97	2.92	22.39	24.52
08/06/95	0.08	0.08	7.73	3.95	26.85	31.41
09/06/95						
10/06/95						
11/06/95	0.00	0.00	9.94	7.28	31.70	28.87
12/06/95	0.00	0.04	7.73	7.73	30.39	29.89
13/06/95	0.04	0.08	4.78	3.81	29.60	32.90
14/06/95	0.16	0.10	3.00	2.80	22.02	27.73
15/06/95						
16/06/95						
17/06/95						
18/06/95	0.12	0.14	4.00	4.20	24.64	29.27
19/06/95	0.12	0.08	7.50	6.30	33.36	34.91
20/06/95	0.08	0.08	10.40	9.28	32.59	35.35
21/06/95	0.50	0.39	10.16	8.47	30.16	35.68
22/06/95	0.28	0.34	9.32	9.03	31.37	35.35
23/06/95						
24/06/95						
25/06/95	0.34	0.34	6.78	6.49	23.03	28.52
26/06/95	0.22	0.28	7.06	7.91	22.87	26.73
27/06/95	0.34	0.34	7.90	7.34	20.29	25.77
28/06/95	0.28	0.22	6.49	6.21	17.55	23.03
29/06/95	0.34	0.34	7.06	6.21	20.84	24.13
30/06/95						
01/07/95						
02/07/95	0.28	0.34	6.78	6.49	17.55	22.48
03/07/95	0.27	0.22	6.01	4.16		19.22
04/07/95	0.13	0.13	3.27	2.04	12.44	22.20
05/07/95	0.13	0.13	2.95	2.82	18.00	22.31
06/07/95	0.22	0.18	5.39	3.97	15.13	19.44
07/07/95						
08/07/95						
09/07/95	0.18	0.18	5.90	5.64	18.45	29.60
10/07/95	0.67	0.26	8.80	7.80	10.83	22.11

PERIOD 3.3.1
SUMMARY DATA 5
LOW FERRIC TO R1 AEROBIC

	DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
	11/07/95	0.26	0.31	9.30	8.80	19.11	26.51
	12/07/95	0.26	0.26	6.60	6.90	13.70	25.23
	13/07/95	0.36	0.26	6.20	6.30	11.71	19.62
	14/07/95						
	15/07/95						
	16/07/95	0.21	0.21	4.00	5.00	12.59	18.37
Average:		0.22	0.19	7.14	5.91	21.16	25.18
Count:		43	43	43	43	42	43
Maximum:		0.67	0.39	10.40	10.04	33.36	35.68
Minimum:		0.00	0.00	2.95	2.04	10.83	12.65
Standard Deviation:		0.14	0.10	2.01	2.13	6.37	5.59

PERIOD 3.3.1
SUMMARY DATA 6
LOW FERRIC TO R1 AEROBIC

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAB1	NO3 R1 fAB2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAB1	NO3 R2 fAB2
16/05/95								
17/05/95								
18/05/95								
19/05/95								
20/05/95								
21/05/95								
22/05/95								
23/05/95								
24/05/95	0.00	3.52	9.08	8.96	0.00	2.92	8.90	6.72
25/05/95								
26/05/95								
27/05/95								
28/05/95								
29/05/95	0.00	3.49	7.84	5.10	0.00	2.09	7.69	5.30
30/05/95								
31/05/95								
01/06/95	0.00	2.52	7.60	5.89	0.06	0.45	5.14	4.00
02/06/95								
03/06/95								
04/06/95	0.06	3.00	7.18	7.33	0.06	0.46	3.67	3.30
05/06/95								
06/06/95								
07/06/95								
08/06/95	0.05	3.37	8.57	7.74	0.08	0.39	3.87	4.07
09/06/95								
10/06/95								
11/06/95	0.04	4.67	10.23	10.23	0.07	4.81	10.23	9.96
12/06/95	0.05	2.43	6.64	6.64	0.04	1.33	7.19	6.64
13/06/95								
14/06/95	0.03	0.07	3.40	3.43	0.04	0.03	2.72	2.49
15/06/95								
16/06/95								
17/06/95								
18/06/95	0.03	1.08	4.20	4.11	0.04	0.06	3.74	3.66
19/06/95	0.07	5.06	10.45	9.36	0.07	3.60	9.91	8.81
20/06/95								
21/06/95	0.08	5.64	8.53	10.18	0.10	3.58	7.15	8.81
22/06/95								
23/06/95								
24/06/95								
25/06/95	0.12	3.99	7.98	7.43	0.11	3.41	6.88	7.43
26/06/95								
27/06/95								
28/06/95	0.11	7.71	7.98	6.88	0.19	6.60	6.60	6.60
29/06/95								
30/06/95								
01/07/95								
02/07/95	0.14	4.35	7.15	6.60	0.18	3.33	6.60	6.05
03/07/95								
04/07/95								
05/07/95	0.05	0.79	3.34	3.34	0.10	0.85	3.54	3.10
06/07/95								
07/07/95								
08/07/95								
09/07/95	0.07	3.15	5.21	4.38	0.11	3.48	4.93	6.30
10/07/95								

PERIOD 3.3.1
SUMMARY DATA 6
LOW FERRIC TO R1 AERROBIC

	DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
	11/07/95								
	12/07/95	0.05	2.02	5.07	6.00	0.07	3.07	5.48	4.38
	13/07/95								
	14/07/95								
	15/07/95								
	16/07/95								
Average:		0.06	3.34	7.09	6.68	0.08	2.38	6.13	5.74
Count:		17	17	17	17	17	17	17	17
Maximum:		0.14	7.71	10.45	10.23	0.19	6.60	10.23	9.96
Minimum:		0.00	0.07	3.34	3.34	0.00	0.03	2.72	2.49
Standard Deviation:		0.04	1.82	2.11	2.12	0.05	1.82	2.20	2.14

PERIOD 3.3.1
SUMMARY DATA 7
LOW FERRIC TO R1 AEROBIC

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAB1	TP R1 fAB2	TP R2 fAN	TP R2 fAX	TP R2 fAB1	TP R2 fAB2
16/05/95	94.83	54.39	41.40	32.82	103.90	59.04	57.72	38.92
17/05/95								
18/05/95	90.75	47.48	31.93	22.53	102.10	55.42	40.35	30.14
19/05/95								
20/05/95								
21/05/95	76.17	44.08	32.25	25.93	87.51	48.29	36.26	32.74
22/05/95	97.48	54.23	38.66	28.51	107.31	58.98	43.41	33.91
23/05/95								
24/05/95	104.03	46.86	24.74	13.27	121.23	53.08	29.98	17.04
25/05/95								
26/05/95								
27/05/95								
28/05/95								
29/05/95	98.18	50.56	32.07	21.44	108.82	56.62	37.80	24.22
30/05/95								
31/05/95								
01/06/95	105.55	49.42	30.76	19.47	117.82	62.02	38.13	24.87
02/06/95								
03/06/95								
04/06/95	89.18	45.98	29.62	21.11	100.64	51.22	34.20	22.58
05/06/95								
06/06/95								
07/06/95								
08/06/95	97.41	53.04	36.83	28.81	105.59	59.75	42.73	31.76
09/06/95								
10/06/95								
11/06/95	107.23	59.59	38.96	30.12	112.96	63.03	41.91	32.41
12/06/95	103.95	58.94	39.94	30.12	112.14	67.61	43.38	31.92
13/06/95								
14/06/95	103.45	52.87	30.71	20.03	113.30	69.78	41.54	25.62
15/06/95								
16/06/95								
17/06/95								
18/06/95	86.20	48.60	35.47	28.24	90.31	59.93	42.20	32.18
19/06/95	97.70	59.77	43.51	34.81	105.91	70.61	49.59	37.93
20/06/95								
21/06/95	94.41	55.83	46.63	33.00	100.16	68.96	51.39	37.77
22/06/95								
23/06/95								
24/06/95								
25/06/95	98.35	51.47	36.55	26.23	107.36	60.48	44.42	31.64
26/06/95								
27/06/95								
28/06/95	83.60	43.77	29.67	22.46	90.97	54.58	39.01	28.85
29/06/95								
30/06/95								
01/07/95								
02/07/95	84.42	43.60	27.70	19.67	98.35	51.14	34.09	25.24
03/07/95								
04/07/95								
05/07/95	104.60	50.43	31.62	19.46	115.95	63.73	42.97	30.81
06/07/95								
07/07/95								
08/07/95								
09/07/95								
10/07/95								

PERIOD 3.3.1
SUMMARY DATA 7
LOW FERRIC TO R1 AEROBIC

	DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
	11/07/95								
	12/07/95	98.92	44.43	25.46	12.32	109.46	53.84	33.89	22.87
	13/07/95								
	14/07/95								
	15/07/95								
	16/07/95								
Average:		95.82	50.77	34.22	24.52	105.59	59.41	41.25	29.67
Count:		20	20	20	20	20	20	20	20
Maximum:		107.23	59.77	46.63	34.81	121.23	70.61	57.72	38.92
Minimum:		76.17	43.60	24.74	12.32	87.51	48.29	29.98	17.04
Standard Deviation:		8.23	5.14	5.82	6.17	8.90	6.36	6.34	5.57

PERIOD 3.3.1.
SUMMARY DATA 8
LOW FERRIC TO R1 AEROBIC

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
16/05/95	0.0	6.7	0.0	18.5	
17/05/95	0.0	6.7	0.0	19.3	
18/05/95	0.0	6.7	0.0	19.0	
19/05/95	0.0	6.7	0.0	19.3	
20/05/95	0.0	6.7	0.0	19.7	
21/05/95	0.0	6.7	0.0	19.4	
22/05/95	0.0	6.7	0.0	18.6	
23/05/95	0.0	6.7	0.0	18.2	
24/05/95	0.0	6.7	0.0	20.2	
25/05/95	0.0	6.7	0.0	20.9	
26/05/95	0.0	6.7	0.0	21.6	
27/05/95	0.0	6.7	0.0	20.9	
28/05/95	0.0	6.7	0.0	19.5	
29/05/95	0.0	6.7	0.0	18.8	
30/05/95	0.0	6.7	0.0	19.9	
31/05/95	0.0	6.7	0.0	19.3	
01/06/95	0.0	6.7	0.0	19.3	
02/06/95	0.0	6.7	0.0	18.6	
03/06/95	0.0	6.7	0.0	18.8	
04/06/95	0.0	6.7	0.0	18.7	
05/06/95	0.0	6.7	0.0	18.8	
06/06/95	0.0	6.7	0.0	18.6	
07/06/95	0.0	6.7	0.0	20.0	
08/06/95	0.0	6.7	0.0	19.8	
09/06/95	0.0	6.7	0.0	20.5	
10/06/95	0.0	6.7	0.0	20.8	
11/06/95	0.0	6.7	0.0	20.6	
12/06/95	0.0	6.7	0.0	20.5	
13/06/95	0.0	6.7	0.0	20.3	
14/06/95	0.0	6.7	0.0	20.3	
15/06/95	0.0	6.7	0.0	20.1	
16/06/95	0.0	6.7	0.0	20.4	
17/06/95	0.0	6.7	0.0	20.2	
18/06/95	0.0	6.7	0.0	20.3	
19/06/95	0.0	6.7	0.0	19.9	
20/06/95	0.0	6.7	0.0	18.3	
21/06/95	0.0	6.7	0.0	18.8	
22/06/95	0.0	6.7	0.0	18.7	
23/06/95	0.0	6.7	0.0	19.1	
24/06/95	0.0	6.7	0.0	19.1	
25/06/95	0.0	6.7	0.0	19.0	
26/06/95	0.0	6.7	0.0	18.7	
27/06/95	0.0	6.7	0.0	18.5	
28/06/95	0.0	6.7	0.0	18.9	
29/06/95	0.0	6.7	0.0	18.8	
30/06/95	0.0	6.7	0.0	19.4	
01/07/95	0.0	6.7	0.0	19.2	
02/07/95	0.0	6.7	0.0	18.8	
03/07/95	0.0	6.7	0.0	19.3	
04/07/95	0.0	6.7	0.0	19.0	
05/07/95	0.0	6.7	0.0	19.1	
06/07/95	0.0	6.7	0.0	18.9	
07/07/95	0.0	6.7	0.0	18.9	
08/07/95	0.0	6.7	0.0	19.4	
09/07/95	0.0	6.7	0.0	19.0	

PERIOD 3.3.1.
SUMMARY DATA 8
LOW FERRIC TO R1 AEROBIC

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
10/07/95	0.0	6.7	0.0	18.9	
11/07/95	0.0	6.7	0.0	20.3	
12/07/95	0.0	6.7	0.0	18.7	
13/07/95	0.0	6.7	0.0	18.6	
14/07/95	0.0	6.7	0.0	18.9	
15/07/95	0.0	6.7	0.0	20.3	
16/07/95	0.0	6.7	0.0	20.0	
Average:				19.4	0.0
Count:	62	62	62	62	0
Maximum:	0.0	6.7	0.0	21.6	
Minimum:	0.0	6.7	0.0	18.2	
Standard Deviation:				0.8	0.0

PERIOD 3.3.1(B)
SUMMARY DATA 1

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
16/06/95	150	35.8	38.4	17.60	21.00						
17/06/95	150	35.5	37.0	17.80							
18/06/95	150	36.7	37.2	16.20		278	18	19	27.6	2.00	2.00
19/06/95	150	36.2	36.2	15.50	19.80	374	20	19			
20/06/95	150	37.2	37.2	14.30	15.30	338	19	17	36.4	2.00	2.00
21/06/95	150		37.0	17.30	16.30	329	16	16			
22/06/95	150	31.7	36.2	15.40	13.00	290	16	16	10.8	2.00	2.00
23/06/95	150			15.10	13.00						
24/06/95	150	38.6	26.6	17.30	16.30						
25/06/95	150	38.4	39.4	16.20	15.10	406	18	14	13.7	2.00	2.00
26/06/95	150	34.8	35.8	15.80	15.70	445	19	20			
27/06/95	150	34.8	34.8	15.50	17.10	376	21	20	33.4	3.92	2.00
28/06/95	150	36.5	36.5	15.70	19.40	333	16	18			
29/06/95	150	34.3	35.8	16.00	14.90	406	19	17	34.9	2.00	2.00
30/06/95	150	34.8	34.8	17.70	15.30						
01/07/95	150	35.0	35.0	17.50	15.00						
02/07/95	150	35.3	35.3	16.10	14.20	349	17	16	29.7	2.00	2.00
03/07/95	150	35.3	34.8	15.70	15.40	478	18	15			
04/07/95	150	35.5	35.5	15.70	16.20	387	17	17	19.1	2.00	2.00
05/07/95	150	34.1	35.3	17.10	15.70	428	14	17			
06/07/95	150	34.8		15.60	14.90	362	16	14	13.2	2.00	2.00
07/07/95	150	34.8	35.5	12.50	15.30						
08/07/95	150	35.8	35.8	12.60	14.30						
09/07/95	150	36.0	36.0	15.10	16.00	460	23	19	25.9	2.00	2.00
10/07/95	150			13.60	16.60	449	29	13			
11/07/95	150		36.5	18.10	19.90	522	26	24	41.8	2.00	2.00
12/07/95	150	37.0	37.0	17.10	17.30	486	25	26			
13/07/95	150	36.7	36.7	18.20	17.50	451	26	25	33.0	3.35	4.44
14/07/95	150	36.7	36.7	17.10	17.20						
15/07/95	150	36.7	37.2	17.00	17.50						
16/07/95	150	34.1	36.0	17.20	15.60	420	26	27	40.2	3.42	4.00
Average:	150	35.7	35.9	16.12	16.23	398	20	19	27.7	2.36	2.34
Count:	31	27	28	31	29	21	21	21	13	13	13
Maximum:	150	38.6	39.4	18.20	21.00	522	29	27	41.8	3.92	4.44
Minimum:	150	31.7	26.6	12.50	13.00	278	14	13	10.8	2.00	2.00
Standard Deviation:	0	1.4	2.1	1.44	1.90	64	4	4	10.1	0.67	0.81

ERIOD 3.3.1(b)
UMMARY DATA 2

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R2 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
16/06/95							
17/06/95							
18/06/95	50.08	27.42	29.39	22.66	20.69	202.14	185.07
19/06/95	49.26	34.97	36.29	14.29	12.97	208.36	184.05
20/06/95	46.63	33.00	36.29	13.63	10.34	186.38	175.36
21/06/95	47.13	31.03	35.80	16.10	11.33	208.13	176.88
22/06/95	46.80	31.69	35.96	15.11	10.84	193.43	177.84
23/06/95							
24/06/95							
25/06/95	49.26	26.11	33.00	23.15	16.26	202.62	178.83
26/06/95	49.34	22.95	26.88	26.39	22.46	203.67	179.67
27/06/95	49.50	22.95	28.52	26.55	20.98	192.27	185.31
28/06/95	50.32	22.29	26.88	28.03	23.44	213.37	183.66
29/06/95	49.83	24.59	29.01	25.24	20.82	218.36	181.07
30/06/95							
01/07/95							
02/07/95	47.54	19.83	25.08	27.71	22.46	208.38	175.60
03/07/95	47.93	19.37	25.44	28.56	22.49	223.46	186.43
04/07/95	45.31	17.89	22.32	27.42	22.99	188.01	185.26
05/07/95	45.96	17.73	22.98	28.23	22.98	234.40	197.26
06/07/95	55.32	15.43	19.04	39.89	36.28	224.26	192.21
07/07/95							
08/07/95							
09/07/95	49.74	19.04	29.71	30.70	20.03	233.23	200.33
10/07/95	48.10	11.65	24.29	36.45	23.81	224.83	183.37
11/07/95	52.70	18.81	25.78	33.89	26.92	231.06	198.13
12/07/95	48.06	14.61	26.79	33.45	21.27	222.44	185.06
13/07/95	47.09	10.72	21.27	36.37	25.82	224.97	190.22
14/07/95							
15/07/95							
16/07/95	50.17	12.18	19.97	37.99	30.20	243.23	200.23
Average:	48.86	21.63	27.65	27.23	21.21	213.67	185.80
Count:	21	21	21	21	21	21	21
Maximum:	55.32	34.97	36.29	39.89	36.28	243.23	200.33
Minimum:	45.31	10.72	19.04	13.63	10.34	186.38	175.36
Standard Deviation:	2.23	6.94	5.24	7.59	6.18	15.83	7.69

PERIOD 3.3.1(B)
SUMMARY DATA 3

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
16/06/95										
17/06/95										
18/06/95	105.35	105.94	4816	2510	4495	2573	52.1	57.2	64	69
19/06/95	108.26	106.08	4702	2443	4334	2498	52.0	57.6		
20/06/95	98.69	101.51	4725	2502	4319	2500	53.0	57.9	68	74
21/06/95	109.33	107.76	3935	2067	4038	2460	52.5	60.9	79	77
22/06/95	101.48	106.17	4401	2309	4052	2419	52.5	59.7	59	79
23/06/95										
24/06/95										
25/06/95	106.02	103.04	4631	2423	4207	2424	52.3	57.6	69	76
26/06/95	101.96	103.46	4678	2342	4246	2445	50.1	57.6	71	78
27/06/95	98.19	106.56	4674	2387	4184	2406	51.1	57.5	73	81
28/06/95	108.56	107.50	4560	2320	4071	2383	50.9	58.5	75	81
29/06/95	106.14	104.94	4633	2252	4155	2408	48.6	58.0	73	79
30/06/95										
01/07/95										
02/07/95	109.37	108.14	4586	2407	4123	2539	52.5	61.6	76	82
03/07/95	117.12	114.22	4415	2314	3981	2439	52.4	61.3	77	85
04/07/95	102.07	105.57	5082	2759	4245	2419	54.3	57.0	67	78
05/07/95	116.30	113.18	4432	2199	4235	2430	49.6	57.4	77	83
06/07/95	111.94	108.17	4634	2313	4325	2434	49.9	56.3	69	79
07/07/95										
08/07/95										
09/07/95	119.29	119.15	4307	2203	4257	2532	51.1	59.5	79	85
10/07/95	112.39	108.12	3783	1891	4418	2605	50.0	59.0	90	81
11/07/95	113.01	110.82	3889	1902	4507	2521	48.9	55.9	77	82
12/07/95	109.30	104.79	4011	1971	4602	2606	49.1	56.6	75	80
13/07/95	109.87	106.45	4212	2057	4637	2595	48.8	56.0	71	82
14/07/95										
15/07/95										
16/07/95	118.46	111.24	4441	2163	4788	2660	48.7	55.6	77	79
Average:	108.72	107.75	4455	2273	4296	2490	51.0	58.0	73	80
Count:	21	21	21	21	21	21	21	21	20	20
Maximum:	119.29	119.15	5082	2759	4788	2660	54.3	61.6	90	85
Minimum:	98.19	101.51	3783	1891	3981	2383	48.6	55.6	59	69
Standard Deviation:	6.01	4.00	324	210	208	79	1.6	1.7	6	4

ERIOD 3.3.1(B)
UMMARY DATA 4

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
16/06/95	7.00	6.98	7.26	7.18	7.40	7.42	10	10		
17/06/95	7.02	6.86	7.29	7.00	7.51	7.09	10	10		
18/06/95	7.02	6.96	7.30	7.52	7.49	7.88	10	10	203.4	230.3
19/06/95	7.08	7.00	7.37	7.33	7.53	7.58	10	10		
20/06/95	7.04	6.93	7.24	7.12	7.41	7.32	10	10		
21/06/95	7.19	7.07	7.30	7.21	7.46	7.43	10	10	208.6	228.3
22/06/95	7.14	7.05	7.32	7.25	7.46	7.42	10	10		
23/06/95	7.21	7.16	7.38	7.27	7.53	7.46	10	10		
24/06/95	7.11	7.03	7.31	7.16	7.49	7.38	10	10		
25/06/95	7.12	7.23	7.07	7.20	7.32	7.41	10	10	212.5	240.4
26/06/95	7.20	7.19	7.42	7.30	7.60	7.63	10	10		
27/06/95	7.25	7.22	7.39	7.41	7.59	7.62	10	10		
28/06/95	7.24	7.25	7.48	7.44	7.67	7.65	10	10	259.3	276.8
29/06/95	7.31	7.24	7.49	7.44	7.67	7.58	10	10		
30/06/95	7.19	7.23	7.42	7.46	7.64	7.73	10	10		
01/07/95	7.21	7.25	7.43	7.46	7.62	7.72	10	10		
02/07/95	7.18	7.18	7.43	7.43	7.64	7.70	10	10		
03/07/95	7.27	7.22	7.47	7.44	7.66	7.76	10	10	201.3	179.2
04/07/95	6.97	7.19	7.34	7.42	7.76	7.68	10	10		
05/07/95	7.19	7.22	7.55	7.44	7.69	7.71	10	10		
06/07/95	7.06	6.98	7.42	7.38	7.61	7.64	10	10	184.4	209.9
07/07/95	7.10	7.02	7.50	7.39	7.66	7.63	10	10		
08/07/95	7.08	6.99	7.38	7.33	7.63	7.58	10	10		
09/07/95	7.07	6.98	7.48	7.35	7.68	7.56	10	10		
10/07/95	7.07	6.97	7.35	7.28	7.62	7.59	10	10		
11/07/95	7.24	6.99	7.51	7.33	7.52	7.60	10	10		
12/07/95	7.05	6.92	7.33	7.30	7.59	7.61	10	10		
13/07/95	7.05	6.82	7.39	7.30	7.64	7.60	10	10		
14/07/95	7.06	6.96	7.41	7.39	7.66	7.67	10	10		
15/07/95	7.16	6.95	7.47	7.28	7.71	7.53	10	10		
16/07/95	6.86	6.85	7.46	7.42	7.72	7.72	10	10		
Average:	7.12	7.06	7.39	7.33	7.59	7.58	10	10	211.6	227.5
Count:	31	31	31	31	31	31	31	31	6	6
Maximum:	7.31	7.25	7.55	7.52	7.76	7.88	10	10	259.3	276.8
Minimum:	6.86	6.82	7.07	7.00	7.32	7.09	10	10	184.4	179.2
Standard Deviation:	0.10	0.13	0.10	0.12	0.10	0.15	0	0	23.1	29.6

APPENDIX 5

PERIOD 3.3.1(B)
SUMMARY DATA 5

DATE	NH3 fR1	NH3 fR2	NO3 fR1	NO3 fR2	SRP fR1	SRP fR2
16/06/95						
17/06/95						
18/06/95	0.12	0.14	4.00	4.20	24.64	29.27
19/06/95	0.12	0.08	7.50	6.30	33.36	34.91
20/06/95	0.08	0.08	10.40	9.28	32.59	35.35
21/06/95	0.50	0.39	10.16	8.47	30.16	35.68
22/06/95	0.28	0.34	9.32	9.03	31.37	35.35
23/06/95						
24/06/95						
25/06/95	0.34	0.34	6.78	6.49	23.03	28.52
26/06/95	0.22	0.28	7.06	7.91	22.87	26.73
27/06/95	0.34	0.34	7.90	7.34	20.29	25.77
28/06/95	0.28	0.22	6.49	6.21	17.55	23.03
29/06/95	0.34	0.34	7.06	6.21	20.84	24.13
30/06/95						
01/07/95						
02/07/95	0.28	0.34	6.78	6.49	17.55	22.48
03/07/95	0.27	0.22	6.01	4.16		19.22
04/07/95	0.13	0.13	3.27	2.04	12.44	22.20
05/07/95	0.13	0.13	2.95	2.82	18.00	22.31
06/07/95	0.22	0.18	5.39	3.97	15.13	19.44
07/07/95						
08/07/95						
09/07/95	0.18	0.18	5.90	5.64	18.45	29.60
10/07/95	0.67	0.26	8.80	7.80	10.83	22.11
11/07/95	0.26	0.31	9.30	8.80	19.11	26.51
12/07/95	0.26	0.26	6.60	6.90	13.70	25.23
13/07/95	0.36	0.26	6.20	6.30	11.71	19.62
14/07/95						
15/07/95						
16/07/95	0.21	0.21	4.00	5.00	12.59	18.37
Average:	0.27	0.24	6.76	6.26	20.31	25.99
Count:	21	21	21	21	20	21
Maximum:	0.67	0.39	10.40	9.28	33.36	35.68
Minimum:	0.08	0.08	2.95	2.04	10.83	18.37
Standard Deviation:	0.13	0.09	2.06	1.96	6.91	5.50

ERIOD 3.3.1(B)
UMMARY DATA 6

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
16/06/95								
17/06/95								
18/06/95	0.03	1.08	4.20	4.11	0.04	0.06	3.74	3.66
19/06/95	0.07	5.06	10.45	9.36	0.07	3.60	9.91	8.81
20/06/95								
21/06/95	0.08	5.64	8.53	10.18	0.10	3.58	7.15	8.81
22/06/95								
23/06/95								
24/06/95								
25/06/95	0.12	3.99	7.98	7.43	0.11	3.41	6.88	7.43
26/06/95								
27/06/95								
28/06/95	0.11	7.71	7.98	6.88	0.19	6.60	6.60	6.60
29/06/95								
30/06/95								
01/07/95								
02/07/95	0.14	4.35	7.15	6.60	0.18	3.33	6.60	6.05
03/07/95								
04/07/95								
05/07/95	0.05	0.79	3.34	3.34	0.10	0.85	3.54	3.10
06/07/95								
07/07/95								
08/07/95								
09/07/95	0.07	3.15	5.21	4.38	0.11	3.48	4.93	6.30
10/07/95								
11/07/95								
12/07/95	0.05	2.02	5.07	6.00	0.07	3.07	5.48	4.38
13/07/95								
14/07/95								
15/07/95								
16/07/95								
Average:	0.08	3.75	6.66	6.48	0.11	3.11	6.09	6.13
Count:	9	9	9	9	9	9	9	9
Maximum:	0.14	7.71	10.45	10.18	0.19	6.60	9.91	8.81
Minimum:	0.03	0.79	3.34	3.34	0.04	0.06	3.54	3.10
Standard Deviation:	0.03	2.12	2.19	2.19	0.05	1.74	1.84	1.96

PERIOD 3.3.1(B)
SUMMARY DATA 7

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
16/06/95								
17/06/95								
18/06/95	86.20	48.60	35.47	28.24	90.31	59.93	42.20	32.18
19/06/95	97.70	59.77	43.51	34.81	105.91	70.61	49.59	37.93
20/06/95								
21/06/95	94.41	55.83	46.63	33.00	100.16	68.96	51.39	37.77
22/06/95								
23/06/95								
24/06/95								
25/06/95	98.35	51.47	36.55	26.23	107.36	60.48	44.42	31.64
26/06/95								
27/06/95								
28/06/95	83.60	43.77	29.67	22.46	90.97	54.58	39.01	28.85
29/06/95								
30/06/95								
01/07/95								
02/07/95	84.42	43.60	27.70	19.67	98.35	51.14	34.09	25.24
03/07/95								
04/07/95								
05/07/95	104.60	50.43	31.62	19.46	115.95	63.73	42.97	30.81
06/07/95								
07/07/95								
08/07/95								
09/07/95								
10/07/95								
11/07/95								
12/07/95	98.92	44.43	25.46	12.32	109.46	53.84	33.89	22.87
13/07/95								
14/07/95								
15/07/95								
16/07/95								
Average:	93.53	49.74	34.58	24.52	102.31	60.41	42.20	30.91
Count:	8	8	8	8	8	8	8	8
Maximum:	104.60	59.77	46.63	34.81	115.95	70.61	51.39	37.93
Minimum:	83.60	43.60	25.46	12.32	90.31	51.14	33.89	22.87
Standard Deviation:	7.32	5.52	7.01	7.04	8.43	6.63	6.02	4.99

PERIOD 3.3.2
SUMMARY DATA 1
HIGH FERRIC TO R1 AEROBIC

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
17/07/95	150	31.7	33.1	13.00	18.60	382	16	19			
18/07/95	150	35.8	40.3	14.50	15.50	343	19	21	35.5	2.00	2.00
19/07/95	150	35.0	34.3	15.50	19.80	389	23	30			
20/07/95	150	34.3	33.8	13.10	15.70	328	20	21	22.2	2.00	2.00
21/07/95	150	34.8	35.5	16.00	15.70						
22/07/95	150	37.4	36.7	15.70	16.80						
23/07/95	150	35.8	36.2	14.20	16.10	342	19	19	28.0	2.00	2.00
24/07/95	150	36.2	37.0	12.30	13.60	270	17	21			
25/07/95	150	35.8	35.8	13.70	14.00	405	20	15	27.6	2.00	2.00
26/07/95	150	36.5	35.8	14.20	15.40	333	18	19			
27/07/95	150	35.8	36.5	13.80	15.30	419	22	17	26.0	2.00	2.00
28/07/95	150	36.2	36.2	13.30	14.30						
29/07/95	150	36.0	36.0	14.50	15.90						
30/07/95	150	35.3	36.2	16.10	16.30	436	21	22	25.2	2.00	2.00
31/07/95	150	36.0	36.0	16.90	20.10	402	23	21			
01/08/95	150	36.0	36.0	14.50	19.10	416	19	20	38.6	2.00	2.00
02/08/95	150	35.8	37.4	15.40	20.80	526	21	18	37.5		
03/08/95	150	36.2		15.50	20.50	449	21	23	32.5	2.00	5.21
04/08/95	150	35.5	35.5	17.10	21.80						
05/08/95	150	36.2	36.2	18.70	22.90						
06/08/95	150	35.8	36.2	14.70	20.70	472	18	19	30.5	3.18	2.00
07/08/95	150	35.8	35.8	16.10	20.00	447	20	22			
08/08/95	150	36.0	36.0								
09/08/95	150	35.5	36.0	17.30	22.40	464	21	25			
10/08/95	150	36.5	36.5	14.80	18.30	387	18	19	27.9	4.11	4.07
11/08/95	150	35.8	35.8	12.70	17.40						
12/08/95	150	36.5	36.0	12.90	15.60						
13/08/95	150	36.0	36.0	13.30	20.80	326	18	17	24.1	2.00	3.56
14/08/95	150	37.4	36.7	17.00	21.20	476	17	19			
15/08/95	150	36.5	36.5	17.50	20.10	413	19	19	39.8	3.13	3.13
16/08/95	150	36.2	35.5			376	18	13			
17/08/95	150	35.5	36.2	15.50	21.10	568	19	19	42.4	2.00	2.00
18/08/95	150										
19/08/95	150	35.0	35.3	12.60	17.10						
Average:	150	35.8	36.0	14.92	18.16	407	19	20	31.3	2.34	2.61
Count:	34	33	32	31	31	23	23	23	14	13	13
Maximum:	150	37.4	40.3	18.70	22.90	568	23	30	42.4	4.11	5.21
Minimum:	150	31.7	33.1	12.30	13.60	270	16	13	22.2	2.00	2.00
Standard Deviation:	0	1.0	1.1	1.64	2.68	67	2	3	6.2	0.66	1.02

PERIOD 3.3.2
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
17/07/95	45.63	10.23	22.25	35.40	23.38	227.20	200.72
18/07/95	44.98	11.04	25.01	33.94	19.97	235.01	206.86
19/07/95	45.95	13.48	26.47	32.47	19.48	264.61	207.79
20/07/95	45.89	13.26	25.97	32.63	19.92	244.05	212.37
21/07/95							
22/07/95							
23/07/95	46.99	10.08	22.60	36.91	24.39	258.24	243.65
24/07/95	46.01	13.98	25.85	32.03	20.16	275.91	217.22
25/07/95	48.45	16.75	29.92	31.70	18.53	285.66	207.96
26/07/95	46.66	13.17	26.50	33.49	20.16	265.87	207.47
27/07/95	48.72	16.24	29.20	32.48	19.52	270.60	210.87
28/07/95							
29/07/95							
30/07/95	52.82	12.47	26.08	40.35	26.74	281.01	210.35
31/07/95	47.08	12.80	19.19	34.28	27.89	286.67	207.70
01/08/95	45.93	16.73	25.10	29.20	20.83	278.55	210.94
02/08/95	54.46	21.65	34.78	32.81	19.68	278.17	213.29
03/08/95	55.28	14.76	23.95	40.52	31.33	261.82	211.02
04/08/95							
05/08/95							
06/08/95	52.99	11.98	26.25	41.01	26.74	274.42	210.49
07/08/95	51.02	6.23	17.55	44.79	33.47	324.28	257.23
08/08/95							
09/08/95	51.03	8.07	19.22	42.96	31.81	257.72	223.12
10/08/95	48.45	12.92	27.45	35.53	21.00	286.48	224.60
11/08/95							
12/08/95							
13/08/95	49.09	19.54	31.49	29.55	17.60	280.46	221.51
14/08/95	51.19	24.06	32.14	27.13	19.05	275.08	222.28
15/08/95	47.48	20.99	31.01	26.49	16.47	270.32	210.41
16/08/95	47.48	22.93	36.82	24.55	10.66	265.27	206.84
17/08/95	48.93	22.77	35.69	26.16	13.24	287.77	215.46
18/08/95							
19/08/95							
Average:	48.80	15.05	26.98	33.76	21.83	271.09	215.66
Count:	23	23	23	23	23	23	23
Maximum:	55.28	24.06	36.82	44.79	33.47	324.28	257.23
Minimum:	44.98	6.23	17.55	24.55	10.66	227.20	200.72
Standard Deviation:	2.91	4.83	5.03	5.34	5.57	19.38	12.38

PERIOD 3.3.2
SUMMARY DATA 3
HIGH FERRIC TO R1 AEROBIC

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
17/07/95	112.54	111.10	4617	2287	4721	2613	49.5	55.3	74	80
18/07/95	115.57	113.38	4496	2211	4669	2559	49.2	54.8	80	81
19/07/95	117.69	116.67	4553	2025	4627	2598	44.5	56.1	78	86
20/07/95	117.78	117.19	4658	2248	4708	2598	48.3	55.2	75	81
21/07/95										
22/07/95										
23/07/95	119.03	134.36	4849	2235	4586	2529	46.1	55.1	74	78
24/07/95	124.60	118.33	4867	2198	4479	2440	45.2	54.5	72	80
25/07/95	129.26	111.92	4893	2214	4547	2447	45.2	53.8	74	79
26/07/95	122.81	114.09	5057	2336	4617	2539	46.2	55.0	73	78
27/07/95	123.97	115.99	4883	2237	4427	2435	45.8	55.0	72	79
28/07/95										
29/07/95										
30/07/95	127.23	116.24	5248	2376	4488	2480	45.3	55.3	72	80
31/07/95	126.95	112.08	5311	2352	4757	2567	44.3	54.0	72	78
01/08/95	124.61	113.76	5121	2291	4658	2512	44.7	53.9	76	79
02/08/95	122.33	119.07	5230	2300	4464	2492	44.0	55.8	76	81
03/08/95	117.57	112.76	5358	2406	4699	2511	44.9	53.4	73	77
04/08/95										
05/08/95										
06/08/95	122.38	115.28	5496	2451	4696	2572	44.6	54.8	73	79
07/08/95	142.09	138.76	5484	2403	4729	2551	43.8	53.9	72	76
08/08/95										
09/08/95	108.02	113.26	6010	2519	5033	2555	41.9	50.8	67	74
10/08/95	127.93	121.66	5668	2531	4752	2574	44.7	54.2	76	76
11/08/95										
12/08/95										
13/08/95	124.57	118.99	5678	2522	4533	2435	44.4	53.7	77	84
14/08/95	123.32	117.96	5775	2589	4545	2412	44.8	53.1	76	84
15/08/95	119.19	114.61	5745	2533	4509	2456	44.1	54.5	78	84
16/08/95	119.52	115.25	5702	2569	4442	2475	45.1	55.7	79	89
17/08/95	131.23	126.05	5230	2385	4010	2346	45.6	58.5	80	97
18/08/95										
19/08/95										
Average:	122.62	117.77	5214	2357	4595	2509	45.3	54.6	75	81
Count:	23	23	23	23	23	23	23	23	23	23
Maximum:	142.09	138.76	6010	2589	5033	2613	49.5	58.5	80	97
Minimum:	108.02	111.10	4496	2025	4010	2346	41.9	50.8	67	74
Standard Deviation:	6.76	6.72	427	141	183	68	1.7	1.4	3	5

PERIOD 3.3.2
SUMMARY DATA 4
HIGH FERRIC TO R1 AEROBIC

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
17/07/95	6.86	6.48	7.22	7.10	7.57	7.49	10	10		
18/07/95	7.00	6.93	7.27	7.24	7.55	7.54	10	10		
19/07/95	7.06	7.00	7.18	7.25	7.43	7.48	10	10	192.3	250.1
20/07/95	6.89	6.88	7.27	7.26	7.46	7.49	10	10		
21/07/95	6.96	6.78	7.26	7.32	7.52	7.60	10	10		
22/07/95							10	10		
23/07/95	6.92	6.86	7.25	7.29	7.50	7.55	10	10		
24/07/95	6.93	6.88	7.33	7.27	7.53	7.56	10	10	211.0	235.2
25/07/95	7.00	6.93	7.20	7.28	7.43	7.50	10	10		
26/07/95	6.86	6.83	7.22	7.26	7.45	7.54	10	10		
27/07/95	6.92	6.80	7.31	7.31	7.50	7.53	10	10	185.0	220.3
28/07/95	6.87	6.80	7.19	7.20	7.45	7.48	10	10		
29/07/95	7.04	6.82	7.19	7.15	7.43	7.40	10	10		
30/07/95							10	10		
31/07/95	6.95	6.87	7.38	7.31	7.59	7.66	10	10	238.5	257.6
01/08/95	7.01	6.85	7.34	7.19	7.58	7.51	10	10		
02/08/95	7.04	6.95	7.23	7.21	7.38	7.46	10	10	196.2	233.4
03/08/95	6.85	6.76	7.19	7.16	7.46	7.54	10	10		
04/08/95	6.89	6.83	7.33	7.23	7.59	7.61	10	10		
05/08/95	6.91	6.84	7.30	7.34	7.62	7.61	10	10		
06/08/95							10	10		
07/08/95	6.87	6.85	7.20	7.24	7.47	7.56	10	10	252.4	287.0
08/08/95	6.93	6.89	7.31	7.33	7.57	7.70	10	10		
09/08/95	6.93	6.82	7.18	7.18	7.47	7.50	10	10	260.3	301.4
10/08/95	6.85	6.80	7.13	7.16	7.43	7.46	10	10		
11/08/95	6.93	6.80	7.24	7.18	7.43	7.48	10	10		
12/08/95							10	10		
13/08/95	6.90	6.83	7.19	7.15	7.41	7.41	10	10		
14/08/95	6.94	6.84	7.11	7.11	7.27	7.32	10	10	193.3	247.1
15/08/95	6.99	6.89	7.24	7.18	7.43	7.48	10	10		
16/08/95	6.85	6.84	7.02	7.03	7.22	7.24	10	10		
17/08/95	7.08	7.00	7.23	7.20	7.37	7.39	10	10	164.1	202.9
18/08/95							10	10		
19/08/95	6.85	6.80	7.05	7.06	7.24	7.30	10	10		
Average:	6.93	6.84	7.23	7.21	7.46	7.50	10	10	210.3	248.3
Count:	29	29	29	29	29	29	34	34	9	9
Maximum:	7.08	7.00	7.38	7.34	7.62	7.70	10	10	260.3	301.4
Minimum:	6.85	6.48	7.02	7.03	7.22	7.24	10	10	164.1	202.9
Standard Deviation:	0.07	0.09	0.08	0.08	0.10	0.10	0	0	31.0	29.1

PERIOD 3.3.2
SUMMARY DATA 5
HIGH FERRIC TO R1 AEROBIC

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
17/07/95	0.31	0.31	4.70	8.00	11.16	23.09
18/07/95	0.31	0.21	7.80	10.20	10.28	26.29
19/07/95	0.21	0.21	6.00	6.00	12.12	24.91
20/07/95	0.31	0.52	4.70	4.40	13.08	24.85
21/07/95						
22/07/95						
23/07/95	1.68	1.12	4.92	5.20	10.38	23.64
24/07/95	1.40	1.40	6.57	5.75	14.69	25.17
25/07/95	1.40	1.40	4.79	5.75	16.41	33.14
26/07/95	1.40	1.40	3.42	3.56	12.86	27.36
27/07/95	1.40	1.40	3.83	4.38	15.87	33.92
28/07/95						
29/07/95						
30/07/95	2.06	1.47	2.77	2.25	12.26	26.29
31/07/95	1.77	1.18	7.09	4.85	13.32	17.34
01/08/95	1.49	0.34	10.55	8.39	16.37	24.59
02/08/95	0.34	0.34	7.58	4.87	21.04	33.96
03/08/95	0.42	0.61	4.19	2.71	13.81	23.64
04/08/95						
05/08/95						
06/08/95	1.12	1.12	3.92	3.25	11.82	25.52
07/08/95	2.31	1.80	3.39	2.85	6.52	18.56
08/08/95						
09/08/95	3.09	1.28	4.34	3.52	8.28	20.66
10/08/95	1.80	1.80	3.79	2.71	13.26	27.95
11/08/95						
12/08/95						
13/08/95	2.58	1.80	4.74	2.71	19.88	31.92
14/08/95	1.80	2.06	7.86	6.91	22.20	30.93
15/08/95	2.06	1.80	10.40	8.94	20.44	31.04
16/08/95	2.58	2.06	13.55	9.22	23.75	36.56
17/08/95	1.80	1.80	9.62	9.89	21.54	34.46
18/08/95						
19/08/95						
Average:	1.46	1.19	6.11	5.49	14.84	27.21
Count:	23	23	23	23	23	23
Maximum:	3.09	2.06	13.55	10.20	23.75	36.56
Minimum:	0.21	0.21	2.77	2.25	6.52	17.34
Standard Deviation:	0.81	0.61	2.74	2.48	4.58	5.11

PERIOD 3.3.2
SUMMARY DATA 6
HIGH FERRIC TO R1 AEROBIC

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
17/07/95								
18/07/95								
19/07/95	0.03	1.23	4.54	4.47	0.10	1.42	4.54	4.69
20/07/95								
21/07/95								
22/07/95								
23/07/95	0.03	1.61	4.54	5.72	0.03	1.70	4.84	4.69
24/07/95								
25/07/95								
26/07/95	0.13	0.97	3.23	3.03	0.05	0.19	3.10	3.37
27/07/95								
28/07/95								
29/07/95								
30/07/95	0.03	0.38	2.69	2.96	0.05	0.19	2.56	2.42
31/07/95								
01/08/95								
02/08/95	0.05	1.10	4.98	5.25	0.07	0.10	3.50	3.10
03/08/95								
04/08/95								
05/08/95								
06/08/95	0.50	1.18	5.38	5.12	0.50	1.27	3.91	3.64
07/08/95								
08/08/95								
09/08/95	0.05	0.43	4.71	5.12	0.05	0.13	3.64	3.50
10/08/95								
11/08/95								
12/08/95								
13/08/95	0.05	0.78	4.45	5.25	0.07	0.19	2.96	2.69
14/08/95								
15/08/95								
16/08/95	0.08	2.20	10.10	9.43	0.05	9.02	7.00	11.86
17/08/95								
18/08/95								
19/08/95								
Average:	0.11	1.10	4.96	5.15	0.11	1.58	4.01	4.44
Count:	9	9	9	9	9	9	9	9
Maximum:	0.50	2.20	10.10	9.43	0.50	9.02	7.00	11.86
Minimum:	0.03	0.38	2.69	2.96	0.03	0.10	2.56	2.42
Standard Deviation:	0.14	0.54	1.98	1.78	0.14	2.70	1.26	2.72

PERIOD 3.3.2
SUMMARY DATA 7
HIGH FERRIC TO R1 AEROBIC

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAB1	TP R1 fAB2	TP R2 fAN	TP R2 fAX	TP R2 fAB1	TP R2 fAB2
17/07/95								
18/07/95								
19/07/95	105.68	62.27	25.69	15.61	115.43	44.71	40.97	29.75
20/07/95								
21/07/95								
22/07/95								
23/07/95	130.07	43.25	24.23	14.14	111.37	57.88	35.93	24.71
24/07/95								
25/07/95								
26/07/95	84.54	38.86	23.57	14.63	99.99	58.86	38.69	27.80
27/07/95								
28/07/95								
29/07/95								
30/07/95	92.67	42.27	20.65	10.89	105.68	55.44	33.49	21.79
31/07/95								
01/08/95								
02/08/95	120.58	59.06	34.12	22.47	133.70	78.91	54.30	37.24
03/08/95								
04/08/95								
05/08/95								
06/08/95	113.19	49.54	24.61	12.80	124.68	61.03	42.98	30.51
07/08/95								
08/08/95								
09/08/95	96.09	48.29	23.09	12.43	107.39	62.33	39.24	26.16
10/08/95								
11/08/95								
12/08/95								
13/08/95	92.86	53.45	30.20	20.99	106.58	65.24	44.41	32.46
14/08/95								
15/08/95								
16/08/95	100.93	64.11	37.63	26.32	103.35	89.79	59.75	41.18
17/08/95								
18/08/95								
19/08/95								
Average:	104.07	51.23	27.09	16.70	112.02	63.80	43.31	30.18
Count:	9	9	9	9	9	9	9	9
Maximum:	130.07	64.11	37.63	26.32	133.70	89.79	59.75	41.18
Minimum:	84.54	38.86	20.65	10.89	99.99	44.71	33.49	21.79
Standard Deviation:	13.92	8.58	5.34	4.98	10.29	12.51	8.07	5.76

PERIOD 3.3.2
SUMMARY DATA 8
HIGH FERRIC TO R1 AEROBIC

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
17/07/95	0.0	13.3	0.0	20.7	
18/07/95	0.0	13.3	0.0	19.5	
19/07/95	0.0	13.3	0.0	19.9	
20/07/95	0.0	13.3	0.0	19.8	
21/07/95	0.0	13.3	0.0	20.0	
22/07/95	0.0	13.3	0.0	19.8	
23/07/95	0.0	13.3	0.0	20.2	
24/07/95	0.0	13.3	0.0	19.9	
25/07/95	0.0	13.3	0.0	20.3	
26/07/95	0.0	13.3	0.0	20.7	
27/07/95	0.0	13.3	0.0	20.3	
28/07/95	0.0	13.3	0.0	20.0	
29/07/95	0.0	13.3	0.0	20.3	
30/07/95	0.0	13.3	0.0	19.5	
31/07/95	0.0	13.3	0.0	20.8	
01/08/95	0.0	13.3	0.0	20.5	
02/08/95	0.0	13.3	0.0	21.3	
03/08/95	0.0	13.3	0.0	20.7	
04/08/95	0.0	13.3	0.0	20.7	
05/08/95	0.0	13.3	0.0	20.9	
06/08/95	0.0	13.3	0.0	17.6	
07/08/95	0.0	13.3	0.0	18.2	
08/08/95	0.0	13.3	0.0		
09/08/95	0.0	13.3	0.0	20.6	
10/08/95	0.0	13.3	0.0	19.1	
11/08/95	0.0	13.3	0.0	18.0	
12/08/95	0.0	13.3	0.0	18.9	
13/08/95	0.0	13.3	0.0	19.6	
14/08/95	0.0	13.3	0.0	21.0	
15/08/95	0.0	13.3	0.0	20.5	
16/08/95	0.0	13.3	0.0		
17/08/95	0.0	13.3	0.0	19.6	
18/08/95	0.0	13.3	0.0		
19/08/95	0.0	13.3	0.0	20.0	
Average:				20.0	0.0
Count:	34	34	34	31	0
Maximum:	0.0	13.3	0.0	21.3	
Minimum:	0.0	13.3	0.0	17.6	
Standard Deviation:				0.9	0.0

PERIOD 3.3.3
SUMMARY DATA 1
LOW FERRIC TO R1 ANAEROBIC

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
08/09/95	150	35.3	36.0	16.50	20.50						
09/09/95	150	34.3	37.7	16.90	18.70						
10/09/95	150	34.6	35.5	14.70	16.70	483	22	23	37.7	2.00	2.00
11/09/95	150	36.5	36.5	14.80	21.60	454	21	22			
12/09/95	150	37.2	37.2	17.10	18.60	517	23	24	38.0	2.00	2.00
13/09/95	150	37.9	37.9	16.80	18.60	457	25	20			
14/09/95	150	34.8	36.2	15.50	17.50	521	25	23	32.8	3.42	2.00
15/09/95	150	35.0	37.2	15.00	16.90						
16/09/95	150	35.3	36.5	15.30	15.60						
17/09/95	150			14.90	15.30	407	21	21	32.5	3.30	3.45
18/09/95	150	35.5	35.5	12.90		369	19	21			
19/09/95	150	35.0	35.0	11.80	12.30	310	18	17	26.2	2.00	3.91
20/09/95	150	34.6	35.3	14.00	16.60	525	18	20			
21/09/95	150	35.3	35.3	15.30	16.70	491	24	26	37.9	4.31	3.76
22/09/95	150	35.3	35.3	14.20	14.60						
23/09/95	150	36.5	36.5	14.80	13.50						
24/09/95	150	35.8	35.3	14.30	15.60	527	20	19	40.4	3.06	3.28
25/09/95	150	34.3	37.4	14.70	15.20	413	22	23			
26/09/95	150	37.7	36.5	14.80	16.30	521	23	22	47.4	3.57	2.00
27/09/95	150	38.2	36.5	14.40	15.60	470	20	22			
28/09/95	150	36.7	36.0	14.40	11.40	483	19	16			
29/09/95	150	36.2	35.5	14.60	11.40						
30/09/95	150	38.9	33.8	13.50	13.60						
02/10/95	150		31.2	13.30	12.60	460	54	15			
03/10/95	150	37.0	33.6	12.60	12.70	429	60	19		5.39	2.00
04/10/95	150	35.8	35.8	13.60	12.80	434	38	17			
05/10/95	150	36.7	36.0	10.30	13.20	398	23	21	22.4	2.00	2.00
Average:	150	36.0	35.8	14.48	15.54	456	26	21	35.0	3.11	2.64
Count:	27	25	26	27	26	19	19	19	9	10	10
Maximum:	150	38.9	37.9	17.10	21.60	527	60	26	47.4	5.39	3.91
Minimum:	150	34.3	31.2	10.30	11.40	310	18	15	22.4	2.00	2.00
Standard Deviation:	0	1.3	1.4	1.49	2.66	57	11	3	7.1	1.09	0.80

PERIOD 3.3.3
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
08/09/95							
09/09/95							
10/09/95	53.11	33.36	37.84	19.75	15.27	192.64	178.60
11/09/95	60.42	25.56	30.54	34.86	29.88	227.09	208.10
12/09/95	58.76	23.90	32.20	34.86	26.56	207.81	202.52
13/09/95	57.43	17.59	21.08	39.84	36.35	226.08	209.17
14/09/95	57.26	17.93	21.58	39.33	35.68	229.49	223.61
15/09/95							
16/09/95							
17/09/95	56.13	23.32	28.15	32.81	27.98	215.70	208.00
18/09/95	47.12	22.68	33.94	24.44	13.18	228.60	204.67
19/09/95	47.12	23.96	30.08	23.16	17.04	230.33	198.37
20/09/95	52.43	28.95	33.61	23.48	18.82	220.86	196.36
21/09/95	50,34	23.80	28.63	26.54	21.71	209.11	178.03
22/09/95							
23/09/95							
24/09/95	53.24	21.55	24.61	31.69	28.63	206.93	200.29
25/09/95	55.65	21.55	22.03	34.10	33.62	205.95	181.51
26/09/95	48.89	18.17	19.62	30.72	29.27	204.87	176.78
27/09/95	48.95	19.32	23.83	29.63	25.12	180.85	178.65
28/09/95	49.60	20.93	26.41	28.67	23.19	217.63	190.16
29/09/95							
30/09/95							
02/10/95	51.53	23.83	28.02	27.70	23.51	205.21	181.67
03/10/95	51.21	30.92	31.40	20.29	19.81	198.59	180.09
04/10/95	50.08	28.50	33.82	21.58	16.26	208.95	178.65
05/10/95	50.89	26.41	31.08	24.48	19.81	210.17	186.41
Average:	52.64	23.80	28.34	28.84	24.30	211.94	192.72
Count:	19	19	19	19	19	19	19
Maximum:	60.42	33.36	37.84	39.84	36.35	230.33	223.61
Minimum:	47.12	17.59	19.62	19.75	13.18	180.85	176.78
Standard Deviation:	3.84	4.26	4.98	5.95	6.72	12.96	13.68

PERIOD 3.3.3
SUMMARY DATA 3
LOW FERRIC TO R1 ANAEROBIC

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
08/09/95										
09/09/95										
10/09/95	107.20	103.74	4196	2335	3872	2249	55.6	58.1	109	108
11/09/95	125.52	125.08	4192	2317	3875	2329	55.3	60.1	95	103
12/09/95	115.62	120.52	4479	2492	3939	2344	55.6	59.5	89	102
13/09/95	122.81	124.25	4352	2364	3914	2325	54.3	59.4	92	112
14/09/95	126.07	130.24	4358	2394	4040	2353	54.9	58.2	92	104
15/09/95										
16/09/95										
17/09/95	118.14	120.84	4506	2468	4126	2397	54.8	58.1	98	102
18/09/95	119.02	117.77	4581	2385	4138	2381	52.1	57.5	92	106
19/09/95	124.02	120.14	4461	2402	3976	2408	53.8	60.6	94	111
20/09/95	119.09	118.27	4551	2454	4066	2449	53.9	60.2	88	108
21/09/95	111.38	105.20	4534	2415	4036	2385	53.3	59.1	88	104
22/09/95										
23/09/95										
24/09/95	107.91	114.74	4844	2526	4219	2417	52.1	57.3		
25/09/95	107.42	103.33	4866	2538	4467	2543	52.2	56.9	86	99
26/09/95	107.27	102.63	4918	2575	4482	2602	52.4	58.1	85	94
27/09/95	105.46	103.67	4474	2609	4489	2605	58.3	58.0	94	98
28/09/95	120.81	116.57	4500	2498	3951	2422	55.5	61.3	98	111
29/09/95										
30/09/95										
02/10/95	103.35	102.50	4690	2362	4399	2482	50.4	56.4	47	100
03/10/95	104.66	102.68	4662	2457	4297	2450	52.7	57.0	90	102
04/10/95	107.68	100.45	4591	2366	4489	2524	51.5	56.2	87	94
05/10/95	105.76	106.79	4644	2337	4177	2393	50.3	57.3	86	105
Average:	113.64	112.60	4547	2437	4155	2424	53.6	58.4	89	104
Count:	19	19	19	19	19	19	19	19	18	18
Maximum:	126.07	130.24	4918	2609	4489	2605	58.3	61.3	109	112
Minimum:	103.35	100.45	4192	2317	3872	2249	50.3	56.2	47	94
Standard Deviation:	7.72	9.32	194	83	216	92	2.0	1.4	12	5

PERIOD 3.3.3
SUMMARY DATA 4
LOW FERRIC TO R1 ANAEROBIC

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
08/09/95	6.93	7.05	7.22	7.32	7.48	7.54	10	10		
09/09/95	7.14	7.20	7.34	7.27	7.54	7.45	10	10		
10/09/95	6.98	7.01	7.19	7.18	7.42	7.37	10	10		
11/09/95	6.90	6.90	7.39	7.36	7.68	7.64	10	10		
12/09/95	6.91	6.91	7.42	7.39	7.66	7.64	10	10		
13/09/95	6.96	6.88	7.47	7.40	7.74	7.72	10	10		
14/09/95	7.02	6.98	7.43	7.44	7.69	7.70	10	10		
15/09/95	7.09	7.10	7.50	7.51	7.82	7.72	10	10		
16/09/95	7.04	7.02	7.46	7.49	7.73	7.73	10	10		
17/09/95							10	10		
18/09/95	7.18	7.29	7.44	7.88	7.61	8.43	10	10		
19/09/95	7.05	7.20	7.46	7.48	7.66	7.63	10	10		
20/09/95	7.07	7.12	7.51	7.42	7.72	7.61	10	10		
21/09/95	7.07	7.15	7.44	7.45		7.67	10	10		
22/09/95	6.99	6.96	7.38	7.44	7.66	7.77	10	10		
23/09/95	6.91	6.93	7.37	7.39	7.64	7.66	10	10		
24/09/95	7.30	7.04	7.63	7.41	7.91	7.87	10	10		
25/09/95	6.88	6.87	7.31	7.33	7.59	7.63	10	10		
26/09/95							10	10		
27/09/95	7.00	6.89	7.45	7.44	7.74	7.75	10	10		
28/09/95	6.89	6.85	7.40	7.38	7.62	7.59	10	10	240.5	256.3
29/09/95	6.97	7.01	7.43	7.60	7.68	7.95	10	10		
30/09/95	7.01	6.99	7.42	7.65	7.69	7.94	10	10		
02/10/95							10	10		
03/10/95	6.77	6.75	7.20	7.22	7.38	7.41	10	10		
04/10/95	7.01	6.83	7.37	7.30	7.53	7.45	10	10		
05/10/95	6.91	6.85	7.33	7.33	7.48	7.54	10	10		
Average:	7.00	6.99	7.40	7.42	7.64	7.68	10	10	240.5	256.3
Count:	24	24	24	24	23	24	27	27	1	1
Maximum:	7.30	7.29	7.63	7.88	7.91	8.43	10	10	240.5	256.3
Minimum:	6.77	6.75	7.19	7.18	7.38	7.37	10	10	240.5	256.3
Standard Deviation:	0.11	0.13	0.10	0.14	0.12	0.21	0	0	0.0	0.0

PERIOD 3.3.3
SUMMARY DATA 5
LOW FERRIC TO R1 ANAEROBIC

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
08/09/95						
09/09/95						
10/09/95	0.99	0.94	6.43	7.55	32.17	36.57
11/09/95	0.99	1.23	4.56	3.99	23.31	29.60
12/09/95	1.23	1.23	4.40	3.00	22.45	30.17
13/09/95	1.40	1.17	4.18	3.62	17.20	20.28
14/09/95	1.17	1.17	4.43	4.12	17.50	21.06
15/09/95						
16/09/95						
17/09/95	1.40	1.64	6.86	8.33	23.17	28.30
18/09/95	1.58	1.40	5.62	7.24	22.45	32.59
19/09/95	1.64	0.99	5.24	5.62	24.14	30.17
20/09/95	0.88	1.17	6.24	6.36	28.96	33.80
21/09/95	1.40	1.40	6.80	6.74	24.02	27.28
22/09/95						
23/09/95						
24/09/95	1.40	1.17	7.30	6.74	21.48	24.26
25/09/95	1.17	1.17	7.89	7.24	21.48	21.97
26/09/95	1.62	1.08	8.39	8.54	17.15	19.19
27/09/95	0.95	0.81	9.29	8.84	19.19	23.80
28/09/95	1.08	1.08	5.24	6.59	20.47	26.36
29/09/95						
30/09/95						
02/10/95	1.09	1.08	4.79	6.14	21.75	27.90
03/10/95	1.09	1.09	5.69	5.84	23.03	31.22
04/10/95	1.38	1.09	5.84	5.84	28.15	34.29
05/10/95	1.09	1.09	5.69	6.74	26.62	31.99
Average:	1.24	1.16	6.05	6.27	22.88	27.94
Count:	19	19	19	19	19	19
Maximum:	1.64	1.64	9.29	8.84	32.17	36.57
Minimum:	0.88	0.81	4.18	3.00	17.15	19.19
Standard Deviation:	0.23	0.18	1.39	1.60	3.89	4.93

PERIOD 3.3.3
SUMMARY DATA 6
LOW FERRIC TO R1 ANAEROBIC

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
08/09/95								
09/09/95								
10/09/95								
11/09/95								
12/09/95								
13/09/95								
14/09/95								
15/09/95								
16/09/95								
17/09/95	0.09	1.85	7.14	6.99	0.10	3.99	8.17	8.36
18/09/95								
19/09/95								
20/09/95								
21/09/95								
22/09/95								
23/09/95								
24/09/95								
25/09/95	0.08	1.30	8.11	7.92	0.12	4.80	7.52	7.11
26/09/95								
27/09/95	0.12	1.12	7.89	7.71	0.32	1.50	6.71	6.61
28/09/95								
29/09/95								
30/09/95								
02/10/95	0.04	0.07	6.06	6.19	0.12	0.94	5.70	5.94
03/10/95								
04/10/95								
05/10/95	0.07	2.16	6.56	6.56	0.07	2.67	6.44	6.69
Average:	0.08	1.30	7.15	7.07	0.15	2.78	6.91	6.94
Count:	5	5	5	5	5	5	5	5
Maximum:	0.12	2.16	8.11	7.92	0.32	4.80	8.17	8.36
Minimum:	0.04	0.07	6.06	6.19	0.07	0.94	5.70	5.94
Standard Deviation:	0.03	0.72	0.78	0.66	0.09	1.45	0.86	0.80

PERIOD 3.3.3
SUMMARY DATA 7
LOW FERRIC TO R1 ANAEROBIC

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
08/09/95								
09/09/95								
10/09/95	123.66	82.16	53.11	37.51	125.32	72.53	54.94	42.99
11/09/95								
12/09/95								
13/09/95								
14/09/95								
15/09/95								
16/09/95								
17/09/95	98.11	56.77	34.58	23.96	100.52	58.06	37.31	29.27
18/09/95								
19/09/95								
20/09/95								
21/09/95								
22/09/95								
23/09/95								
24/09/95								
25/09/95	102.93	62.40	31.84	18.98	108.56	46.32	33.13	19.30
26/09/95								
27/09/95	95.69	56.13	29.43	18.01	102.93	59.83	35.87	24.29
28/09/95								
29/09/95								
30/09/95								
02/10/95	95.01	67.47	32.37	20.13	107.09	68.92	42.67	30.44
03/10/95								
04/10/95								
05/10/95	91.79	56.36	35.11	26.09	99.04	60.23	40.58	31.72
Average:	101.20	63.55	36.07	24.11	107.24	60.98	40.75	29.67
Count:	6	6	6	6	6	6	6	6
Maximum:	123.66	82.16	53.11	37.51	125.32	72.53	54.94	42.99
Minimum:	91.79	56.13	29.43	18.01	99.04	46.32	33.13	19.30
Standard Deviation:	10.60	9.27	7.84	6.62	8.75	8.38	7.06	7.29

PERIOD 3.3.3
SUMMARY DATA 8
LOW FERRIC TO R1 ANAEROBIC

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
08/09/95	0.0	6.7	0.0	22.0	
09/09/95	0.0	6.7	0.0	20.8	
10/09/95	0.0	6.7	0.0	21.5	
11/09/95	0.0	6.7	0.0	21.3	
12/09/95	0.0	6.7	0.0	19.5	
13/09/95	0.0	6.7	0.0	19.9	
14/09/95	0.0	6.7	0.0	20.0	
15/09/95	0.0	6.7	0.0	20.1	
16/09/95	0.0	6.7	0.0	20.0	
17/09/95	0.0	6.7	0.0	19.9	
18/09/95	0.0	6.7	0.0	19.7	
19/09/95	0.0	6.7	0.0	19.6	
20/09/95	0.0	6.7	0.0	20.6	
21/09/95	0.0	6.7	0.0	19.8	
22/09/95	0.0	6.7	0.0	19.9	
23/09/95	0.0	6.7	0.0	20.0	
24/09/95	0.0	6.7	0.0	20.0	
25/09/95	0.0	6.7	0.0	19.1	
26/09/95	0.0	6.7	0.0	19.1	
27/09/95	0.0	6.7	0.0	18.8	
28/09/95	0.0	6.7	0.0	19.3	
29/09/95	0.0	6.7	0.0	18.8	
30/09/95	0.0	6.7	0.0	18.8	
02/10/95	0.0	6.7	0.0	19.0	
03/10/95	0.0	6.7	0.0	18.8	
04/10/95	0.0	6.7	0.0	18.9	
05/10/95	0.0	6.7	0.0	18.8	
Average:				19.8	0.0
Count:	27	27	27	27	0
Maximum:	0.0	6.7	0.0	22.0	
Minimum:	0.0	6.7	0.0	18.8	
Standard Deviation:				0.9	0.0

PERIOD 3.3.4
SUMMARY DATA 1
LOW FERRIC TO R1 ANAEROBIC, 10d Rs

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
06/10/95	150	35.8	35.0	15.10	14.30						
07/10/95	150	35.5	32.2	15.60	15.40						
08/10/95	150	37.2	37.2	16.10	15.80	437	21	22	36.7	3.12	2.00
09/10/95	150	36.2	37.0	15.30	15.50	436	27	23			
10/10/95	150	36.2	36.2	14.70	14.30	501	24	24	29.9	2.00	2.00
11/10/95	150	36.2	39.8	14.20	14.20	393	20	20			
12/10/95	150	36.7	34.6	13.80	13.30	470	21	20	35.3	4.01	2.00
13/10/95	150	36.5	36.5	13.60	12.80						
14/10/95	150	36.5	36.0	13.40	13.10						
15/10/95	150	34.3	36.0	13.40	13.60	425	23	19	25.9	3.71	3.22
16/10/95	150	36.5	37.2	13.40	13.40	457	22	22			
17/10/95	150	34.6	36.0	12.50	12.90	426	25	20	34.5	4.05	5.22
18/10/95	150	36.2	36.7	12.80		591	25	24			
19/10/95	150	35.5	36.2	13.80	14.50	560	20	18		3.29	4.55
20/10/95	150	34.8	35.5	14.50	14.20						
21/10/95	150	31.2	35.3	12.30	12.90						
22/10/95	150	38.9	36.7	13.70	13.10	567	20	19	38.9	3.49	3.46
23/10/95	150	39.1	37.0	14.30	12.80	271	17	14			
Average:	150	36.0	36.2	14.03	13.89	461	22	20	33.5	3.38	3.21
Count:	18	18	18	18	17	12	12	12	6	7	7
Maximum:	150	39.1	39.8	16.10	15.80	591	27	24	38.9	4.05	5.22
Minimum:	150	31.2	32.2	12.30	12.80	271	17	14	25.9	2.00	2.00
Standard Deviation:	0	1.7	1.5	1.02	0.96	84	3	3	4.4	0.65	1.21

PERIOD 3.3.4
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
06/10/95							
07/10/95							
08/10/95	49.28	16.91	19.00	32.37	30.28	209.87	176.09
09/10/95	47.99	14.98	13.85	33.01	34.14	199.51	185.03
10/10/95	51.83	16.68	16.36	35.15	35.47	192.40	185.39
11/10/95	51.47	15.97	16.78	35.50	34.69	238.46	190.29
12/10/95	50.02	16.62	18.07	33.40	31.95	222.04	206.44
13/10/95							
14/10/95							
15/10/95	49.21	17.10	21.46	32.11	27.75	225.11	212.31
16/10/95	48.40	18.39	22.10	30.01	26.30	229.63	210.41
17/10/95	47.11	18.23	21.14	28.88	25.97	239.00	210.57
18/10/95	54.70	25.33	34.04	29.37	20.66	217.98	195.26
19/10/95	55.65	25.21	27.01	30.44	28.64	219.71	202.74
20/10/95							
21/10/95							
22/10/95	51.23	20.62	19.81	30.61	31.42	231.74	206.28
23/10/95	50.41	20.46	24.39	29.95	26.02	217.46	211.44
Average:	50.61	18.88	21.17	31.73	29.44	220.24	199.35
Count:	12	12	12	12	12	12	12
Maximum:	55.65	25.33	34.04	35.50	35.47	239.00	212.31
Minimum:	47.11	14.98	13.85	28.88	20.66	192.40	176.09
Standard Deviation:	2.46	3.27	5.19	2.11	4.19	13.71	11.94

PERIOD 3.3.4
SUMMARY DATA 3
LOW FERRIC TO R1 ANAEROBIC, 10d Rs

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
06/10/95										
07/10/95										
08/10/95	108.19	102.56	4644	2394	4004	2332	51.6	58.2	86	95
09/10/95	103.25	104.24	4570	2365	3955	2228	51.8	56.3	88	96
10/10/95	108.46	107.60	4435	2500	3823	2219	56.4	58.0	81	94
11/10/95	122.34	96.72	3719	1908	4287	2179	51.3	50.8	97	86
12/10/95	129.76	113.68	3643	2129	3690	2032	58.4	55.1	88	92
13/10/95										
14/10/95										
15/10/95	112.36	119.20	4035	2014	3411	1915	49.9	56.1	74	94
16/10/95	113.26	115.55	3832	1890	3365	1848	49.3	54.9	75	95
17/10/95	121.04	115.14	3639	1843	3195	1747	50.6	54.7	82	94
18/10/95	111.13	112.95	3615	1843	3314	1917	51.0	57.8	77	91
19/10/95	113.12	114.97	3603	1855	3303	1873	51.5	56.7	83	91
20/10/95										
21/10/95										
22/10/95	116.39	114.43	3347	1681	3290	1825	50.2	55.5	78	85
23/10/95	109.71	118.19	3342	1686	3102	1734	50.4	55.9	78	87
Average:	114.08	111.27	3869	2009	3562	1987	51.9	55.8	82	92
Count:	12	12	12	12	12	12	12	12	12	12
Maximum:	129.76	119.20	4644	2500	4287	2332	58.4	58.2	97	96
Minimum:	103.25	96.72	3342	1681	3102	1734	49.3	50.8	74	85
Standard Deviation:	6.97	6.63	433	265	362	196	2.6	1.9	6	4

PERIOD 3.3.4
SUMMARY DATA 4
LOW FERRIC TO R1 ANAEROBIC, 10d Rs

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk R1	H2CO3* Alk R2
06/10/95	6.93	6.93	7.44	7.45	7.66	7.70	10	10		
07/10/95	6.89	6.84	7.43	7.41	7.68	7.65	10	10		
08/10/95	6.95	6.95	7.50	7.50	7.76	7.79	10	10		
09/10/95	6.86	6.89	7.51	7.55	7.65	7.74	10	10		
10/10/95	6.94	6.83	7.51	7.45	7.63	7.70	10	10		
11/10/95	6.93	6.86	7.40	7.38	7.61	7.69	10	10		
12/10/95	6.86	6.89	7.38	7.39	7.60	7.68	10	10		
13/10/95	7.07	6.99	7.53	7.49	7.70	7.76	10	10		
14/10/95	6.94	6.92	7.36	7.43	7.60	7.69	10	10		
15/10/95	6.90	6.87	7.43	7.50	7.58	7.66	10	10		
16/10/95	6.90	6.85	7.38	7.38	7.62	7.67	10	10		
17/10/95	6.85	6.74	7.30	7.38	7.56	7.62	10	10		
18/10/95	6.76	6.74	7.35	7.42	7.56	7.66	10	10		
19/10/95	6.79	6.75	7.32	7.41	7.57	7.68	10	10		
20/10/95	7.01	6.77	7.43	7.42	7.63	7.68	10	10		
21/10/95							10	10		
22/10/95	6.89	6.84	7.34	7.25	7.54	7.52	10	10		
23/10/95	6.83	6.86	7.42	7.49	7.57	7.62	10	10		
Average:	6.90	6.85	7.41	7.43	7.62	7.68	10	10	0.0	0.0
Count:	17	17	17	17	17	17	18	18	0	0
Maximum:	7.07	6.99	7.53	7.55	7.76	7.79	10	10		
Minimum:	6.76	6.74	7.30	7.25	7.54	7.52	10	10		
Standard Deviation:	0.07	0.07	0.07	0.07	0.06	0.06	0	0	0.0	0.0

PERIOD 3.3.4
SUMMARY DATA 5
LOW FERRIC TO R1 ANAEROBIC, 10d Rs

	DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
	06/10/95						
	07/10/95						
	08/10/95	1.09	1.09	6.29	6.14	17.40	19.45
	09/10/95	2.63	2.10	6.38	6.15	14.76	14.91
	10/10/95	2.17	1.64	7.05	6.78	16.79	15.41
	11/10/95	1.58	2.17	7.45	6.98	14.76	17.23
	12/10/95	1.31	1.18	7.58	7.05	15.13	16.74
	13/10/95						
	14/10/95						
	15/10/95	1.38	1.45	7.05	6.25	16.00	20.21
	16/10/95	1.97	3.68	7.05	6.32	19.00	22.32
	17/10/95	3.55	3.41	6.32	6.18	16.87	20.03
	18/10/95	1.88	1.01	4.43	4.11	25.07	33.33
	19/10/95	1.30	1.30	2.91	2.69	24.74	26.25
	20/10/95						
	21/10/95						
	22/10/95	1.15	0.94	6.32	6.25	20.10	19.44
	23/10/95	0.87	0.94	7.85	7.56	19.77	24.30
Average:		1.74	1.74	6.39	6.04	18.37	20.80
Count:		12	12	12	12	12	12
Maximum:		3.55	3.68	7.85	7.56	25.07	33.33
Minimum:		0.87	0.94	2.91	2.69	14.76	14.91
Standard Deviation:		0.73	0.90	1.35	1.29	3.40	4.99

PERIOD 3.3.4
SUMMARY DATA 6
LOW FERRIC TO R1 ANAEROBIC, 10d Rs

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
06/10/95								
07/10/95								
08/10/95	0.15	1.31	6.56	6.44	0.10	1.73	5.94	5.94
09/10/95								
10/10/95								
11/10/95	0.07	2.30	7.18	6.93	0.12	2.48	6.69	6.69
12/10/95								
13/10/95								
14/10/95								
15/10/95	0.07	2.05	6.69	6.56	0.09	1.78	6.07	5.94
16/10/95								
17/10/95								
18/10/95	0.04	0.25	7.51	3.32	0.08	0.68	3.86	3.62
19/10/95								
20/10/95								
21/10/95								
22/10/95	0.03	1.91	3.49	7.64	0.09	2.63	7.51	7.71
23/10/95								
Average:	0.07	1.56	6.29	6.18	0.10	1.86	6.01	5.98
Count:	5	5	5	5	5	5	5	5
Maximum:	0.15	2.30	7.51	7.64	0.12	2.63	7.51	7.71
Minimum:	0.03	0.25	3.49	3.32	0.08	0.68	3.86	3.62
Standard Deviation:	0.04	0.73	1.44	1.49	0.01	0.69	1.21	1.35

PERIOD 3.3.4
SUMMARY DATA 7
LOW FERRIC TO R1 ANAEROBIC, 10d Rs

	DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
	06/10/95								
	07/10/95								
	08/10/95	125.52	63.49	33.36	19.43	128.76	62.84	33.20	18.46
	09/10/95								
	10/10/95								
	11/10/95	101.22	50.69	26.24	14.25	108.51	54.74	28.99	15.55
	12/10/95								
	13/10/95								
	14/10/95								
	15/10/95	94.74	48.59	27.53	16.36	106.89	56.85	33.69	21.05
	16/10/95								
	17/10/95								
	18/10/95	113.76	64.16	39.45	26.52	125.21	73.00	49.27	36.17
	19/10/95								
	20/10/95								
	21/10/95								
	22/10/95	93.30	56.14	32.74	20.46	101.48	55.65	36.34	23.90
	23/10/95								
Average:		105.71	56.61	31.86	19.40	114.17	60.62	36.30	23.03
Count:		5	5	5	5	5	5	5	5
Maximum:		125.52	64.16	39.45	26.52	128.76	73.00	49.27	36.17
Minimum:		93.30	48.59	26.24	14.25	101.48	54.74	28.99	15.55
Standard Deviation:		12.26	6.39	4.71	4.19	10.78	6.81	6.90	7.13

PERIOD 3.3.4
SUMMARY DATA 8
LOW FERRIC TO R1 ANAEROBIC, 10d Rs

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
06/10/95	0.0	6.7	0.0	19.3	
07/10/95	0.0	6.7	0.0	18.9	
08/10/95	0.0	6.7	0.0	18.9	
09/10/95	0.0	6.7	0.0	18.8	
10/10/95	0.0	6.7	0.0	18.9	
11/10/95	0.0	6.7	0.0	18.6	
12/10/95	0.0	6.7	0.0	18.7	
13/10/95	0.0	6.7	0.0	18.8	
14/10/95	0.0	6.7	0.0	17.8	
15/10/95	0.0	6.7	0.0	18.7	
16/10/95	0.0	6.7	0.0	18.8	
17/10/95	0.0	6.7	0.0	18.6	
18/10/95	0.0	6.7	0.0	19.0	
19/10/95	0.0	6.7	0.0	18.9	
20/10/95	0.0	6.7	0.0	19.3	
21/10/95	0.0	6.7	0.0	18.9	
22/10/95	0.0	6.7	0.0	19.5	
23/10/95	0.0	6.7	0.0	18.9	
Average:				18.9	0.0
Count:	18	18	18	18	0
Maximum:	0.0	6.7	0.0	19.5	
Minimum:	0.0	6.7	0.0	17.8	
Standard Deviation:				0.3	0.0

PERIOD 3.3.5
SUMMARY DATA 1
HIGH FERRIC TO R1 ANAEROBIC, 10d Rs

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
24/10/95	150	36.7	36.7	11.30	10.98	421	39	15	19.8	3.48	3.32
25/10/95	150	36.0	36.0	10.60	10.50	345	15	16			
26/10/95	150	35.5	36.2	9.80	11.50	459	40	17	34.6	3.43	2.00
27/10/95	150	35.8	35.8	13.00	13.30						
28/10/95	150	36.5	36.5	7.70	13.20						
29/10/95	150	36.0	34.3	14.10	12.90	340	21	21	33.4	3.68	3.34
30/10/95	150	36.2	36.2	13.10	12.60	372	21	22			
31/10/95	150	35.8	36.5	12.60	11.70	437	21	23	35.8	2.00	3.60
01/11/95	150	35.8	36.5	12.20	12.90	360	18	20			
02/11/95	150	35.3	36.0	13.60	14.00	317	20	21	32.0	4.04	2.00
03/11/95	150	35.8	37.2		14.40						
04/11/95	150	35.3	34.3	14.40	13.60						
05/11/95	150	38.2	37.0	15.20	14.90	478	20	22	38.0	2.00	2.00
06/11/95	150	40.3		15.00	15.20	402	21	19			
07/11/95	150	37.2	37.0	13.40	13.80	494	21	21	27.6	4.15	3.35
08/11/95	150	36.5	36.5	12.20	12.60	416	23	28			
09/11/95	150	37.0	37.0	13.30	13.50	404	21	21	26.3	2.00	2.00
10/11/95	150	37.9	35.3	12.20	12.40						
11/11/95	150	35.3	35.8	11.30	11.60						
12/11/95	150	35.8	36.2	11.60	11.30	268	19	25	23.8	3.29	3.14
13/11/95	150	34.8	35.5	12.20	12.50	451	25	25			
Average:	150	36.4	36.1	12.44	12.83	398	23	21	30.1	3.12	2.75
Count:	21	21	20	20	21	15	15	15	9	9	9
Maximum:	150	40.3	37.2	15.20	15.20	494	40	28	38.0	4.15	3.60
Minimum:	150	34.8	34.3	7.70	10.50	268	15	15	19.8	2.00	2.00
Standard Deviation:	0	1.2	0.8	1.75	1.24	61	7	3	5.7	0.83	0.68

PERIOD 3.3.5
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
24/10/95	47.42	18.80	26.46	28.62	20.96	208.84	188.52
25/10/95	49.92	18.47	27.46	31.45	22.46	226.27	192.47
26/10/95	48.25	20.97	28.79	27.28	19.46	221.58	192.91
27/10/95							
28/10/95							
29/10/95	45.59	11.31	21.47	34.28	24.12	234.96	197.69
30/10/95	50.42	10.82	23.63	39.60	26.79	238.60	210.25
31/10/95	48.42	12.65	23.96	35.77	24.46	252.62	217.46
01/11/95	52.75	22.30	32.28	30.45	20.47	290.35	222.89
02/11/95	51.66	15.67	24.31	35.99	27.35	236.08	203.10
03/11/95							
04/11/95							
05/11/95	48.94	9.44	17.59	39.50	31.35	275.35	226.06
06/11/95	48.62	9.44	15.35	39.18	33.27	242.67	227.72
07/11/95	59.34	12.96	22.71	46.38	36.63	251.80	219.82
08/11/95	55.82	18.71	28.95	37.11	26.87	165.87	159.10
09/11/95	50.86	20.79	30.87	30.07	19.99	260.98	194.61
10/11/95							
11/11/95							
12/11/95	49.74	19.83	28.63	29.91	21.11	327.22	215.11
13/11/95	47.18	18.23	26.87	28.95	20.31	278.06	244.25
Average:	50.33	16.03	25.29	34.30	25.04	247.42	207.46
Count:	15	15	15	15	15	15	15
Maximum:	59.34	22.30	32.28	46.38	36.63	327.22	244.25
Minimum:	45.59	9.44	15.35	27.28	19.46	165.87	159.10
Standard Deviation:	3.40	4.35	4.55	5.22	5.12	36.33	20.13

PERIOD 3.3.5
SUMMARY DATA 3
HIGH FERRIC TO R1 ANAEROBIC, 10d Rs

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
24/10/95	102.89	102.37	3477	1713	3186	1730	49.3	54.3	75	85
25/10/95	110.41	104.17	3406	1662	3019	1634	48.8	54.1	76	83
26/10/95	107.29	105.16	3288	1592	2959	1613	48.4	54.5	76	84
27/10/95										
28/10/95										
29/10/95	109.96	106.16	3329	1558	2931	1574	46.8	53.7	72	82
30/10/95	110.35	113.18	3468	1604	2911	1567	46.3	53.8	69	79
31/10/95	118.30	117.68	3404	1594	2842	1538	46.8	54.1	73	77
01/11/95	138.92	122.18	3294	1576	2751	1508	47.8	54.8	73	84
02/11/95	115.73	115.97	3317	1626	2648	1512	49.0	57.1	72	87
03/11/95										
04/11/95										
05/11/95	132.05	123.88	3355	1609	2750	1507	48.0	54.8	67	79
06/11/95	113.71	120.31	3404	1595	2845	1503	46.9	52.8	66	74
07/11/95	119.58	120.73	3384	1607	2782	1528	47.5	54.9	65	75
08/11/95	100.06	89.97	3085	1861	2764	1563	60.3	56.5	78	80
09/11/95	149.33	96.96	2667	1526	3398	1693	57.2	49.8	82	62
10/11/95										
11/11/95										
12/11/95	117.95	117.19	3268	1178	2634	1435	36.0	54.5	64	72
13/11/95	131.99	140.79	2981	1415	2238	1290	47.5	57.6		
Average:	118.57	113.11	3275	1581	2844	1546	48.4	54.5	72	79
Count:	15	15	15	15	15	15	15	15	14	14
Maximum:	149.33	140.79	3477	1861	3398	1730	60.3	57.6	82	87
Minimum:	100.06	89.97	2667	1178	2238	1290	36.0	49.8	64	62
Standard Deviation:	13.36	12.17	207	142	253	101	5.1	1.8	5	6

PERIOD 3.3.5
SUMMARY DATA 4
HIGH FERRIC TO R1 ANAEROBIC, 10d Rs

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
24/10/95	6.79	6.82	7.39	7.47	7.48	7.54	10	10		
25/10/95	7.02	6.95	7.37	7.40	7.47	7.47	10	10		
26/10/95	6.82	6.88	7.32	7.32	7.53	7.63	10	10		
27/10/95	6.84	6.85	7.19	7.27	7.46	7.54	10	10		
28/10/95	7.07	7.05	7.66	7.35	7.97	7.52	10	10		
29/10/95	6.80	6.85	7.22	7.22	7.48	7.51	10	10		
30/10/95	7.02	7.21	7.35	7.44	7.59	7.67	10	10		
31/10/95	6.92	7.13	7.42	7.34	7.65	7.55	10	10		
01/11/95	7.07	7.20	7.40	7.45	7.74	7.69	10	10	210.5	252.4
02/11/95	7.07	7.14	7.34	7.59	7.62	7.87	10	10		
03/11/95	6.87	6.91	7.41	7.52	7.70	7.78	10	10		
04/11/95	6.88	6.85	7.27	7.27	7.53	7.60	10	10		
05/11/95	6.91	6.92	7.30	7.43	7.52	7.62	10	10		
06/11/95	6.78	6.86	7.18	7.32	7.45	7.50	10	10	218.7	269.3
07/11/95	6.93	7.10	7.36	7.57	7.59	7.74	10	10		
08/11/95	6.77	6.80	7.25	7.34	7.48	7.60	10	10	219.3	249.1
09/11/95	6.87	6.85	7.30	7.44	7.54	7.69	10	10		
10/11/95							10	10		
11/11/95							10	10		
12/11/95	6.87	6.91	7.33	7.36	7.55	7.62	10	10		
13/11/95							10	10	203.1	242.5
Average:	6.91	6.96	7.34	7.39	7.58	7.62	10	10	212.9	253.3
Count:	18	18	18	18	18	18	21	21	4	4
Maximum:	7.07	7.21	7.66	7.59	7.97	7.87	10	10	219.3	269.3
Minimum:	6.77	6.80	7.18	7.22	7.45	7.47	10	10	203.1	242.5
Standard Deviation:	0.10	0.13	0.11	0.10	0.13	0.10	0	0	6.6	9.9

PERIOD 3.3.5
SUMMARY DATA 5
HIGH FERRIC TO R1 ANAEROBIC, 10d Rs

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
24/10/95	1.08	1.15	4.51	3.96	19.30	27.87
25/10/95	1.23	1.30	3.42	2.98	18.45	28.33
26/10/95	2.20	1.56	5.20	4.82	20.77	28.50
27/10/95						
28/10/95						
29/10/95	1.56	1.45	6.18	7.67	10.71	21.65
30/10/95	1.42	1.35	6.93	7.98	9.13	22.36
31/10/95	2.19	1.46	8.00	8.13	12.15	23.31
01/11/95	2.07	2.31	7.05	7.59	22.06	32.51
02/11/95	2.19	1.70	5.15	5.35	15.49	22.41
03/11/95						
04/11/95						
05/11/95	2.31	2.00	6.84	7.73	9.06	17.84
06/11/95	1.94	1.70	9.22	10.40	9.06	14.25
07/11/95	2.07	2.37	5.96	8.54	10.65	22.89
08/11/95	2.31	2.19	4.07	5.63	18.34	29.16
09/11/95	2.37	2.00	3.56	5.69	21.21	29.60
10/11/95						
11/11/95						
12/11/95	2.10	1.23	4.09	5.62	19.96	28.10
13/11/95	1.05	1.11	5.11	6.77	17.67	26.37
Average:	1.87	1.66	5.69	6.59	15.60	25.01
Count:	15	15	15	15	15	15
Maximum:	2.37	2.37	9.22	10.40	22.06	32.51
Minimum:	1.05	1.11	3.42	2.98	9.06	14.25
Standard Deviation:	0.45	0.41	1.63	1.89	4.76	4.74

PERIOD 3.3.5
SUMMARY DATA 6
HIGH FERRIC TO R1 ANAEROBIC, 10d Rs

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAR1	NO3 R1 fAR2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAR1	NO3 R2 fAR2
24/10/95								
25/10/95								
26/10/95	0.04	1.48	5.01	6.65	0.09	1.48	6.76	6.69
27/10/95								
28/10/95								
29/10/95	0.05	0.05	7.11	7.17	0.09	2.05	7.42	7.73
30/10/95	0.10	0.79	6.37	7.54	0.07	1.64	7.61	7.92
31/10/95								
01/11/95								
02/11/95								
03/11/95								
04/11/95								
05/11/95	0.03	0.72	8.29	8.38	0.04	3.71	8.43	8.78
06/11/95								
07/11/95								
08/11/95								
09/11/95								
10/11/95								
11/11/95								
12/11/95	0.03	0.95	4.47	4.27	0.07	3.50	5.59	6.10
13/11/95								
Average:	0.05	0.80	6.25	6.80	0.07	2.48	7.16	7.44
Count:	5	5	5	5	5	5	5	5
Maximum:	0.10	1.48	8.29	8.38	0.09	3.71	8.43	8.78
Minimum:	0.03	0.05	4.47	4.27	0.04	1.48	5.59	6.10
Standard Deviation:	0.03	0.46	1.39	1.39	0.02	0.94	0.95	0.95

PERIOD 3.3.5
SUMMARY DATA 7
HIGH FERRIC TO R1 ANAEROBIC, 10d Rs

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
24/10/95								
25/10/95								
26/10/95	81.53	54.41	36.44	22.80	97.34	65.06	42.10	29.12
27/10/95								
28/10/95								
29/10/95	86.53	53.58			86.53	58.07	36.27	22.63
30/10/95	81.53	50.58	23.79	10.48	97.34	64.40	38.77	24.46
31/10/95								
01/11/95								
02/11/95								
03/11/95								
04/11/95								
05/11/95	87.17	53.90	23.35	9.28	105.56	54.38	35.03	19.67
06/11/95								
07/11/95								
08/11/95								
09/11/95								
10/11/95								
11/11/95								
12/11/95	74.37	39.83	23.35	15.67	91.17	46.06	33.59	25.91
13/11/95								
Average:	82.23	50.46	26.73	14.56	95.59	57.59	37.15	24.36
Count:	5	5	4	4	5	5	5	5
Maximum:	87.17	54.41	36.44	22.80	105.56	65.06	42.10	29.12
Minimum:	74.37	39.83	23.35	9.28	86.53	46.06	33.59	19.67
Standard Deviation:	4.60	5.48	5.61	5.33	6.44	7.01	3.00	3.16

PERIOD 3.3.5
SUMMARY DATA 8
HIGH FERRIC TO R1 ANAEROBIC, 10d Rs

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
24/10/95	0.0	13.3	0.0	18.9	
25/10/95	0.0	13.3	0.0	18.7	
26/10/95	0.0	13.3	0.0	18.8	
27/10/95	0.0	13.3	0.0	18.8	
28/10/95	0.0	13.3	0.0	19.0	
29/10/95	0.0	13.3	0.0	18.5	
30/10/95	0.0	13.3	0.0	18.8	
31/10/95	0.0	13.3	0.0	19.3	
01/11/95	0.0	13.3	0.0	19.0	
02/11/95	0.0	13.3	0.0	19.0	
03/11/95	0.0	13.3	0.0	18.8	
04/11/95	0.0	13.3	0.0	19.1	
05/11/95	0.0	13.3	0.0	19.1	
06/11/95	0.0	13.3	0.0	19.2	
07/11/95	0.0	13.3	0.0	19.6	
08/11/95	0.0	13.3	0.0	19.0	
09/11/95	0.0	13.3	0.0	19.2	
10/11/95	0.0	13.3	0.0	18.8	
11/11/95	0.0	13.3	0.0	18.9	
12/11/95	0.0	13.3	0.0	19.0	
13/11/95	0.0	13.3	0.0	19.0	
Average:				19.0	0.0
Count:	21	21	21	21	0
Maximum:	0.0	13.3	0.0	19.6	
Minimum:	0.0	13.3	0.0	18.5	
Standard Deviation:				0.2	0.0

PERIOD 3.3.6
SUMMARY DATA 1
HIGH FERRIC TO R1 AEROBIC, 10d Rs

	DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
	14/11/95	150	35.8	39.4	12.00	12.60	426	19	20	31.4	3.13	2.00
	15/11/95	150	37.9	35.8	12.40	13.50	368	17	20			
	16/11/95	150	35.0	36.2	12.00	12.80	310	16	24	28.0	2.00	2.00
	17/11/95	150	36.0	36.0	11.40	13.50						
	18/11/95	150	35.5	35.5	13.40	14.30						
	19/11/95	150	36.2	36.2	13.60	15.50	453	23	25	31.0	5.02	4.13
	20/11/95	150	34.8	34.8	12.70	14.40	223	29	27			
	21/11/95	150	36.2	37.0	20.80	17.50	427	29	24	27.7	2.00	2.00
	22/11/95	150	35.8	36.2	13.50	17.90	423	23	20			
	23/11/95	150	36.7	36.7	11.90	16.40	536	21	20	26.5	2.00	3.08
	24/11/95	150	36.0	36.7	11.90	17.30						
	25/11/95	150	36.0	36.5	10.80	16.00						
	26/11/95	150	36.2	36.7	10.60	15.80	420	26	22	25.6	2.00	2.00
	27/11/95	150	37.2	37.2	10.10	14.70	268	17	18			
	28/11/95	150	37.0	36.2	9.00	13.30	242	14	15	22.9	3.33	3.12
	29/11/95	150	37.2	37.2	9.70	13.50	271	16	19			
	30/11/95	150	36.2	36.2	9.40	12.00	233	19	21	19.4	2.00	2.00
	01/12/95	150	37.0	37.0	9.20	13.60						
	02/12/95	150	37.0	37.7	8.60	13.80						
	03/12/95	150	37.0	37.0	12.20	16.00	354	23	23	27.4	2.00	2.00
Average:		150	36.3	36.6	11.76	14.72	354	21	21	26.7	2.61	2.48
Count:		20	20	20	20	20	14	14	14	9	9	9
Maximum:		150	37.9	39.4	20.80	17.90	536	29	27	31.4	5.02	4.13
Minimum:		150	34.8	34.8	8.60	12.00	223	14	15	19.4	2.00	2.00
Standard Deviation:		0	0.8	0.9	2.57	1.69	94	5	3	3.5	0.99	0.74

PERIOD 3.3.6
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
14/11/95	49.11	15.89	23.43	33.22	25.68	246.07	210.52
15/11/95	44.30	12.36	18.46	31.94	25.84	239.54	213.91
16/11/95	43.98	11.23	18.46	32.75	25.52	255.70	231.78
17/11/95							
18/11/95							
19/11/95	49.59	10.59	15.25	39.00	34.34	239.01	202.22
20/11/95	49.11	9.79	13.32	39.32	35.79	232.39	207.40
21/11/95	47.67	13.64	16.05	34.03	31.62	240.02	220.67
22/11/95	46.86	13.64	19.74	33.22	27.12	252.84	232.07
23/11/95	46.87	17.01	22.15	29.86	24.72	249.27	225.50
24/11/95							
25/11/95							
26/11/95	46.55	19.26	25.52	27.29	21.03	258.91	261.42
27/11/95	44.46	18.30	25.84	26.16	18.62	256.62	226.59
28/11/95	45.58	19.42	26.96	26.16	18.62	241.62	239.23
29/11/95	46.39					259.92	239.54
30/11/95	45.26					254.28	228.90
01/12/95							
02/12/95							
03/12/95	38.52	18.78	26.96	19.74	11.56	229.45	204.10
Average:	46.02	14.99	21.01	31.06	25.04	246.83	224.56
Count:	14	12	12	12	12	14	14
Maximum:	49.59	19.42	26.96	39.32	35.79	259.92	261.42
Minimum:	38.52	9.79	13.32	19.74	11.56	229.45	202.22
Standard Deviation:	2.71	3.41	4.59	5.36	6.65	9.59	15.74

PERIOD 3.3.6
SUMMARY DATA 3
HIGH FERRIC TO R1 AEROBIC, 10d Rs

	DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
	14/11/95	117.49	118.15	3060	1461	2418	1357	47.7	56.1	69	83
	15/11/95	113.66	115.81	3389	1608	2453	1328	47.4	54.1	62	82
	16/11/95	117.29	119.82	3462	1588	2478	1281	45.9	51.7	64	81
	17/11/95										
	18/11/95										
	19/11/95	118.68	117.75	3462	1719	2576	1500	49.7	58.2	64	82
	20/11/95	113.25	118.86	3472	1692	2633	1509	48.7	57.3	63	80
	21/11/95	116.19	118.48	3481	1685	2628	1411	48.4	53.7	60	80
	22/11/95	119.99	128.75	3424	1625	2518	1397	47.5	55.5	64	83
	23/11/95	113.36	119.15	3483	1584	2748	1452	45.5	52.8	63	80
	24/11/95										
	25/11/95										
	26/11/95	120.44	132.84	3145	1463	2332	1185	46.5	50.8	67	87
	27/11/95	119.96	126.46	2997	1401	2272	1268	46.7	55.8	67	88
	28/11/95	108.98	124.92	3093	1395	2300	1201	45.1	52.2	65	87
	29/11/95	120.65	128.38	2807	1303	2213	1186	46.4	53.6	71	86
	30/11/95	115.74	120.72	2843	1294	2247	1185	45.5	52.7	65	85
	01/12/95										
	02/12/95										
	03/12/95	109.98	122.84	2758	1322	2012	1211	47.9	60.2	73	94
Average:		116.12	122.35	3205	1510	2416	1319	47.1	54.6	66	84
Count:		14	14	14	14	14	14	14	14	14	14
Maximum:		120.65	132.84	3483	1719	2748	1509	49.7	60.2	73	94
Minimum:		108.98	115.81	2758	1294	2012	1185	45.1	50.8	60	80
Standard Deviation:		3.68	4.92	268	146	192	115	1.3	2.6	3	4

PERIOD 3.3.6
SUMMARY DATA 4
HIGH FERRIC TO R1 AEROBIC, 10d Rs

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
14/11/95	7.02	6.92	7.29	7.40	7.54	7.59	10	10		
15/11/95	7.03	6.81	7.30	7.50	7.51	7.64	10	10	199.9	241.5
16/11/95	6.93	6.90	7.26	7.46	7.51	7.64	10	10		
17/11/95							10	10		
18/11/95							10	10		
19/11/95	7.02	6.97	7.38	7.63	7.67	7.86	10	10		
20/11/95	6.80	6.95	7.29	7.47	7.61	7.74	10	10	247.2	273.1
21/11/95	6.96	6.88	7.34	7.42	7.55	7.64	10	10		
22/11/95	7.05	7.00	7.33	7.42	7.60	7.64	10	10		
23/11/95	7.04	6.98	7.29	7.46	7.57	7.64	10	10	181.5	258.2
24/11/95							10	10		
25/11/95							10	10		
26/11/95	6.84	7.05	7.26	7.43	7.51	7.61	10	10		
27/11/95	7.16	6.99	7.30	7.37	7.53	7.60	10	10	213.8	247.2
28/11/95							10	10		
29/11/95	7.30	7.21	7.28	7.33	7.42	7.48	10	10	219.2	228.8
30/11/95	7.05	6.92	7.20	7.23	7.39	7.44	10	10		
01/12/95							10	10		
02/12/95							10	10		
03/12/95	7.14	6.96	7.43	7.31	7.64	7.54	10	10		
Average:	7.03	6.96	7.30	7.42	7.54	7.62	10	10	212.3	249.8
Count:	13	13	13	13	13	13	20	20	5	5
Maximum:	7.30	7.21	7.43	7.63	7.67	7.86	10	10	247.2	273.1
Minimum:	6.80	6.81	7.20	7.23	7.39	7.44	10	10	181.5	228.8
Standard Deviation:	0.13	0.09	0.06	0.09	0.08	0.10	0	0	21.8	15.0

PERIOD 3.3.6
SUMMARY DATA 5
HIGH FERRIC TO R1 AEROBIC, 10d Rs

	DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
	14/11/95	1.05	1.17	5.37	6.39	16.02	23.86
	15/11/95	1.40	1.05	4.98	7.28	11.59	23.75
	16/11/95	0.93	1.17	5.94	8.43	11.34	18.49
	17/11/95						
	18/11/95						
	19/11/95	1.05	1.40	3.96	5.43	9.61	16.02
	20/11/95	1.11	1.23	4.09	5.78	9.72	13.43
	21/11/95	1.40	1.23	3.58	5.94	13.70	16.45
	22/11/95	0.29	0.18	3.68	5.26	14.03	18.33
	23/11/95	0.18	0.30	5.00	6.05	16.90	21.30
	24/11/95						
	25/11/95						
	26/11/95	0.18	0.12	4.73	5.26	17.84	23.28
	27/11/95	0.18	0.12	4.73	5.78	16.84	24.28
	28/11/95	0.18	0.21	4.99	6.04	17.84	25.27
	29/11/95	0.30	0.24	5.26	6.57	23.78	24.77
	30/11/95	0.18	0.18	5.52	7.36	28.94	28.61
	01/12/95						
	02/12/95						
	03/12/95	0.51	0.34	3.89	4.62	19.33	26.73
	========	====	====	====	====	=====	=====
Average:		0.64	0.64	4.69	6.16	16.25	21.76
Count:		14	14	14	14	14	14
Maximum:		1.40	1.40	5.94	8.43	28.94	28.61
Minimum:		0.18	0.12	3.58	4.62	9.61	13.43
Standard Deviation:		0.47	0.50	0.71	0.96	5.19	4.34

PERIOD 3.3.6
SUMMARY DATA 6
HIGH FERRIC TO R1 AEROBIC, 10d Rs

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
14/11/95								
15/11/95	0.08	1.51	6.26	5.37	0.08	5.68	7.79	7.47
16/11/95								
17/11/95								
18/11/95								
19/11/95	0.03	0.15	4.41	4.22	0.06	3.65	5.37	5.11
20/11/95								
21/11/95								
22/11/95	0.13	0.03	4.98	4.47	0.03	3.76	5.30	5.24
23/11/95								
24/11/95								
25/11/95								
26/11/95								
27/11/95	0.05	1.30	6.64	5.62	0.05	4.67	3.83	5.62
28/11/95								
29/11/95	0.05	2.90	5.46	4.92	0.05	5.67	6.28	6.28
30/11/95								
01/12/95								
02/12/95								
03/12/95								
Average:	0.07	1.18	5.55	4.92	0.05	4.69	5.71	5.94
Count:	5	5	5	5	5	5	5	5
Maximum:	0.13	2.90	6.64	5.62	0.08	5.68	7.79	7.47
Minimum:	0.03	0.03	4.41	4.22	0.03	3.65	3.83	5.11
Standard Deviation:	0.03	1.05	0.82	0.53	0.02	0.88	1.30	0.86

PERIOD 3.3.6
SUMMARY DATA 7
HIGH FERRIC TO R1 AEROBIC, 10d Rs

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
14/11/95								
15/11/95	94.69	44.14	23.41	12.36	106.73	37.23	28.57	21.02
16/11/95								
17/11/95								
18/11/95								
19/11/95	95.49	52.96	10.43	23.27	116.36	35.79	23.75	15.09
20/11/95								
21/11/95								
22/11/95	79.44	53.77	24.07	13.64	96.30	36.43	26.80	19.90
23/11/95								
24/11/95								
25/11/95								
26/11/95								
27/11/95	66.61	41.46	27.93	19.74	81.86	36.92	30.82	27.13
28/11/95								
29/11/95	59.39	39.00	26.48	24.72	68.21	36.92	33.55	30.82
30/11/95								
01/12/95								
02/12/95								
03/12/95								
Average:	79.12	46.27	22.46	18.75	93.89	36.66	28.70	22.79
Count:	5	5	5	5	5	5	5	5
Maximum:	95.49	53.77	27.93	24.72	116.36	37.23	33.55	30.82
Minimum:	59.39	39.00	10.43	12.36	68.21	35.79	23.75	15.09
Standard Deviation:	14.53	6.03	6.23	4.98	17.20	0.50	3.35	5.55

PERIOD 3.3.6
SUMMARY DATA 8
HIGH FERRIC TO R1 AEROBIC, 10d Rs

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
14/11/95	0.0	13.3	0.0	18.8	
15/11/95	0.0	13.3	0.0	18.7	
16/11/95	0.0	13.3	0.0	18.9	
17/11/95	0.0	13.3	0.0	19.1	
18/11/95	0.0	13.3	0.0	18.4	
19/11/95	0.0	13.3	0.0	19.1	
20/11/95	0.0	13.3	0.0	19.0	
21/11/95	0.0	13.3	0.0	19.9	
22/11/95	0.0	13.3	0.0	19.6	
23/11/95	0.0	13.3	0.0	20.2	
24/11/95	0.0	13.3	0.0	20.2	
25/11/95	0.0	13.3	0.0	19.7	
26/11/95	0.0	13.3	0.0	20.0	
27/11/95	0.0	13.3	0.0	20.2	
28/11/95	0.0	13.3	0.0	19.3	
29/11/95	0.0	13.3	0.0	19.4	
30/11/95	0.0	13.3	0.0	19.4	
01/12/95	0.0	13.3	0.0	19.6	
02/12/95	0.0	13.3	0.0	19.8	
03/12/95	0.0	13.3	0.0	19.7	
Average:				19.5	0.0
Count:	20	20	20	20	0
Maximum:	0.0	13.3	0.0	20.2	
Minimum:	0.0	13.3	0.0	18.4	
Standard Deviation:				0.5	0.0

PERIOD 3.4.1
SUMMARY DATA 1
HIGH FERROUS-FERRIC TO R1 AEROBIC

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
13/12/95	150	36.0	36.0	8.93	11.27	310	11	9			
14/12/95	150	37.2	35.8	8.74	10.69	295	20	11			
15/12/95	150	37.0	35.8	11.06	14.01						
16/12/95	150	36.5	36.0	11.83	13.74						
17/12/95	150	37.2	36.5	11.92	11.08	317	22	20	22.9	3.12	3.22
18/12/95	150	34.8	36.0		11.95	269	24	12			
19/12/95	150	37.2	35.8	8.41	8.54	262	19	32	14.1	3.49	2.00
20/12/95	150	36.7	33.8	7.56	7.76	181	5	18			
21/12/95	150	37.9	37.2	7.77		206			12.8	2.00	2.00
22/12/95	150	37.2	33.8	7.20	7.54						
23/12/95	150	36.5	38.6	7.97	8.80						
24/12/95	150	35.0	36.7	7.97	8.80						
25/12/95	150	35.8	35.8	7.55							
26/12/95	150	35.5	35.3	6.97	10.31	148			14.2		
27/12/95	150	36.5	36.5	6.58	7.59	202					
28/12/95	150	39.1	39.1	6.65	6.61	237	9	14	15.0	2.00	2.00
29/12/95	150	34.3	35.5	5.41	5.34						
30/12/95	150	35.3	34.8	4.79	4.93						
31/12/95	150	35.3	36.2	4.56	4.16						
01/01/96	150	30.0	35.8	4.05	5.23	156	9	18			
02/01/96	150	34.8	36.2	6.90	7.45	324	6	6	22.2	2.00	2.00
03/01/96	150		35.5		9.02	253	13	26			
04/01/96	150	37.0	37.0	10.76	9.36	268	18	11	20.8	2.00	2.00
05/01/96	150	36.5	35.3	9.63							
06/01/96	150	36.0	36.0	9.15	9.80						
07/01/96	150	38.2	34.8	9.73	8.94	250	16	18	14.7	2.00	2.00
08/01/96	150	37.7	36.2	8.14	8.21	242	20	21			
09/01/96	150	34.3	32.6	6.73	6.76	164	15	26	9.1	2.00	2.00
10/01/96	150	35.5	34.6	6.26	5.94	226	12	5			
11/01/96	150	34.6	36.0	6.01	5.66	197	9	5	8.6	2.00	2.00
12/01/96	150	34.8	36.0	8.35	7.78						
13/01/96	150		35.5	8.71	10.04						
Average:	150	36.0	35.8	7.88	8.53	237	14	16	15.4	2.29	2.14
Count:	32	30	32	30	29	19	16	16	10	9	9
Maximum:	150	39.1	39.1	11.92	14.01	324	24	32	22.9	3.49	3.22
Minimum:	150	30.0	32.6	4.05	4.16	148	5	5	8.6	2.00	2.00
Standard Deviation:	0	1.6	1.2	1.97	2.46	53	6	8	4.8	0.55	0.38

PERIOD 3.4.1
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
13/12/95	44.20	22.26	28.26	21.94	15.94	222.24	240.76
14/12/95	44.52	23.37	26.55	21.15	17.97	228.55	335.13
15/12/95							
16/12/95							
17/12/95	46.74	12.88	22.89	33.86	23.85	351.96	316.07
18/12/95	43.56	11.61	22.26	31.95	21.30	520.80	663.87
19/12/95	48.32	12.37	20.12	35.95	28.20	51.33	129.76
20/12/95	45.36	15.34	28.20	30.02	17.16	78.67	93.79
21/12/95	47.99	21.28	32.82	26.71	15.17	256.89	227.16
22/12/95							
23/12/95							
24/12/95							
25/12/95							
26/12/95	45.69	18.47	27.05	27.22	18.64	259.01	327.36
27/12/95	46.48	19.46	22.03	27.02	24.45	339.93	179.11
28/12/95	40.85	17.21	21.07	23.64	19.78	202.01	217.00
29/12/95							
30/12/95							
31/12/95							
01/01/96	39.08	18.49	29.75	20.59	9.33	78.12	128.92
02/01/96	43.59	21.79	30.51	21.80	13.08	156.68	96.85
03/01/96	42.65	21.79	28.33	20.86	14.32	135.81	117.82
04/01/96	43.59	20.08	27.24	23.51	16.35	204.27	207.85
05/01/96							
06/01/96							
07/01/96	43.28	17.12	23.51	26.16	19.77	174.22	156.79
08/01/96	39.23	13.70	21.48	25.53	17.75	278.29	298.56
09/01/96	39.85	15.26	22.42	24.59	17.43	442.86	325.03
10/01/96	42.59	21.37	28.12	21.22	14.47	339.25	258.80
11/01/96	40.34	18.16	27.65	22.18	12.69	519.91	407.23
12/01/96							
13/01/96							
Average:	43.57	18.00	25.80	25.57	17.77	254.78	248.83
Count:	19	19	19	19	19	19	19
Maximum:	48.32	23.37	32.82	35.95	28.20	520.80	663.87
Minimum:	39.08	11.61	20.12	20.59	9.33	51.33	93.79
Standard Deviation:	2.74	3.54	3.58	4.45	4.39	134.13	132.44

ERIOD 3.4.1
UMMARY DATA 3
IGH FERROUS-FERRIC TO R1 AEROBIC

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
13/12/95	101.92	123.11	3042	1395	2118	1083	45.9	51.1	56	82
14/12/95	105.84	182.32	3440	1593	1465	797	46.3	54.4	41	119
15/12/95										
16/12/95										
17/12/95	161.38	162.65	2000	917	1300	669	45.9	51.5	70	138
18/12/95	156.24	223.47	2890	867	2234	752	30.0	33.7	45	85
19/12/95	22.72	70.20	4937	2185	3242	1754	44.3	54.1	25	60
20/12/95	27.73	55.85	4937	1740	3632	2163	35.2	59.6	26	53
21/12/95	118.04	136.30	3591	1650	2045	1227	45.9	60.0	33	88
22/12/95										
23/12/95										
24/12/95										
25/12/95										
26/12/95	104.52	183.51	3219	1299	2121	1189	40.4	56.1	31	80
27/12/95	133.93	103.34	3122	1230	2163	1248	39.4	57.7	31	79
28/12/95	76.31	116.24	3772	1425	2255	1208	37.8	53.6	24	71
29/12/95										
30/12/95										
31/12/95										
01/01/96	27.10	65.32	4154	1441	2388	1210	34.7	50.7	18	59
02/01/96	57.73	50.88	3775	1391	2509	1318	36.8	52.5	21	57
03/01/96	53.93	63.05	4561	1811	2321	1242	39.7	53.5	24	56
04/01/96	77.52	106.41	3655	1387	2092	1071	37.9	51.2	22	72
05/01/96										
06/01/96										
07/01/96	64.92	78.22	3333	1242	2229	1112	37.3	49.9	45	39
08/01/96	113.21	162.90	3149	1281	1787	975	40.7	54.6	25	78
09/01/96	162.05	163.19	2536	928	1450	728	36.6	50.2	32	94
10/01/96	117.68	127.81	2854	990	1622	801	34.7	49.4	28	80
11/01/96	184.86	189.57	3060	1088	2204	1026	35.6	46.6	25	54
12/01/96										
13/01/96										
.verage:	98.30	124.44	3475	1361	2167	1135	39.2	52.1	33	76
'ount:	19	19	19	19	19	19	19	19	19	19
.aximum:	184.86	223.47	4937	2185	3632	2163	46.3	60.0	70	138
Minimum:	22.72	50.88	2000	867	1300	669	30.0	33.7	18	39
Standard Deviation:	47.39	50.67	747	329	549	349	4.5	5.5	13	23

APPENDIX 5

PERIOD 3.4.1 .
SUMMARY DATA 4
HIGH FERROUS-FERRIC TO R1 AEROBIC

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk R1	H2CO3* Alk R2
13/12/95	7.15	7.00	7.37	7.41	7.57	7.62	10	10		
14/12/95	7.15	7.14	7.53	7.46	7.72	7.63	10	10	257.2	271.4
15/12/95							10	10		
16/12/95							10	10		
17/12/95	7.05	6.93	7.38	7.38	7.60	7.76	10	10		
18/12/95	7.24	7.00	7.38	7.43	7.62	7.78	10	10		
19/12/95	7.25	7.08	7.42	7.41	7.61	7.66	10	10	251.2	305.2
20/12/95	7.27	7.06	7.39	7.34	7.55	7.66	10	10	236.6	288.0
21/12/95	7.20	7.02	7.35	7.45	7.55	7.72	10	10	269.8	284.2
22/12/95							10	10		
23/12/95							10	10		
24/12/95							10	10		
25/12/95							10	10		
26/12/95	7.24	7.09	7.34	7.46	7.56	7.68	10	10		
27/12/95	7.19	7.07	7.27	7.34	7.45	7.65	10	10	290.1	232.4
28/12/95	7.30	7.21	7.35	7.37	7.52	7.67	10	10		
29/12/95							10	10		
30/12/95							10	10		
31/12/95							10	10		
01/01/96	7.05	7.02	7.25	7.31	7.42	7.57	10	10	256.6	262.9
02/01/96	7.14	6.98	7.34	7.24	7.51	7.55	10	10		
03/01/96	7.16	6.95	7.37	7.29	7.54	7.60	10	10	230.3	255.5
04/01/96	7.10	6.97	7.28	7.25	7.50	7.56	10	10		
05/01/96							10	10		
06/01/96							10	10		
07/01/96	7.04	6.93	7.30	7.23	7.57	7.57	10	10	268.0	314.8
08/01/96	7.16	6.96	7.28	7.29	7.48	7.62	10	10		
09/01/96	7.18	6.98	7.65	7.20	7.99	7.52	10	10		
10/01/96	7.12	6.97	7.21	7.22	7.40	7.56	10	10		
11/01/96	6.93	6.93	7.11	7.15	7.33	7.46	10	10	263.6	284.5
12/01/96							10	10		
13/01/96							10	10		
Average:	7.15	7.02	7.35	7.33	7.55	7.62	10	10	258.2	277.7
Count:	19	19	19	19	19	19	32	32	9	9
Maximum:	7.30	7.21	7.65	7.46	7.99	7.78	10	10	290.1	314.8
Minimum:	6.93	6.93	7.11	7.15	7.33	7.46	10	10	230.3	232.4
Standard Deviation:	0.09	0.07	0.11	0.09	0.13	0.08	0	0	16.9	23.9

PERIOD 3.4.1
SUMMARY DATA 5
HIGH FERROUS-FERRIC TO R1 AEROBIC

DATE	NH3 fR1	NH3 fR2	NO3 fR1	NO3 fR2	SRP fR1	SRP fR2
13/12/95	0.00	0.00	1.95	2.43	19.98	20.91
14/12/95	0.00	0.00	1.70	2.19	14.87	23.70
15/12/95						
16/12/95						
17/12/95	0.00	0.00	2.68	3.41	16.73	9.29
18/12/95	0.17	0.00	4.38	2.92	9.29	18.59
19/12/95	0.77	0.86	2.92	1.94	9.29	16.73
20/12/95	5.30	1.40	2.78	1.52	16.57	26.62
21/12/95	1.40	1.40	2.28	1.77	16.68	32.59
22/12/95						
23/12/95						
24/12/95						
25/12/95						
26/12/95	1.40	0.19	3.79	3.54	17.56	19.22
27/12/95	1.40	1.40	4.05	3.03	18.28	22.23
28/12/95	2.40	1.40	4.05	2.79	16.57	21.32
29/12/95						
30/12/95						
31/12/95						
01/01/96	3.70	3.70	2.20	1.93	18.23	30.27
02/01/96	3.08	2.60	3.86	3.56	19.83	27.38
03/01/96	3.08	3.08	4.75	3.86	20.30	25.49
04/01/96	3.08	2.86	4.16	3.86	18.41	24.08
05/01/96						
06/01/96						
07/01/96	1.00	0.47	3.11	1.75	16.93	24.22
08/01/96	0.47	0.47	3.24	2.06	13.59	21.01
09/01/96	0.47	0.47	3.37	3.27	14.33	22.24
10/01/96	0.47	0.47	4.08	3.15	19.55	27.19
11/01/96	0.47	0.47	3.71	3.90	17.89	26.29
12/01/96						
13/01/96						
========	====	====	====	====	=====	=====
Average:	1.51	1.12	3.32	2.78	16.57	23.12
Count:	19	19	19	19	19	19
Maximum:	5.30	3.70	4.75	3.90	20.30	32.59
Minimum:	0.00	0.00	1.70	1.52	9.29	9.29
Standard Deviation:	1.47	1.13	0.86	0.79	3.08	5.07

PERIOD 3.4.1
SUMMARY DATA 6
HIGH FERROUS-FERRIC TO R1 AEROBIC

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
13/12/95	0.15	0.66	2.81	2.30	0.13	2.32	2.81	3.06
14/12/95								
15/12/95								
16/12/95								
17/12/95	0.06	1.94	4.09	3.57	0.06	1.15	4.35	3.32
18/12/95								
19/12/95								
20/12/95								
21/12/95	0.05	1.55	2.70	2.98	0.06	0.82	1.88	1.88
22/12/95								
23/12/95								
24/12/95								
25/12/95								
26/12/95	0.05	2.70	4.06	4.08	0.08	1.29	2.35	2.82
27/12/95								
28/12/95	0.14	2.49	3.92	3.76	0.06	1.25	2.66	2.82
29/12/95								
30/12/95								
31/12/95								
01/01/96	0.17	1.73	2.10	2.00	0.09	0.20	1.73	1.29
02/01/96								
03/01/96								
04/01/96	0.05	2.79	4.49	5.24	0.06	2.59	4.36	4.80
05/01/96								
06/01/96								
07/01/96	0.06	1.47	2.88	2.30	0.07	0.89	1.40	1.73
08/01/96								
09/01/96	0.06	2.16	3.46	3.17	0.04	1.67	2.02	2.31
10/01/96								
11/01/96	0.05	2.19	3.65	3.49	0.05	1.67	2.62	2.74
12/01/96								
13/01/96								
Average:	0.08	1.97	3.42	3.29	0.07	1.39	2.62	2.68
Count:	10	10	10	10	10	10	10	10
Maximum:	0.17	2.79	4.49	5.24	0.13	2.59	4.36	4.80
Minimum:	0.05	0.66	2.10	2.00	0.04	0.20	1.40	1.29
Standard Deviation:	0.05	0.61	0.72	0.92	0.02	0.67	0.97	0.93

PERIOD 3.4.1
SUMMARY DATA 7
HIGH FERROUS-FERRIC TO R1 AEROBIC

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
13/12/95	83.47	44.99	31.16	23.21	94.60	38.63	32.59	27.98
14/12/95								
15/12/95								
16/12/95								
17/12/95	90.62	42.93	24.01	15.74	109.70	58.35	37.52	26.39
18/12/95								
19/12/95	69.27	33.65	20.95	14.02	83.29	49.15	35.46	25.73
20/12/95								
21/12/95	76.69	42.22	28.70	22.27	92.36	55.91	44.04	35.46
22/12/95								
23/12/95								
24/12/95								
25/12/95								
26/12/95	60.20	31.34	22.93	16.99	69.27	36.12	25.23	16.33
27/12/95								
28/12/95	64.33	31.52	23.16	18.17	71.56	39.72	27.82	27.66
29/12/95								
30/12/95								
31/12/95								
01/01/96	53.87	24.44	17.85	16.89	71.56	60.63	33.77	31.04
02/01/96								
03/01/96								
04/01/96	74.72	36.43	26.46	19.46	84.06	48.57	37.21	29.42
05/01/96								
06/01/96								
07/01/96	77.06	36.27	23.66	15.72	86.40	43.43	31.76	23.97
08/01/96								
09/01/96	56.04	28.18	21.48	16.35	64.60	35.65	30.51	24.91
10/01/96								
11/01/96	61.07	31.18	24.75	19.28	39.10	37.93	33.10	26.19
12/01/96								
13/01/96								
Average:	69.76	34.83	24.10	18.01	78.77	45.83	33.55	26.83
Count:	11	11	11	11	11	11	11	11
Maximum:	90.62	44.99	31.16	23.21	109.70	60.63	44.04	35.46
Minimum:	53.87	24.44	17.85	14.02	39.10	35.65	25.23	16.33
Standard Deviation:	11.23	6.17	3.51	2.70	17.75	8.80	4.85	4.52

PERIOD 3.4.1
SUMMARY DATA 8
HIGH FERROUS-FERRIC TO R1 AEROBIC

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
13/12/95	0.0	0.0	12.4	19.8	20.3
14/12/95	0.0	0.0	12.4	19.6	19.9
15/12/95	0.0	0.0	12.4	19.8	20.3
16/12/95	0.0	0.0	12.4	20.2	20.2
17/12/95	0.0	0.0	12.4	20.8	20.9
18/12/95	0.0	0.0	12.4		20.2
19/12/95	0.0	0.0	12.4	20.0	20.5
20/12/95	0.0	0.0	12.4	19.4	19.9
21/12/95	0.0	0.0	12.4	19.8	
22/12/95	0.0	0.0	12.4	20.6	20.7
23/12/95	0.0	0.0	12.4	20.6	20.8
24/12/95	0.0	0.0	12.4	20.6	20.8
25/12/95	0.0	0.0	12.4	19.9	
26/12/95	0.0	0.0	12.4	19.8	20.2
27/12/95	0.0	0.0	12.4	20.0	20.5
28/12/95	0.0	0.0	12.4	17.9	20.3
29/12/95	0.0	0.0	12.4	19.7	20.2
30/12/95	0.0	0.0	12.4	19.6	20.1
31/12/95	0.0	0.0	12.4	19.5	20.0
01/01/96	0.0	0.0	12.4	19.0	20.0
02/01/96	0.0	0.0	12.4	20.0	20.6
03/01/96	0.0	0.0	12.4		20.1
04/01/96	0.0	0.0	12.4	20.5	21.1
05/01/96	0.0	0.0	12.4	19.4	
06/01/96	0.0	0.0	12.4	19.5	20.2
07/01/96	0.0	0.0	12.4	19.4	19.9
08/01/96	0.0	0.0	12.4	19.7	20.6
09/01/96	0.0	0.0	12.4	19.5	20.0
10/01/96	0.0	0.0	12.4	19.6	20.1
11/01/96	0.0	0.0	12.4	19.7	20.0
12/01/96	0.0	0.0	12.4	19.6	20.1
13/01/96	0.0	0.0	12.4	19.6	20.1
Average:				19.8	20.3
Count:	32	32	32	30	29
Maximum:	0.0	0.0	12.4	20.8	21.1
Minimum:	0.0	0.0	12.4	17.9	19.9
Standard Deviation:				0.5	0.3

PERIOD 3.4.2
SUMMARY DATA 1
LOW FERROUS-FERRIC TO R1 AEROBIC

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
15/01/96	150	36.0	36.0	7.79	9.79	216	15	17			
16/01/96	150	35.5	41.3	8.40	10.61	263	14	19	18.3	2.00	2.00
17/01/96	150	12.5	36.7		7.32	232		18			
18/01/96	150	38.4		9.05	9.52	356	20	16	20.0	2.00	2.00
19/01/96	150	37.0		9.17	10.64						
20/01/96	150	36.7	37.0	9.30	9.76						
21/01/96	150	36.0	36.0	8.82	9.44	313	18	15	18.9	2.00	2.00
22/01/96	150	36.0	35.8	7.79	12.54	245	13	12			
23/01/96	150	35.8	35.8	7.18	8.75	271	21	13	13.0	2.00	2.00
24/01/96	150	36.0		7.50	8.35	248		10			
25/01/96	150	35.8	35.8	7.04	7.46	232	4	14	12.5	2.00	2.00
26/01/96	150	36.0	35.8	7.14	7.95						
27/01/96	150	36.0	35.8	6.51	7.01						
28/01/96	150	36.7	35.5	6.38	6.95	251	13	13	14.4	2.00	2.00
29/01/96	150	35.8	35.5	6.84	7.51	263	13	12			
30/01/96	150	35.5	35.5	7.11	7.74	208	18	13	12.7	2.00	2.00
31/01/96	150	35.3	36.0	8.21	8.85	303	12	11			
01/02/96	150	36.7	37.0	8.10	10.40	257	15	15	13.4		
02/02/96	150	35.8	35.8	11.30	11.30						
03/02/96	150	35.8	35.3	12.00	11.30						
04/02/96	150	35.5	35.5	11.30	12.00	342	9	8	16.8	2.00	2.00
05/02/96	150	35.0	34.6	10.00	11.60	233	8	18			
06/02/96	150	35.0	35.8	11.30	13.60	264	16	7	22.6	2.00	2.00
07/02/96	150	35.0	34.3	10.90	12.60	413	10	18			
08/02/96	150	35.0	35.0	8.10	13.80	297	18	21		2.00	2.00
09/02/96	150	35.3	35.3	11.10	12.90						
10/02/96	150	35.0	34.1	10.70	12.30						
11/02/96	150	36.7	37.9	13.50	14.70	350	22	20	17.4	2.00	2.00
12/02/96	150	37.0	37.7	12.50	14.70	395	7	21			
13/02/96	150	35.5	37.7	12.10	15.00	349	25	21	24.7	2.00	2.00
14/02/96	150	35.0	35.8	10.50	14.40						
15/02/96	150	36.2	36.2	11.20	13.20	336	21	19	29.4	4.16	4.25
16/02/96	150	36.5	36.5	9.40	9.40						
17/02/96	150	36.2	36.0	7.60	8.50	188	13	11			
Average:	150	35.2	36.1	9.27	10.64	284	15	15	18.0	2.17	2.17
Count:	34	34	31	33	34	24	22	24	13	13	13
Maximum:	150	38.4	41.3	13.50	15.00	413	25	21	29.4	4.16	4.25
Minimum:	150	12.5	34.1	6.38	6.95	188	4	7	12.5	2.00	2.00
Standard Deviation:	0	4.0	1.3	1.95	2.46	59	5	4	5.0	0.58	0.60

PERIOD 3.4.2
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
15/01/96	51.75	17.84	22.34	33.91	29.41	292.48	283.59
16/01/96	45.00	20.73	25.71	24.27	19.29	461.62	293.68
17/01/96	45.16		19.77		25.39	254.10	331.79
18/01/96	46.27	28.20	28.52	18.07	17.75	179.18	257.54
19/01/96							
20/01/96							
21/01/96	42.94	18.54	21.71	24.40	21.23	219.69	323.20
22/01/96	41.99	19.01	28.52	22.98	13.47	409.65	366.05
23/01/96	41.83	19.01	20.28	22.82	21.55	285.00	271.44
24/01/96	40.88	19.81	22.34	21.07	18.54	353.84	297.77
25/01/96	40.38	18.36	19.47	22.02	20.91	240.04	278.49
26/01/96							
27/01/96							
28/01/96	42.62	26.18	24.90	16.44	17.72	422.99	387.84
29/01/96	41.02	26.98	24.58	14.04	16.44	436.42	371.44
30/01/96	42.62	26.66	23.62	15.96	19.00	561.89	290.72
31/01/96	39.91	27.77	29.05	12.14	10.86	316.73	322.60
01/02/96	40.83	21.80	21.80	19.03	19.03	336.38	296.34
02/02/96							
03/02/96							
04/02/96	44.09	22.29	27.00	21.80	17.09	292.48	404.23
05/02/96	43.27	20.99	27.00	22.28	16.27	464.35	278.29
06/02/96	45.88	24.08	31.40	21.80	14.48	487.23	238.07
07/02/96	44.57	24.73	33.67	19.84	10.90	461.95	351.84
08/02/96	45.66	25.38	34.00	20.28	11.66	209.97	235.76
09/02/96							
10/02/96							
11/02/96	48.37	29.69	39.27	18.68	9.10	226.42	261.44
12/02/96	48.69	28.57	34.96	20.12	13.73	329.52	271.24
13/02/96	45.82	22.35	28.10	23.47	17.72	357.77	223.97
14/02/96							
15/02/96	48.81	24.32	32.76	24.49	16.05	304.68	232.98
16/02/96							
17/02/96	42.86	24.16	32.43	18.70	10.43	309.68	264.42
Average:	44.22	23.37	27.22	20.81	17.00	342.25	297.28
Count:	24	23	24	23	24	24	24
Maximum:	51.75	29.69	39.27	33.91	29.41	561.89	404.23
Minimum:	39.91	17.84	19.47	12.14	9.10	179.18	223.97
Standard Deviation:	2.99	3.59	5.30	4.26	4.73	99.03	49.33

'ERIOD 3.4.2
;UMMARY DATA 3
.OW FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
15/01/96	109.50	144.39	2583	967	1636	833	37.4	50.9	31	88
16/01/96	164.62	138.97	2333	832	1642	777	35.7	47.3	43	73
17/01/96	161.21	175.99	2183	1385	1808	959	63.4	53.0	32	75
18/01/96	106.70	132.85	2272	1353	1956	1009	59.6	51.6	31	72
19/01/96										
20/01/96										
21/01/96	124.45	161.52	2279	1291	1913	956	56.6	50.0	39	75
22/01/96	168.46	186.57	1994	820	1809	922	41.1	51.0	45	83
23/01/96	134.17	138.95	2173	1023	1893	969	47.1	51.2	46	74
24/01/96	167.33	155.10	2140	1012	1941	1011	47.3	52.1	45	67
25/01/96	102.37	134.32	2760	1177	1949	940	42.6	48.2	29	67
26/01/96										
27/01/96										
28/01/96	181.84	176.33	1940	834	1720	782	43.0	45.5	52	70
29/01/96	202.84	165.39	1747	812	1882	838	46.5	44.5	57	71
30/01/96	237.91	144.95	1939	821	1751	873	42.3	49.9	50	64
31/01/96	151.29	154.41	1857	887	1592	762	47.8	47.9	54	75
01/02/96	158.18	144.40	1882	885	1611	785	47.0	48.7	53	73
02/02/96										
03/02/96										
04/02/96	139.08	194.00	2164	1029	1719	825	47.6	48.0	46	76
05/02/96	233.88	152.78	2045	1030	1725	947	50.4	54.9	53	75
06/02/96	241.43	124.81	2008	995	1877	984	49.6	52.4	56	69
07/02/96	228.29	182.06	1981	979	1662	860	49.4	51.7	53	81
08/02/96	105.13	130.95	2217	1110	1597	887	50.1	55.5	50	97
09/02/96										
10/02/96										
11/02/96	117.22	150.00	1893	980	1607	922	51.8	57.4	58	106
12/02/96	169.74	156.55	2116	1090	1601	924	51.5	57.7	54	112
13/02/96	186.38	125.19	1576	821	1696	948	52.1	55.9	54	106
14/02/96										
15/02/96	158.72	130.61	1814	945	1609	902	52.1	56.1	61	116
16/02/96										
17/02/96	157.63	146.17	1774	903	1449	801	50.9	55.3	62	131
.verage:	162.85	151.97	2070	999	1735	892	48.5	51.5	48	83
'ount:	24	24	24	24	24	24	24	24	24	24
:aximum:	241.43	194.00	2760	1385	1956	1011	63.4	57.7	62	131
:inimum:	102.37	124.81	1576	812	1449	762	35.7	44.5	29	64
'tandard Deviation:	41.78	19.28	260	163	138	75	6.2	3.6	9	18

PERIOD 3.4.2
SUMMARY DATA 4
LOW FERROUS-FERRIC TO R1 AEROBIC

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
15/01/96	7.27	7.26	7.42	7.40	7.63	7.69	10	10	315.8	285.1
16/01/96	7.33	7.29	7.44	7.46	7.62	7.79	10	10		
17/01/96	7.18	7.11	7.40	7.34	7.52	7.61	10	10		314.3
18/01/96	7.20	7.14	7.49	7.48	7.68	7.78	10	10		
19/01/96							10	10		
20/01/96							10	10		
21/01/96	7.13	7.16	7.49	7.34	7.71	7.72	10	10	286.9	307.6
22/01/96	7.16	7.09	7.45	7.45	7.71	7.82	10	10		
23/01/96	7.12	7.13	7.38	7.35	7.63	7.59	10	10		
24/01/96	6.99	7.15	7.36	7.42	7.57	7.74	10	10	271.3	294.4
25/01/96	7.03	7.02	7.39	7.37	7.62	7.67	10	10		
26/01/96							10	10		
27/01/96							10	10		
28/01/96	7.03	6.85	7.30	7.26	7.57	7.60	10	10	274.7	293.4
29/01/96	7.05	7.14	7.28	7.33	7.50	7.54	10	10		
30/01/96	6.91	7.02	7.36	7.28	7.59	7.58	10	10		
31/01/96	6.86	6.92	7.27	7.25	7.55	7.60	10	10	272.8	286.8
01/02/96	7.00	7.09	7.30	7.30	7.51	7.65	10	10		
02/02/96							10	10		
03/02/96							10	10		
04/02/96	6.91	7.08	7.25	7.27	7.51	7.60	10	10	272.1	281.4
05/02/96	6.90	7.01	7.36	7.38	7.54	7.58	10	10		
06/02/96	7.03	7.03	7.30	7.25		7.48	10	10		
07/02/96	7.16	7.20	7.34	7.30	7.54	7.50	10	10	245.0	288.4
08/02/96	7.37	7.30	7.51	7.37	7.71	7.52	10	10		
09/02/96							10	10		
10/02/96							10	10		
11/02/96	7.09	7.02	7.36	7.30	7.61	7.57	10	10	272.2	247.8
12/02/96	7.02	6.95	7.13	7.29	7.20	7.69	10	10		
13/02/96	7.09	7.12	7.41	7.39	7.54	7.61	10	10	262.3	274.2
14/02/96	7.19	7.01	7.65	7.25	7.80	7.53	10	10		
15/02/96	7.18	7.09	7.42	7.73	7.62	8.09	10	10		
16/02/96							10	10		
17/02/96							10	10	271.2	280.9
Average:	7.09	7.09	7.38	7.36	7.59	7.65	10	10	274.4	286.8
Count:	24	24	24	24	23	24	34	34	10	11
Maximum:	7.37	7.30	7.65	7.73	7.80	8.09	10	10	315.8	314.3
Minimum:	6.86	6.85	7.13	7.25	7.20	7.48	10	10	245.0	247.8
Standard Deviation:	0.13	0.11	0.10	0.10	0.11	0.13	0	0	17.1	16.6

PERIOD 3.4.2
SUMMARY DATA 5
LOW FERROUS-FERRIC TO R1 AEROBIC

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
15/01/96	2.45	16.17	4.10	2.40	15.36	22.42
16/01/96	1.96	1.96	3.60	3.10	16.29	21.88
17/01/96		1.71		3.30		19.33
18/01/96	1.47	1.22	4.53	3.80	26.53	26.07
19/01/96						
20/01/96						
21/01/96	1.47	1.47	4.06	3.10	18.16	21.43
22/01/96	0.50	0.30	1.90	1.00	9.27	13.28
23/01/96	0.40	0.30	1.50	1.10	19.44	20.10
24/01/96	0.30	0.30	1.60	1.30	20.88	21.43
25/01/96	0.40	0.30	1.60	1.30	19.00	19.22
26/01/96						
27/01/96						
28/01/96	0.30	0.30	2.00	1.90	26.07	24.63
29/01/96	0.78	0.36	5.03	4.15	28.95	25.39
30/01/96	0.30	0.27	4.87	4.25	28.00	22.90
31/01/96	0.27	0.30	3.81	3.44	29.30	28.48
01/02/96	0.30	0.48	2.56	2.22	22.78	21.24
02/02/96						
03/02/96						
04/02/96	0.48	0.48	5.37	4.87	22.54	26.10
05/02/96	0.50	0.50	5.50	5.00	18.54	23.58
06/02/96	0.50	0.50	5.50	6.00	23.92	31.26
07/02/96	0.50	0.50	8.00	7.50	24.26	30.53
08/02/96	0.50	0.50	8.00	7.50	24.26	30.80
09/02/96						
10/02/96						
11/02/96	0.50	0.50	8.00	6.00	29.38	38.11
12/02/96	1.36	0.54	8.00	6.30	27.50	33.01
13/02/96	0.68	0.68	5.70	6.05	22.98	29.05
14/02/96						
15/02/96	0.81	0.68	8.10	6.30	23.86	32.78
16/02/96						
17/02/96	0.54	0.54	3.75	3.25	24.63	31.70
Average:	0.75	1.29	4.66	3.96	22.69	25.61
Count:	23	24	23	24	23	24
Maximum:	2.45	16.17	8.10	7.50	29.38	38.11
Minimum:	0.27	0.27	1.50	1.00	9.27	13.28
Standard Deviation:	0.57	3.14	2.19	1.98	4.92	5.61

PERIOD 3.4.2
SUMMARY DATA 6
LOW FERROUS-FERRIC TO R1 AEROBIC

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
15/01/96								
16/01/96	0.00	2.53	4.30	4.61	0.00	1.78	3.43	3.51
17/01/96								
18/01/96	0.06	2.12	3.78	3.85	0.05	2.01	4.13	3.92
19/01/96								
20/01/96								
21/01/96	0.05	2.17	4.04	4.16	0.03	1.72	3.37	3.43
22/01/96								
23/01/96	0.00	1.41	2.71	2.34	0.00	1.22	2.84	2.32
24/01/96								
25/01/96	0.00	1.70	3.00	3.10	0.00	1.20	2.70	2.50
26/01/96								
27/01/96								
28/01/96	0.00	2.40	4.00	4.20	0.00	2.00	3.50	3.50
29/01/96								
30/01/96	0.03	2.69	4.24	5.37	0.03	2.65	3.97	3.95
31/01/96								
01/02/96	0.30	0.93	2.48	2.49	0.03	0.81	2.12	2.06
02/02/96								
03/02/96								
04/02/96	0.05	2.49	4.88	5.34	0.03	2.47	4.15	4.80
05/02/96								
06/02/96	0.08	4.53	7.73	7.98	0.04	4.08	5.64	7.19
07/02/96								
08/02/96								
09/02/96								
10/02/96								
11/02/96	0.11	4.03	8.58	6.09	0.67	3.89	7.65	6.40
12/02/96								
13/02/96	0.09	3.33	6.97	6.81	0.10	3.24	5.68	6.56
14/02/96								
15/02/96	0.07	4.46	8.48	8.12	0.08	4.12	7.39	7.27
16/02/96								
17/02/96								
Average:	0.06	2.68	5.01	4.96	0.08	2.40	4.35	4.42
Count:	13	13	13	13	13	13	13	13
Maximum:	0.30	4.53	8.58	8.12	0.67	4.12	7.65	7.27
Minimum:	0.00	0.93	2.48	2.34	0.00	0.81	2.12	2.06
Standard Deviation:	0.08	1.08	2.08	1.82	0.17	1.08	1.67	1.78

PERIOD 3.4.2
SUMMARY DATA 7
LOW FERROUS-FERRIC TO R1 AEROBIC

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAB1	TP R1 fAB2	TP R2 fAN	TP R2 fAX	TP R2 fAB1	TP R2 fAB2
15/01/96								
16/01/96	80.35	39.85	30.05	22.66	92.40	47.09	35.19	26.52
17/01/96								
18/01/96	84.77	47.22	35.18	27.09	101.41	46.27	36.28	27.57
19/01/96								
20/01/96								
21/01/96	68.13	35.81	25.83	17.27	79.22	40.72	28.36	23.13
22/01/96								
23/01/96	73.68	36.28	24.72	18.22	83.19	37.08	25.51	18.22
24/01/96								
25/01/96	70.23	34.80	25.22	18.04	68.64	37.99	26.50	18.68
26/01/96								
27/01/96								
28/01/96	79.01	44.69	34.64	27.61	83.00	45.97	33.52	26.18
29/01/96								
30/01/96	70.23	36.87	30.65	25.54	72.63	35.60	28.25	23.62
31/01/96								
01/02/96	83.78	40.67	27.98	19.85	84.59	39.69	27.82	18.87
02/02/96								
03/02/96								
04/02/96	96.79	48.48	31.07	21.47	101.68	53.85	36.93	27.00
05/02/96								
06/02/96	89.47	48.48	34.00	25.38	95.17	53.03	41.65	32.21
07/02/96								
08/02/96								
09/02/96								
10/02/96								
11/02/96	105.36	51.72	36.24	27.30	116.53	56.67	45.34	35.92
12/02/96								
13/02/96	86.20	45.82	31.93	22.67	83.81	48.37	36.88	27.78
14/02/96								
15/02/96	81.91	41.04	29.29	21.18	87.70	49.17	39.55	29.95
16/02/96								
17/02/96								
Average:	82.30	42.44	30.52	22.64	88.46	45.50	33.98	25.82
Count:	13	13	13	13	13	13	13	13
Maximum:	105.36	51.72	36.24	27.61	116.53	56.67	45.34	35.92
Minimum:	68.13	34.80	24.72	17.27	68.64	35.60	25.51	18.22
Standard Deviation:	10.37	5.42	3.70	3.54	12.45	6.55	6.03	5.10

PERIOD 3.4.2
SUMMARY DATA 8
LOW FERROUS-FERRIC TO R1 AEROBIC

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
15/01/96	0.0	0.0	6.2	19.5	20.1
16/01/96	0.0	0.0	6.2	19.9	20.2
17/01/96	0.0	0.0	6.2	20.9	21.1
18/01/96	0.0	0.0	6.2	19.8	20.1
19/01/96	0.0	0.0	6.2	20.1	20.4
20/01/96	0.0	0.0	6.2	20.0	20.3
21/01/96	0.0	0.0	6.2	19.7	20.2
22/01/96	0.0	0.0	6.2	20.0	20.9
23/01/96	0.0	0.0	6.2	19.5	20.0
24/01/96	0.0	0.0	6.2	19.5	19.9
25/01/96	0.0	0.0	6.2	19.5	19.8
26/01/96	0.0	0.0	6.2	20.3	21.1
27/01/96	0.0	0.0	6.2	19.9	20.0
28/01/96	0.0	0.0	6.2	20.0	20.2
29/01/96	0.0	0.0	6.2	20.0	20.4
30/01/96	0.0	0.0	6.2	19.8	20.3
31/01/96	0.0	0.0	6.2	19.8	20.5
01/02/96	0.0	0.0	6.2	19.6	20.0
02/02/96	0.0	0.0	6.2	20.0	20.8
03/02/96	0.0	0.0	6.2	19.5	19.9
04/02/96	0.0	0.0	6.2	19.7	20.1
05/02/96	0.0	0.0	6.2	19.9	20.4
06/02/96	0.0	0.0	6.2	19.6	20.0
07/02/96	0.0	0.0	6.2	19.6	20.1
08/02/96	0.0	0.0	6.2	19.7	20.2
09/02/96	0.0	0.0	6.2	19.6	20.2
10/02/96	0.0	0.0	6.2	19.9	20.4
11/02/96	0.0	0.0	6.2	20.1	20.3
12/02/96	0.0	0.0	6.2	19.6	20.0
13/02/96	0.0	0.0	6.2	19.6	20.2
14/02/96	0.0	0.0	6.2	19.9	19.7
15/02/96	0.0	0.0	6.2	20.0	19.7
16/02/96	0.0	0.0	6.2	20.1	20.5
17/02/96	0.0	0.0	6.2	19.6	20.0
Average:				19.8	20.2
Count:	34	34	34	34	34
Maximum:	0.0	0.0	6.2	20.9	21.1
Minimum:	0.0	0.0	6.2	19.5	19.7
Standard Deviation:				0.3	0.3

PERIOD 3.4.3
SUMMARY DATA 1
LOW FERROUS-FERRIC TO R1 ANAEROBIC

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
18/02/96	150	36.5	35.3	8.00	9.50						
19/02/96	150	36.7	36.0	8.00	9.70	155	11	21			
20/02/96	150	37.4	36.5	7.70	10.50	379	12	12	13.0	3.56	
21/02/96	150	36.7	35.3	8.00	9.60	345	16	14			
22/02/96	150	36.7	36.2	9.60	12.50	345	18	16	10.1	2.00	4.84
23/02/96	150	36.5	35.5	9.30	12.60						
24/02/96	150	36.5	35.5								
25/02/96	150	36.7		10.30	11.40						
26/02/96	150	36.5	33.6	9.90	11.60	338	18	19			
27/02/96	150	36.5	33.6	9.40	10.10	302	17	18	11.4	5.00	2.00
28/02/96	150	37.7	19.4		8.00	372	18				
29/02/96	150	36.7	35.5	8.60	10.20	324	17	21	20.3	2.00	2.00
01/03/96	150	37.4	41.8	11.10	11.40						
02/03/96	150	37.9	35.5	9.90	9.90						
03/03/96	150	37.0	35.0	10.70	9.00	235	18	18	14.9	2.00	2.00
04/03/96	150	37.4	36.7	8.50		255	12	16			
05/03/96	150	37.4	36.0	8.30	9.30	222	18	18	17.2	2.00	2.00
06/03/96	150	37.2	37.2	9.00	10.60	215	15	20			
07/03/96	150	35.8	35.8	9.40	10.30	163	14	20	18.5	2.00	2.00
08/03/96	150	36.0	36.0	10.80	11.60						
09/03/96	150	36.5	36.0	9.80	10.90						
10/03/96	150	37.2	36.7	8.80	11.60	145	20	19	16.5	2.00	2.00
11/03/96	150	36.7	36.7	9.00	11.20	229	19	16			
12/03/96	150	37.0	37.4	9.60		251	17	18	12.6	2.00	2.00
13/03/96	150	36.0	36.0	7.90	11.00	203	17	16			
14/03/96	150	36.7	37.0	8.24	11.40	285	18	15	15.4	2.00	2.00
15/03/96	150	34.8	36.7	8.30	11.30						
16/03/96	150	37.2	36.5	8.30	10.90						
17/03/96	150	35.8	36.7	7.20	10.90	242	15	15	21.7	7.85	7.43
18/03/96	150	35.8	35.8			284	15	14			
Average:	150	36.7	35.6	9.02	10.65	264	16	17	15.6	2.95	2.83
Count:	30	30	29	27	26	20	20	19	11	11	10
Maximum:	150	37.9	41.8	11.10	12.60	379	20	21	21.7	7.85	7.43
Minimum:	150	34.8	19.4	7.20	8.00	145	11	12	10.1	2.00	2.00
Standard Deviation:	0	0.6	3.4	1.00	1.05	69	2	2	3.5	1.80	1.75

PERIOD 3.4.3
SUMMARY DATA 2
ENHANCED CULTURE DEVELOPMENT

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
18/02/96							
19/02/96	42.19	24.99	31.11	17.20	11.08	392.33	281.84
20/02/96	35.74	26.81	32.43	8.93	3.31	300.01	231.79
21/02/96	41.37	26.14	34.25	15.23	7.12	311.58	241.35
22/02/96	44.69	22.42	30.48	22.27	14.21	365.99	278.19
23/02/96							
24/02/96							
25/02/96							
26/02/96	45.01	21.63	31.11	23.38	13.90	351.13	268.67
27/02/96	45.32	21.32	28.90	24.00	16.42	292.05	227.23
28/02/96	43.43	25.27		18.16		339.60	
29/02/96	44.20	23.71	32.03	20.49	12.17	287.90	239.91
01/03/96							
02/03/96							
03/03/96	38.34	18.79	25.41	19.55	12.93	368.93	235.52
04/03/96	46.35	22.02	29.26	24.33	17.09	312.92	610.35
05/03/96	48.20	25.72	34.19	22.48	14.01	359.65	263.11
06/03/96	46.52	30.18	39.27	16.34	7.25	391.22	255.01
07/03/96	46.79	21.64	31.40	25.15	15.39	326.04	205.01
08/03/96							
09/03/96							
10/03/96	42.07	19.51	28.50	22.56	13.57	352.38	200.40
11/03/96	41.15	16.31	27.13	24.84	14.02	281.78	214.92
12/03/96	42.37	19.82	29.11	22.55	13.26	281.55	204.66
13/03/96	40.39	18.14	30.48	22.25	9.91	295.65	223.52
14/03/96	41.79	19.57	29.05	22.22	12.74	344.62	209.92
15/03/96							
16/03/96							
17/03/96	40.86	20.66	33.56	20.20	7.30	361.84	226.64
18/03/96	41.17	23.61	34.95	17.56	6.22	337.96	214.05
Average:	42.90	22.41	31.19	20.48	11.68	332.76	254.32
Count:	20	20	19	20	19	20	19
Maximum:	48.20	30.18	39.27	25.15	17.09	392.33	610.35
Minimum:	35.74	16.31	25.41	8.93	3.31	281.55	200.40
Standard Deviation:	2.98	3.32	3.09	3.89	3.70	34.72	87.36

PERIOD 3.4.3
SUMMARY DATA 3
LOW FERROUS-FERRIC TQ R1 ANAEROBIC

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
18/02/96										
19/02/96	192.16	140.05	1860	911	1465	728	49.0	49.7	59	123
20/02/96	148.58	131.02	1793	888	1364	771	49.5	56.5	61	125
21/02/96	149.51	144.04	1638	786	1436	857	48.0	59.7	67	122
22/02/96	188.77	157.44	1648	850	1334	755	51.6	56.6	67	135
23/02/96										
24/02/96										
25/02/96										
26/02/96	172.13	148.81	1789	877	1475	817	49.0	55.4	53	125
27/02/96	138.80	126.97	1900	903	1480	827	47.5	55.9	53	115
28/02/96	167.64		1884	930			49.4		77	
29/02/96	157.57	133.76	1681	920	1347	751	54.7	55.8		145
01/03/96										
02/03/96										
03/03/96	177.81	131.51	1940	935	1370	765	48.2	55.8	49	150
04/03/96	160.81	341.96	1944	999	1369	767	51.4	56.0	46	146
05/03/96	175.09	147.92	1935	942	1341	755	48.7	56.2	47	164
06/03/96	188.87	146.50	1916	925	1356	779	48.3	57.4	50	155
07/03/96	164.78	123.40	1850	935	1334	803	50.5	60.2	54	146
08/03/96										
09/03/96										
10/03/96	169.45	114.95	1961	943	1379	791	48.1	57.4	51	160
11/03/96	132.78	127.74	1963	925	1420	844	47.1	59.4	51	141
12/03/96	131.75	122.54	2013	942	1418	849	46.8	59.9	47	134
13/03/96	134.95	126.15	2033	928	1398	789	45.6	56.4	47	136
14/03/96	157.30	121.36	1906	870	1344	777	45.6	57.8	50	130
15/03/96										
16/03/96										
17/03/96	170.03	136.06	1745	820	1176	706	47.0	60.0	57	132
18/03/96	156.17	137.49	1701	786	1096	704	46.2	64.2	53	141
Average:	161.75	145.25	1855	901	1363	781	48.6	57.4	55	138
Count:	20	19	20	20	19	19	20	19	19	19
Maximum:	192.16	341.96	2033	999	1480	857	54.7	64.2	77	164
Minimum:	131.75	114.95	1638	786	1096	704	45.6	49.7	46	115
Standard Deviation:	18.00	47.60	117	54	91	43	2.2	2.8	8	13

PERIOD 3.4.3
SUMMARY DATA 5
LOW FERROUS-FERRIC TO R1 ANAEROBIC

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
18/02/96						
19/02/96	0.54	0.81	5.45	4.70	24.52	30.89
20/02/96	0.38	0.51	4.49	3.46	27.06	33.89
21/02/96	0.51	0.51	2.37	1.19	25.68	34.18
22/02/96	0.51	0.51	4.22	2.64	22.57	30.89
23/02/96						
24/02/96						
25/02/96						
26/02/96	0.48	0.36	6.11	5.04	20.17	29.32
27/02/96	0.36	0.36	6.10	5.44	20.41	27.92
28/02/96	0.36		6.10		24.16	
29/02/96	0.36	0.36	5.57	5.30	22.75	32.37
01/03/96						
02/03/96						
03/03/96	0.49	0.36	5.57	4.11	18.30	24.40
04/03/96	0.72	0.48	5.54	4.65	20.56	29.95
05/03/96	0.48	0.60	5.54	4.30	23.96	30.91
06/03/96	0.60	0.36	5.66	4.28	27.79	34.74
07/03/96	0.48	0.48	4.66	3.40	21.08	31.15
08/03/96						
09/03/96						
10/03/96	0.48	0.48	4.66	2.89	18.69	28.51
11/03/96	0.58	0.70	4.49	3.04	13.83	23.27
12/03/96	0.70	0.70	5.08	3.96	18.10	27.41
13/03/96	0.53	0.64	5.02	3.70	17.07	27.67
14/03/96	0.53	0.70	5.68	4.36	19.39	25.60
15/03/96						
16/03/96						
17/03/96	0.70	0.58	4.62	3.70	18.49	28.18
18/03/96	0.64	0.94	4.82	3.30	20.43	30.25
	====	====	====	====	=====	=====
Average:	0.52	0.55	5.09	3.87	21.25	29.55
Count:	20	19	20	19	20	19
Maximum:	0.72	0.94	6.11	5.44	27.79	34.74
Minimum:	0.36	0.36	2.37	1.19	13.83	23.27
Standard Deviation:	0.11	0.16	0.85	1.00	3.45	3.07

PERIOD 3.4.3
SUMMARY DATA 6
LOW FERROUS-FERRIC TO R1 ANAEROBIC

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
18/02/96								
19/02/96								
20/02/96	0.08	1.62	2.91	2.91	0.08	1.30	1.57	1.57
21/02/96								
22/02/96	0.06	2.74	5.41	5.28	0.26	1.60	3.03	3.36
23/02/96								
24/02/96								
25/02/96								
26/02/96	0.07	3.56	6.60	6.46	0.06	3.22	5.01	5.38
27/02/96								
28/02/96								
29/02/96	0.11	2.89	4.91	5.04	0.11	2.01	3.58	3.84
01/03/96								
02/03/96								
03/03/96	0.05	3.21	5.03	5.83	0.07	2.78	4.11	4.24
04/03/96								
05/03/96	0.07	3.42	5.44	5.57	0.13	2.76	3.84	4.24
06/03/96								
07/03/96	0.10	2.87	4.53	4.41	0.09	4.48	2.01	2.51
08/03/96								
09/03/96								
10/03/96	0.05	2.79	4.91	5.03	0.12	1.54	2.64	2.77
11/03/96								
12/03/96	0.05	3.04	5.28	5.22	0.04	2.17	3.43	3.70
13/03/96								
14/03/96	0.04	3.42	6.41	6.08	0.05	2.72	4.09	4.76
15/03/96								
16/03/96								
17/03/96								
18/03/96								
Average:	0.07	2.96	5.14	5.18	0.10	2.46	3.33	3.64
Count:	10	10	10	10	10	10	10	10
Maximum:	0.11	3.56	6.60	6.46	0.26	4.48	5.01	5.38
Minimum:	0.04	1.62	2.91	2.91	0.04	1.30	1.57	1.57
Standard Deviation:	0.02	0.52	0.97	0.94	0.06	0.90	0.99	1.07

PERIOD 3.4.3
SUMMARY DATA 7
LOW FERROUS-FERRIC TO R1 ANAEROBIC

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
18/02/96								
19/02/96								
20/02/96	92.66	49.81	38.55	30.94	98.45	53.45	45.01	37.89
21/02/96								
22/02/96	94.75	46.27	31.90	22.58	90.01	50.06	39.64	30.16
23/02/96								
24/02/96								
25/02/96								
26/02/96	86.85	45.16	30.48	22.90	89.22	52.11	39.64	30.48
27/02/96								
28/02/96								
29/02/96	83.16	43.58	29.26	20.33	83.16	54.98	44.66	34.80
01/03/96								
02/03/96								
03/03/96	63.91	34.19	25.41	19.25	63.14	36.34	30.95	25.41
04/03/96								
05/03/96	80.08	42.35	34.49	29.41	83.93	48.35	41.27	36.03
06/03/96								
07/03/96	63.26	30.64	23.47	17.53	67.07	41.61	35.06	24.24
08/03/96								
09/03/96								
10/03/96	84.60	43.29	28.50	22.25				
11/03/96								
12/03/96	81.55	43.29	28.81	20.88	83.07	47.56	38.56	31.55
13/03/96								
14/03/96	73.79	40.70	27.34	20.20	80.00	46.91	38.37	31.38
15/03/96								
16/03/96								
17/03/96								
18/03/96								
Average:	80.46	41.93	29.82	22.63	82.01	47.93	39.24	31.33
Count:	10	10	10	10	9	9	9	9
Maximum:	94.75	49.81	38.55	30.94	98.45	54.98	45.01	37.89
Minimum:	63.26	30.64	23.47	17.53	63.14	36.34	30.95	24.24
Standard Deviation:	10.17	5.36	4.14	4.09	10.41	5.56	4.14	4.28

ERIOD 3.4.3
-JMMARY DATA 8
)W FERROUS-FERRIC TO R1 ANAEROBIC

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
18/02/96	0.0	0.0	6.2	20.5	21.4
19/02/96	0.0	0.0	6.2	19.7	20.2
20/02/96	0.0	0.0	6.2	21.2	22.7
21/02/96	0.0	0.0	6.2	20.0	20.8
22/02/96	0.0	0.0	6.2	20.4	21.1
23/02/96	0.0	0.0	6.2	19.7	20.3
24/02/96	0.0	0.0	6.2		
25/02/96	0.0	0.0	6.2	19.6	19.9
26/02/96	0.0	0.0	6.2	19.6	20.4
27/02/96	0.0	0.0	6.2	20.1	20.4
28/02/96	0.0	0.0	6.2		20.4
29/02/96	0.0	0.0	6.2	20.1	20.7
01/03/96	0.0	0.0	6.2	20.1	20.3
02/03/96	0.0	0.0	6.2	19.9	20.3
03/03/96	0.0	0.0	6.2	19.5	19.6
04/03/96	0.0	0.0	6.2	18.6	
05/03/96	0.0	0.0	6.2	19.3	19.5
06/03/96	0.0	0.0	6.2	20.0	20.5
07/03/96	0.0	0.0	6.2	19.7	20.2
08/03/96	0.0	0.0	6.2	19.9	20.7
09/03/96	0.0	0.0	6.2	19.6	20.0
10/03/96	0.0	0.0	6.2	19.6	20.1
11/03/96	0.0	0.0	6.2	20.0	20.5
12/03/96	0.0	0.0	6.2	20.2	
13/03/96	0.0	0.0	6.2	19.4	19.4
14/03/96	0.0	0.0	6.2	20.0	20.5
15/03/96	0.0	0.0	6.2	19.8	20.1
16/03/96	0.0	0.0	6.2	20.2	20.7
17/03/96	0.0	0.0	6.2	20.1	20.3
18/03/96	0.0	0.0	6.2		
verage:				19.9	20.4
ount:	30	30	30	27	26
aximum:	0.0	0.0	6.2	21.2	22.7
inimum:	0.0	0.0	6.2	18.6	19.4
tandard Deviation:				0.5	0.6

PERIOD 3.4.4
SUMMARY DATA 1
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
01/04/96	150	36.0	37.4	11.30	18.30	406	17	14			
02/04/96	150	36.2	34.3	11.30	16.00	326	18	12	33.7	2.00	2.00
03/04/96	150	36.7	36.7	11.20	17.10	272	24	24			
04/04/96	150	36.5	36.2	11.50	8.74	163	18	18	21.6	2.00	2.00
05/04/96	150	37.4	37.0								
06/04/96	150	36.7		12.50	9.30	229	18	21	21.2	3.34	2.00
07/04/96	150	37.0	37.0	13.30	10.10						
08/04/96	150	37.0	36.0	13.10	8.20	193	19	19			
09/04/96	150	36.7									
10/04/96	150	36.5	35.0	11.50	8.50	304	22	21			
11/04/96	150	37.2	36.5	11.10	8.50	183	15	8	20.5	2.00	2.00
12/04/96	150	36.7	35.5	10.00	7.70						
13/04/96	150	36.0	36.7	8.80	7.30						
14/04/96	150	37.7	37.7	8.90	6.60	198	16	11	18.4	2.00	2.00
15/04/96	150	35.8	37.0	10.10	7.90	291	17	17			
16/04/96	150	35.0	36.0	9.40	8.40	219	22	20	19.0	2.00	2.00
17/04/96	150	35.8	37.9	11.00	11.50	266	18	19			
18/04/96	150	35.8	36.7	10.70	8.80	247	20	12	21.9	2.00	2.00
19/04/96	150	36.0	36.7	12.50	11.10						
20/04/96	150	35.8	35.8	6.60	11.10						
21/04/96	150			10.20	9.70	343	28	25	32.0	4.85	3.74
22/04/96	150	35.8	33.8	12.50	10.30	299	26	13			
23/04/96	150	35.8	36.5	12.00	9.40	254	19	24	22.1	3.84	2.00
24/04/96	150	35.5	36.2	11.70	10.50	282	25	24			
25/04/96	150	35.8	36.5	11.60	12.30	370	26	15	24.2	2.00	2.00
26/04/96	150	35.0	39.1	11.90	12.80						
27/04/96	150	35.5	37.4	13.90	13.60						
28/04/96	150	45.1	45.1	13.20	12.80	375	29	23	22.9	2.00	2.00
29/04/96	150	30.5	37.9			393	27	26			
30/04/96	150	35.0	36.5	12.80	13.40	337	29	25			
02/05/96	150	35.0	35.0	15.80	10.80						
03/05/96	150	36.2	37.0	13.30	13.50						
04/05/96	150	36.2	37.2	13.20	12.70						
05/05/96	150			12.00	12.40						
06/05/96	150	35.8	33.4								
07/05/96	150	35.3	35.3	17.70	21.10	384	27	28	20.7	2.00	2.00
08/05/96	150	35.3	33.8	13.20	11.90	330	23	21			
09/05/96	150	36.0	34.6	13.50	11.60	383	22	21	32.9	2.00	3.00
10/05/96	150	35.0	34.1	13.50	11.50						
11/05/96	150	37.7	37.0	15.10	13.00						
12/05/96	150	35.8	34.6	13.00		425	25	20	28.1	2.00	2.00
13/05/96	150	36.7	35.5	17.30	13.10	479	20	19			
14/05/96	150	37.2	36.5			351	23	20	28.2	2.00	3.04
15/05/96	150	36.2	35.5	13.30	12.00	356	23	19			
16/05/96	150	36.7	36.0	12.40	12.90	336	20	18	34.9	2.00	2.00
17/05/96	150	36.7	35.3	13.10	11.00						
18/05/96	150	37.7	37.2	15.60	13.20						
19/05/96	150	36.2	36.7	13.60	13.60	326	226	15	18.2	2.00	2.00
20/05/96	150	36.2	38.2	14.40		275	21	20			
21/05/96	150	35.8	36.2	13.70	12.10	281	20	19	27.7	2.00	2.00
22/05/96	150	37.0	36.2	12.50	9.50	382	20	18			
23/05/96	150	36.5	36.2	11.20	9.70	320	17	17	20.8	2.00	2.00
24/05/96	150	35.8	36.5	11.10	10.40	339	20	20	27.4	2.00	2.00
25/05/96	150	35.8	34.8	13.50	12.20						
26/05/96	150	36.5	35.8	14.71	9.86						
27/05/96	150	36.2	36.7	14.27	10.79						
28/05/96	150	36.2	36.2	14.81	10.81	347	17	17	27.6	2.00	2.00

PERIOD 3.4.4
SUMMARY DATA 1
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P

	DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
	29/05/96	150	36.0	36.7	18.22	12.75	438	21	20			
	30/05/96	150	35.5	35.5	18.00	13.14	339	18	18	35.0	2.00	2.00
	31/05/96	150	37.2	37.0	13.27	12.94						
	01/06/96	150	36.2	36.2	15.93	10.66						
	02/06/96	150	37.0	37.4	15.93	11.92	386	20	16	34.7	2.00	2.00
	03/06/96	150	36.5	36.5			339	21	22			
	04/06/96	150	36.7	36.0	15.80	12.20	417	24	26	32.9	3.30	3.22
	05/06/96	150	35.3	35.3	20.80	13.30	342	22	24			
	06/06/96	150	36.7	36.5								
	07/06/96	150	34.8	35.3	14.03	10.67						
	08/06/96	150	35.5	36.0	17.15	12.47						
	09/06/96	150	36.0	36.0	18.14	12.97	392	27	25	37.0	2.00	3.93
	10/06/96	150	36.7	35.5	17.58	14.33						
	11/06/96	20	35.8	35.8	19.45	14.66	312	22	23	29.1	2.00	2.00
Average:		148	36.2	36.3	13.35	11.64	323	26	19	26.6	2.28	2.27
Count:		71	69	67	64	62	44	44	44	26	26	26
Maximum:		150	45.1	45.1	20.80	21.10	479	226	28	37.0	4.85	3.93
Minimum:		20	30.5	33.4	6.60	6.60	163	15	8	18.2	2.00	2.00
Standard Deviation:		15	1.4	1.5	2.69	2.56	71	31	4	5.9	0.71	0.57

PERIOD 3.4.4
SUMMARY DATA 2
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
01/04/96	15.81	0.01	1.90	15.80	13.91	244.64	126.78
02/04/96	14.07	0.01	1.58	14.06	12.49	200.05	152.85
03/04/96						204.01	175.38
04/04/96	15.65	0.01	0.15	15.64	15.50	204.77	143.82
05/04/96							
06/04/96	15.65	1.70	2.01	13.95	13.64	194.57	169.28
07/04/96							
08/04/96	15.80	2.32	6.04	13.48	9.76	182.83	160.45
09/04/96							
10/04/96	14.87	0.46	1.24	14.41	13.63	194.79	156.78
11/04/96	15.91	0.07	0.60	15.84	15.31	224.44	182.73
12/04/96							
13/04/96							
14/04/96	14.24	0.58	4.02	13.66	10.22	213.48	192.79
15/04/96	15.00	0.76	3.22	14.24	11.78	276.69	218.86
16/04/96	12.57	0.68	2.44	11.89	10.13	195.94	169.18
17/04/96	16.06	0.78	3.49	15.28	12.57	221.19	188.24
18/04/96	13.25	0.67	1.25	12.58	12.00	213.78	178.05
19/04/96							
20/04/96							
21/04/96	15.64	1.39	2.02	14.25	13.62	163.94	150.36
22/04/96	14.85	0.40	0.54	14.45	14.31	188.82	164.81
23/04/96	15.17	0.82	1.28	14.35	13.89	171.59	172.68
24/04/96	14.21	0.36	0.38	13.85	13.83	184.28	186.15
25/04/96	17.76	2.03	3.49	15.73	14.27	141.22	137.82
26/04/96							
27/04/96							
28/04/96	15.33	0.82	1.50	14.51	13.83	135.93	150.86
29/04/96	18.36	1.43	0.95	16.93	17.41	199.59	158.22
30/04/96	16.85	0.87	0.91	15.98	15.94	241.02	159.33
02/05/96							
03/05/96							
04/05/96							
05/05/96							
06/05/96							
07/05/96	15.20	0.58	0.77	14.62	14.43	127.92	124.59
08/05/96	15.04	0.74	0.76	14.30	14.28	149.25	143.82
09/05/96	17.87	0.76	0.84	17.11	17.03	156.91	157.02
10/05/96							
11/05/96							
12/05/96	17.86	2.45	3.96	15.41	13.90	160.30	139.93
13/05/96	10.27	0.94	1.44	9.33	8.83	143.67	175.77
14/05/96	16.91	0.72	1.18	16.19	15.73	142.34	143.96
15/05/96	16.91	0.89	1.24	16.02	15.67	148.27	162.00
16/05/96	26.18	0.91	2.36	25.27	23.82	161.78	156.41
17/05/96							
18/05/96							
19/05/96	23.86	1.51	3.69	22.35	20.17	222.39	202.38
20/05/96	24.19	1.64	5.78	22.55	18.41	202.81	183.55
21/05/96	23.03	1.29	4.71	21.74	18.32	169.26	211.87
22/05/96	17.30	3.15	6.55	14.15	10.75	169.53	153.58
23/05/96	16.25	1.85	5.23	14.40	11.02	147.21	153.49
24/05/96	13.84	1.08	2.59	12.76	11.25	148.87	149.11
25/05/96							
26/05/96							
27/05/96							
28/05/96	14.89	0.51	0.93	14.38	13.96	177.71	186.59

PERIOD 3.4.4
SUMMARY DATA 2
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
29/05/96	15.20	0.53	1.00	14.67	14.20	182.41	176.91
30/05/96	14.14	0.31	0.56	13.83	13.58	161.89	168.57
31/05/96							
01/06/96							
02/06/96	16.62	0.39	0.77	16.23	15.85	159.73	169.38
03/06/96	15.46	0.38	0.76	15.08	14.70	151.22	156.01
04/06/96	18.11	1.40	2.64	16.71	15.47	153.38	165.21
05/06/96	17.12	0.93	1.01	16.19	16.11	175.39	157.16
06/06/96							
07/06/96							
08/06/96							
09/06/96	18.77	0.55	0.59	18.22	18.18	145.30	135.46
10/06/96							
11/06/96	17.83	0.46	0.67	17.37	17.16	134.93	132.66
Average:	16.51	0.93	2.07	15.58	14.44	179.32	163.66
Count:	43	43	43	43	43	44	44
Maximum:	26.18	3.15	6.55	25.27	23.82	276.69	218.86
Minimum:	10.27	0.01	0.15	9.33	8.83	127.92	124.59
Standard Deviation:	3.00	0.68	1.66	2.85	2.86	33.20	20.90

PERIOD 3.4.4
SUMMARY DATA 3
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
01/04/96	121.84	89.61	1518	756	1129	798	49.8	70.7	66	164
02/04/96	110.37	100.37	1604	885	1197	786	55.2	65.7	65	155
03/04/96	115.42	116.78	1718	972	1194	795	56.6	66.6	64	157
04/04/96	108.92	95.02	1645	875	1288	851	53.2	66.1	73	140
05/04/96										
06/04/96	112.37	114.71	1806	1043	1337	906	57.8	67.8	69	138
07/04/96										
08/04/96	100.58	100.89	1756	966	1382	869	55.0	62.9	74	130
09/04/96										
10/04/96	111.40	100.33	1794	1026	1436	919	57.2	64.0	72	118
11/04/96	124.68	115.33	1847	1026	1445	912	55.5	63.1	68	114
12/04/96										
13/04/96										
14/04/96	113.85	123.34	1650	880	1302	833	53.3	64.0	76	115
15/04/96	138.17	122.97	1568	783	1269	713	49.9	56.2	77	118
16/04/96	107.94	105.02	1572	866	1284	797	55.1	62.1	76	117
17/04/96	123.55	118.76	1545	863	1314	829	55.9	63.1	78	110
18/04/96	109.85	105.31	1555	799	1334	789	51.4	59.1	77	105
19/04/96										
20/04/96										
21/04/96	99.15	93.84	1594	964	1378	860	60.5	62.4	64	105
22/04/96	102.03	100.65	1549	837	1364	833	54.0	61.1	65	103
23/04/96	95.04	105.56	1495	828	1361	832	55.4	61.1	67	103
24/04/96	95.94	109.36	1481	771	1343	789	52.1	58.7	61	101
25/04/96	92.27	103.45	1102	720	1203	903	65.3	75.1	77	115
26/04/96										
27/04/96										
28/04/96	80.03	96.98	1498	882	1565	1006	58.9	64.3	67	88
29/04/96	113.30	96.79	1286	730	1615	988	56.8	61.2	74	84
30/04/96	139.91	97.38	1280	743	1574	962	58.0	61.1	74	89
02/05/96										
03/05/96										
04/05/96										
05/05/96										
06/05/96										
07/05/96	77.61	79.12	1373	833	1644	1044	60.7	63.5	138	97
08/05/96	89.81	88.60	1396	840	1698	1046	60.2	61.6	136	91
09/05/96	91.46	97.15	1388	809	1613	998	58.3	61.9	137	87
10/05/96										
11/05/96										
12/05/96	95.20	91.63	1411	838	1466	960	59.4	65.5	142	99
13/05/96	84.59	109.98	1476	869	1595	998	58.9	62.6	149	94
14/05/96	84.37	95.88	1461	866	1467	977	59.3	66.6	151	109
15/05/96	86.68	101.42	1495	874	1527	956	58.5	62.6	147	108
16/05/96	93.54	95.31	1541	891	1582	964	57.8	60.9	149	107
17/05/96										
18/05/96										
19/05/96	128.89	124.57	1684	976	1636	1007	58.0	61.6	107	107
20/05/96	115.23	113.01	1783	1013	1642	1011	56.8	61.6	112	116
21/05/96	96.42	125.34	1873	1067	1692	1001	57.0	59.2	101	106
22/05/96	93.36	89.74	1805	994	1643	960	55.1	58.4	102	107
23/05/96	81.41	92.88	1848	1022	1717	1039	55.3	60.5	45	55
24/05/96	85.24	92.70	1818	1041	1623	1009	57.3	62.2		
25/05/96										
26/05/96										

'ERIOD 3.4.4
SUMMARY DATA 3
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
27/05/96										
28/05/96	98.52	111.54	1802	999	1713	1024	55.4	59.8	89	123
29/05/96	111.74	119.75	1683	1031	1470	995	61.3	67.7	92	150
30/05/96	94.54	108.17	1846	1078	1669	1071	58.4	64.2		
31/05/96										
01/06/96										
02/06/96	93.22	103.02	1854	1082	1710	1040	58.4	60.8	94	143
03/06/96	88.27	96.09	1845	1077	1643	1012	58.4	61.6	85	158
04/06/96	90.90	102.60	1883	1116	1636	1016	59.3	62.1	85	165
05/06/96	108.36	100.49	1871	1156	1786	1142	61.8	63.9	80	134
06/06/96										
07/06/96										
08/06/96										
09/06/96	89.45	87.60	2063	1270	1803	1166	61.6	64.7	87	133
10/06/96										
11/06/96	84.36	84.97	2169	1356	1822	1167	62.5	64.1	92	132
Average:	101.81	102.82	1642	939	1503	945	57.2	63.0	91	116
Count:	44	44	44	44	44	44	44	44	42	42
Maximum:	139.91	125.34	2169	1356	1822	1167	65.3	75.1	151	165
Minimum:	77.61	79.12	1102	720	1129	713	49.8	56.2	45	55
Standard Deviation:	15.25	11.28	214	139	184	108	3.2	3.3	29	24

PERIOD 3.4.4
SUMMARY DATA 4
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
01/04/96	7.26	7.30	7.53	7.44	7.75	7.73	0	0	241.9	253.5
02/04/96	7.35	7.37	7.52	7.48	7.68	7.66	0	0		
03/04/96	7.28	7.31	7.39	7.36	7.51	7.54	0	0	244.6	263.0
04/04/96							0	0		
05/04/96							0	0		
06/04/96							0	0		
07/04/96							0	0		
08/04/96	7.11	7.03	7.41	7.43	7.58	7.59	0	0	261.1	281.3
09/04/96	7.19	7.19	7.44	7.52	7.61	7.57	0	0		
10/04/96	7.11	7.01	7.32	7.33	7.47	7.52	0	0		
11/04/96	7.20	7.14	7.34	7.34	7.48	7.50	0	0	252.0	270.2
12/04/96							0	0		
13/04/96							0	0		
14/04/96	7.00	6.92	7.15	7.17	7.33	7.38	0	0		
15/04/96	7.26	7.25	7.63	7.77	7.84	8.00	0	0		
16/04/96	7.41	7.01	7.60	7.68	7.78	7.79	0	0		
17/04/96	7.24	7.36	7.39	7.60	7.55	7.84	0	0	208.3	232.0
18/04/96							0	0		
19/04/96							0	0		
20/04/96							0	0		
21/04/96	7.46	7.43	7.49	7.73	7.78	7.86	0	0		
22/04/96	7.26	7.35	7.54	7.62	7.55	7.79	0	0	222.0	251.8
23/04/96	7.38	7.42	7.44	7.55	7.63	7.66	0	0		
24/04/96	7.22	7.16	7.44	7.44	7.65	7.73	0	0	231.1	249.6
25/04/96	7.18	7.09	7.42	7.38	7.63	7.66	0	0		
26/04/96							0	0		
27/04/96							0	0		
28/04/96	7.04	7.02	7.33	7.35	7.48	7.56	0	0		
29/04/96	7.18	7.10	7.41	7.48	7.58	7.72	0	0	227.8	235.9
30/04/96							0	0	238.7	250.6
02/05/96	7.19	7.02	7.40	7.30	7.47	7.56	0	0		
03/05/96							0	0		
04/05/96							0	0		
05/05/96							0	0		
06/05/96							0	0		
07/05/96	7.43	7.21	7.59	7.53	7.69	7.72	0	0	225.4	246.9
08/05/96	7.47	7.25	7.59	7.55	7.71	7.80	0	0	220.0	257.0
09/05/96	7.48	7.27	7.62	7.61	7.88	7.84	0	0		
10/05/96							0	0		
11/05/96							0	0		
12/05/96	7.30	7.16	7.59	7.60	7.76	7.89	0	0	238.4	250.5
13/05/96	7.35	7.21	7.52	7.59	7.64	7.85	0	0		
14/05/96	7.42	7.28	7.55	7.52	7.74	7.80	0	0		
15/05/96	7.35	7.24	7.57	7.50	7.83	7.81	0	0	210.0	236.4
16/05/96	7.29	7.24	7.48	7.48	7.70	7.76	0	0		
17/05/96							0	0		
18/05/96							0	0		
19/05/96	7.28	7.23	7.52	7.55	7.78	7.84	0	0	209.2	235.3
20/05/96	7.30	7.26	7.50	7.58	7.72	7.92	0	0		
21/05/96	7.23	7.23	7.47	7.52	7.73	7.81	0	0		
22/05/96	7.26	7.21	7.59	7.71	7.83	8.00	0	0	218.1	244.1
23/05/96							0	0		
24/05/96							0	0		
25/05/96	7.29	7.27	7.62	7.66	7.83	7.95	0	0		
26/05/96	7.19	7.18	7.51	7.55	7.71	7.82	0	0		

PERIOD 3.4.4
SUMMARY DATA 4
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
27/05/96	7.23	7.20	7.54	7.64	7.74	7.90	0	0		
28/05/96	7.27	7.24	7.57	7.64	7.76	7.86	0	0	226.5	272.1
29/05/96	7.31	7.28	7.56	7.57	7.69	7.80	0	0		
30/05/96	7.28	7.32	7.54	7.56	7.79	7.75	0	0	224.5	239.4
31/05/96							0	0		
01/06/96							0	0		
02/06/96	7.23	7.22	7.42	7.43	7.56	7.68	0	0	215.7	229.3
03/06/96	7.19	7.22	7.40	7.49	7.62	7.73	0	0		
04/06/96	7.23	7.21	7.53	7.52	7.81	7.74	0	0		
05/06/96	7.22	7.15	7.51	7.52	7.72	7.77	0	0	232.9	245.8
06/06/96		7.38		7.64		7.90	0	0		
07/06/96							0	0		
08/06/96							0	0		
09/06/96	7.35	7.31	7.71	7.72	7.93	7.97	0	0	232.1	257.9
10/06/96	7.35	7.33	7.68	7.72	7.88	7.93	0	0		
11/06/96							0	0	227.2	270.7
Average:	7.27	7.22	7.50	7.53	7.68	7.76	0	0	228.9	251.1
Count:	43	44	43	44	43	44	71	71	21	21
Maximum:	7.48	7.43	7.71	7.77	7.93	8.00	0	0	261.1	281.3
Minimum:	7.00	6.92	7.15	7.17	7.33	7.38	0	0	208.3	229.3
Standard Deviation:	0.10	0.11	0.11	0.13	0.13	0.14	0	0	13.5	14.0

PERIOD 3.4.4
SUMMARY DATA 5
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	NH3 fR1	NH3 fR2	NO3 fR1	NO3 fR2	SRP fR1	SRP fR2
01/04/96	0.09	0.09	5.15	2.75	0.45	2.46
02/04/96	0.14	0.14	5.07	3.14	0.39	1.79
03/04/96	0.11	0.05	6.07	4.39	0.17	0.97
04/04/96	0.00	0.00	6.15	5.56	0.11	0.35
05/04/96						
06/04/96	0.11	0.11	3.53	4.06	0.58	0.98
07/04/96						
08/04/96	0.20	0.16	3.02	3.56	0.43	0.68
09/04/96						
10/04/96	0.15	0.22	4.27	4.68	0.35	0.58
11/04/96	0.16	0.15	5.52	6.43	0.26	0.63
12/04/96						
13/04/96						
14/04/96	0.19	0.15	6.56	7.14	0.63	4.15
15/04/96	0.20	0.15	7.06	7.65	2.94	7.52
16/04/96	0.19	0.15	6.83	6.93	0.95	2.44
17/04/96	0.25	0.24	7.32	7.32	1.39	6.52
18/04/96	0.14	0.23	8.28	8.02	0.70	0.88
19/04/96						
20/04/96						
21/04/96	2.76	0.11	7.51	8.80	3.72	3.34
22/04/96	0.09	0.02	8.54	8.67	1.17	0.61
23/04/96	0.32	0.46	9.59	8.54	0.45	1.30
24/04/96	0.14	0.09	9.19	7.37	1.16	0.75
25/04/96	0.69	0.62	7.49	8.68	6.10	4.28
26/04/96						
27/04/96						
28/04/96	0.75	0.50	4.90	5.63	1.47	0.35
29/04/96	0.56	0.50	5.35	6.30	2.05	0.35
30/04/96	0.75	0.50	5.88	6.72	1.88	0.29
02/05/96						
03/05/96						
04/05/96						
05/05/96						
06/05/96						
07/05/96	3.83	1.58	7.58	8.71	1.24	1.48
08/05/96	0.30	0.14	7.10	7.89	0.63	0.54
09/05/96	0.22	0.12	8.10	8.61	1.01	1.04
10/05/96						
11/05/96						
12/05/96	0.25	0.16	5.60	7.26	2.45	4.68
13/05/96	0.25	0.14	7.39	8.07	0.64	1.30
14/05/96	0.19	0.13	7.84	7.39	0.57	0.92
15/05/96	0.13	0.14	9.55	9.77	0.42	1.03
16/05/96	0.14	0.14	8.31	8.01	0.86	1.85
17/05/96						
18/05/96						
19/05/96	0.17	0.13	6.93	6.59	1.56	4.60
20/05/96	0.13	0.12	7.54	7.54	1.73	6.32
21/05/96	0.15	0.13	7.99	7.45	1.40	4.49
22/05/96	0.15	0.13	5.82	5.48	2.95	7.37
23/05/96	0.15	0.15	4.13	3.84	1.43	4.63
24/05/96	0.19	0.15	5.23	5.12	0.61	1.59
25/05/96						
26/05/96						
27/05/96						

PERIOD 3.4.4
SUMMARY DATA 5
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P

	DATE	NH3 fR1	NH3 fR2	NO3 fR1	NO3 fR2	SRP fR1	SRP fR2
	28/05/96	0.16	0.11	4.59	4.35	0.34	0.87
	29/05/96	0.30	0.10	7.11	6.58	0.70	0.84
	30/05/96	0.15	0.11	8.45	8.19	0.24	0.48
	31/05/96						
	01/06/96						
	02/06/96	0.17	0.09	8.05	8.39	0.34	0.75
	03/06/96	0.15	0.09	6.10	6.64	0.30	0.69
	04/06/96	0.30	0.15	4.87	5.48	1.20	2.11
	05/06/96	0.17	0.17	4.41	4.87	0.69	0.69
	06/06/96						
	07/06/96						
	08/06/96						
	09/06/96	0.22	0.20	4.24	4.78	0.29	0.95
	10/06/96						
	11/06/96	0.19	0.12	4.14	4.94	0.42	0.49
Average:		0.36	0.21	6.46	6.55	1.12	2.07
Count:		44	44	44	44	44	44
Maximum:		3.83	1.58	9.59	9.77	6.10	7.52
Minimum:		0.00	0.00	3.02	2.75	0.11	0.29
Standard Deviation:		0.67	0.25	1.66	1.75	1.11	2.03

PERIOD 3.4.4
SUMMARY DATA 6
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
01/04/96								
02/04/96	0.08	2.75	5.31	5.07	0.07	1.65	2.24	3.59
03/04/96								
04/04/96	0.08	3.02	5.53	5.87	0.08	3.70	6.05	6.05
05/04/96								
06/04/96	0.17	1.49	3.65	3.51	0.10	1.83	3.93	3.83
07/04/96								
08/04/96								
09/04/96								
10/04/96	0.06	2.19	4.09	4.20	0.05	2.73	4.80	4.86
11/04/96	0.07	3.40	5.62	6.05	0.06	4.16	6.69	6.43
12/04/96								
13/04/96								
14/04/96	0.09	4.06	6.46	6.82	0.08	4.59	6.85	7.09
15/04/96								
16/04/96	0.08	3.92	6.41	6.57	0.06	4.09	6.67	6.47
17/04/96								
18/04/96	0.09	4.52	8.58	8.13	0.07	4.94	8.13	8.00
19/04/96								
20/04/96								
21/04/96								
22/04/96	0.08	4.49	8.54	8.41	0.08	4.96	8.10	8.41
23/04/96	0.07	5.10	8.71	9.15	0.09	5.34	8.81	9.22
24/04/96								
25/04/96								
26/04/96								
27/04/96								
28/04/96	0.08	1.48	5.19	5.22	0.07	3.07	6.03	5.97
29/04/96								
30/04/96								
02/05/96								
03/05/96								
04/05/96								
05/05/96								
06/05/96								
07/05/96	0.08	2.87	6.44	6.82	0.10	4.67	7.83	7.77
08/05/96								
09/05/96	0.08	3.84	8.13	8.17	0.06	5.27	8.61	8.20
10/05/96								
11/05/96								
12/05/96								
13/05/96								
14/05/96	0.08	3.86	7.73	8.64	0.07	5.23	7.93	8.47
15/05/96								
16/05/96	0.07	3.24	7.04	6.93	0.06	3.94	6.70	6.70
17/05/96								
18/05/96								
19/05/96	0.07	3.78	7.16	7.22	0.06	3.82	6.93	6.82
20/05/96								
21/05/96	0.09	4.34	7.99	8.02	0.07	4.50	7.65	7.62
22/05/96								
23/05/96								
24/05/96	0.09	2.17	4.57	4.94	0.09	2.17	5.37	5.28
25/05/96								
26/05/96								
27/05/96								

PERIOD 3.4.4
SUMMARY DATA 6
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAB1	NO3 R1 fAB2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAB1	NO3 R2 fAB2
28/05/96	0.04	2.05	4.50	4.53	0.05	2.15	4.50	4.46
29/05/96								
30/05/96	0.04	4.39	7.65	8.19	0.05	4.52	7.78	8.05
31/05/96								
01/06/96								
02/06/96	0.05	3.22	5.90	6.24	0.06	3.49	6.61	6.58
03/06/96								
04/06/96	0.07	3.24	3.59	5.42	0.06	3.77	5.72	5.72
05/06/96								
06/06/96								
07/06/96								
08/06/96								
09/06/96	0.08	0.83	2.92	3.13	0.09	2.30	4.50	4.40
10/06/96								
11/06/96	0.06	1.39	2.92	4.38	0.04	2.36	4.15	4.76
Average:	0.08	3.15	6.03	6.32	0.07	3.72	6.36	6.45
Count:	24	24	24	24	24	24	24	24
Maximum:	0.17	5.10	8.71	9.15	0.10	5.34	8.81	9.22
Minimum:	0.04	0.83	2.92	3.13	0.04	1.65	2.24	3.59
Standard Deviation:	0.02	1.13	1.80	1.68	0.02	1.15	1.65	1.56

PERIOD 3.4.4
SUMMARY DATA 7
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
01/04/96								
02/04/96	41.10	14.38	1.42	0.00	49.00	18.02	8.22	3.32
03/04/96								
04/04/96	27.89	9.91	0.31	0.00	30.21	10.69	1.08	0.00
05/04/96								
06/04/96	49.57	17.97	1.70	2.63	64.29	21.84	7.13	3.41
07/04/96								
08/04/96								
09/04/96								
10/04/96	38.73	13.63	2.01	0.62	41.83	15.03	4.34	0.93
11/04/96	51.51	14.85	4.85	0.30	55.30	16.67	7.88	6.82
12/04/96								
13/04/96								
14/04/96	49.24	12.27	8.94	0.56	54.54	16.51	14.39	12.57
15/04/96								
16/04/96	55.30	15.60	9.09	0.65	84.08	21.82	15.45	18.18
17/04/96								
18/04/96	34.32	12.45	4.47	1.24	39.91	13.89	4.79	1.76
19/04/96								
20/04/96								
21/04/96								
22/04/96	36.72	13.57	3.51	0.66	43.10	13.89	3.83	1.12
23/04/96	38.31	15.48	5.43	0.70	47.89	17.40	6.07	1.44
24/04/96								
25/04/96								
26/04/96								
27/04/96								
28/04/96	36.42	16.85	6.37	0.71	56.15	18.97	4.40	0.30
29/04/96								
30/04/96								
02/05/96								
03/05/96								
04/05/96								
05/05/96								
06/05/96								
07/05/96	59.55	11.75	2.66	0.25	121.45	19.75	4.39	0.16
08/05/96								
09/05/96	78.36	15.83	4.54	0.47	135.56	21.94	7.84	1.88
10/05/96								
11/05/96								
12/05/96								
13/05/96								
14/05/96	49.78	18.02	4.27	0.49	65.58	22.44	9.48	2.84
15/05/96								
16/05/96	60.48	22.53	8.95	1.46	76.22	27.17	12.59	5.47
17/05/96								
18/05/96								
19/05/96	57.99	21.37	8.45	1.58	68.76	26.18	13.75	6.63
20/05/96								
21/05/96	48.05	18.06	7.46	1.38	56.33	23.20	13.59	6.96
22/05/96								
23/05/96								
24/05/96	51.15	18.51	4.51	0.75	57.92	23.92	7.67	1.65
25/05/96								
26/05/96								
27/05/96								

RIOD 3.4.4
MMARY DATA 7
W FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAB1	TP R1 fAB2	TP R2 fAN	TP R2 fAX	TP R2 fAB1	TP R2 fAB2
28/05/96	51.15	18.05	3.31	0.40	57.92	20.46	6.32	2.56
29/05/96								
30/05/96	45.89	14.89	2.71	0.23	54.16	18.96	12.19	10.23
31/05/96								
01/06/96								
02/06/96	50.69	17.95	4.99	0.56	54.84	22.44	8.31	1.66
03/06/96								
04/06/96	54.84	23.93	11.97	2.19	61.49	26.92	14.13	6.65
05/06/96								
06/06/96								
07/06/96								
08/06/96								
09/06/96	62.55	21.42	3.75	0.37	70.37	25.02	7.04	2.03
10/06/96								
11/06/96	62.55	20.96	3.28	0.25	70.37	25.02	6.72	1.56
verage:	49.67	16.68	4.96	0.77	63.22	20.34	8.40	4.17
ount:	24	24	24	24	24	24	24	24
aximum:	78.36	23.93	11.97	2.63	135.56	27.17	15.45	18.18
inimum:	27.89	9.91	0.31	0.00	30.21	10.69	1.08	0.00
tandard Deviation:	10.99	3.56	2.83	0.65	23.05	4.36	3.87	4.32

PERIOD 3.4.4
SUMMARY DATA 8
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
01/04/96	0.0	0.0	6.2	20.0	20.3
02/04/96	0.0	0.0	6.2	19.9	20.0
03/04/96	0.0	0.0	6.2	20.0	20.2
04/04/96	0.0	0.0	6.2	19.7	19.9
05/04/96	0.0	0.0	6.2		
06/04/96	0.0	0.0	6.2	19.7	19.8
07/04/96	0.0	0.0	6.2	19.9	20.1
08/04/96	0.0	0.0	6.2	19.3	19.3
09/04/96	0.0	0.0	6.2		
10/04/96	0.0	0.0	6.2	19.4	19.8
11/04/96	0.0	0.0	6.2	19.5	19.6
12/04/96	0.0	0.0	6.2	19.6	19.9
13/04/96	0.0	0.0	6.2	19.8	20.0
14/04/96	0.0	0.0	6.2	19.5	19.8
15/04/96	0.0	0.0	6.2	19.9	20.6
16/04/96	0.0	0.0	6.2	19.7	19.9
17/04/96	0.0	0.0	6.2	19.6	19.7
18/04/96	0.0	0.0	6.2	19.6	19.9
19/04/96	0.0	0.0	6.2	20.3	21.0
20/04/96	0.0	0.0	6.2	18.6	18.8
21/04/96	0.0	0.0	6.2	18.7	19.0
22/04/96	0.0	0.0	6.2	19.9	19.9
23/04/96	0.0	0.0	6.2	20.1	20.6
24/04/96	0.0	0.0	6.2	20.0	20.4
25/04/96	0.0	0.0	6.2	21.2	21.9
26/04/96	0.0	0.0	6.2	19.7	20.1
27/04/96	0.0	0.0	6.2	19.8	19.7
28/04/96	0.0	0.0	6.2	19.9	20.1
29/04/96	0.0	0.0	6.2		
30/04/96	0.0	0.0	6.2	20.1	20.6
02/05/96	0.0	0.0	6.2	20.0	20.6
03/05/96	0.0	0.0	6.2	21.3	20.2
04/05/96	0.0	0.0	6.2	19.6	19.7
05/05/96	0.0	0.0	6.2	19.7	19.7
06/05/96	0.0	0.0	6.2		
07/05/96	0.0	0.0	6.2	20.1	20.7
08/05/96	0.0	0.0	6.2	20.0	20.3
09/05/96	0.0	0.0	6.2	19.9	20.2
10/05/96	0.0	0.0	6.2	20.7	21.0
11/05/96	0.0	0.0	6.2	20.4	21.5
12/05/96	0.0	0.0	6.2	20.4	
13/05/96	0.0	0.0	6.2	20.2	20.5
14/05/96	0.0	0.0	6.2		
15/05/96	0.0	0.0	6.2	19.0	19.4
16/05/96	0.0	0.0	6.2	19.4	20.0
17/05/96	0.0	0.0	6.2	19.0	19.6
18/05/96	0.0	0.0	6.2	19.1	19.2
19/05/96	0.0	0.0	6.2	19.0	19.0
20/05/96	0.0	0.0	6.2	18.8	
21/05/96	0.0	0.0	6.2	19.0	19.7
22/05/96	0.0	0.0	6.2	19.0	19.0
23/05/96	0.0	0.0	6.2	18.8	18.9
24/05/96	0.0	0.0	6.2	20.8	20.0
25/05/96	0.0	0.0	6.2	20.9	20.2
26/05/96	0.0	0.0	6.2	19.6	19.3

ERIOD 3.4.4
JMMARY DATA 8
)W FERROUS-FERRIC TO R1 AEROBIC, LOW P

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
27/05/96	0.0	0.0	6.2	19.3	19.1
28/05/96	0.0	0.0	6.2	19.3	19.1
29/05/96	0.0	0.0	6.2	19.3	20.1
30/05/96	0.0	0.0	6.2	19.3	19.3
31/05/96	0.0	0.0	6.2	19.6	19.6
01/06/96	0.0	0.0	6.2	18.9	18.6
02/06/96	0.0	0.0	6.2	18.9	18.7
03/06/96	0.0	0.0	6.2		
04/06/96	0.0	0.0	6.2	17.1	17.6
05/06/96	0.0	0.0	6.2	20.6	19.4
06/06/96	0.0	0.0	6.2		
07/06/96	0.0	0.0	6.2	19.4	19.2
08/06/96	0.0	0.0	6.2	19.6	19.3
09/06/96	0.0	0.0	6.2	19.5	19.3
10/06/96	0.0	0.0	6.2	19.9	19.6
11/06/96	0.0	0.0	6.2	19.8	19.8
verage:				19.7	19.8
ount:	71	71	71	64	62
aximum:	0.0	0.0	6.2	21.3	21.9
inimum:	0.0	0.0	6.2	17.1	17.6
tandard Deviation:				0.7	0.7

PERIOD 3.5.1
SUMMARY DATA 1
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P, LOW ACETATE

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
12/06/96	20	34.8	33.8	12.10	10.20						
13/06/96	20	34.8	36.7	14.72	14.10	400	21	24	28.8	2.00	3.08
14/06/96	20	37.2	37.2	13.93	12.80						
15/06/96	20	37.2	37.2	14.69	12.30						
16/06/96	20	35.8	35.0	10.77	11.47	240	22	23	27.6	2.00	2.00
17/06/96	20	36.0	36.2	9.79		125	18	18			
18/06/96	20	36.5	35.8	11.69	11.27	259	18	19	27.3	2.00	2.00
19/06/96	20	36.0	36.0	10.67	8.75	157	14	18			
20/06/96	20	35.0	35.0	11.77	12.27	267	13	15	33.5	2.00	2.00
21/06/96	20	36.2	35.5	12.70	11.80						
22/06/96	20	36.7	36.7	9.07	11.95						
23/06/96	20	35.3	35.3	11.62	11.53	268	19	18	40.1	3.06	3.31
24/06/96	20	36.2	36.0	9.37	11.41	281	21	22			
25/06/96	20	36.0	36.0	10.24	11.15	223	22	21	37.6	2.00	2.00
26/06/96	20	36.0	36.0	10.35	11.14	384	22	21			
27/06/96	20	35.8	35.8	10.70	11.30	320	29	22	29.6	2.00	2.00
28/06/96	20	36.5	36.5	11.80	11.60						
29/06/96	20	35.8	35.8	11.00	12.05						
30/06/96	20		36.0								
01/07/96	20		31.2	23.00	11.40						
02/07/96	20	36.2	36.2	13.62	12.21	396	22	21	31.8	2.00	2.00
03/07/96	20	36.5	36.2	13.31	12.36	337	17	12			
04/07/96	20	36.5	36.5	13.80	12.90	342	22	22	39.5	2.00	2.00
05/07/96	20	35.8	35.8	13.32	13.83	294	22	22			
06/07/96	20	36.2	36.2	12.61	12.18	317	22	25	32.9	3.80	2.00
07/07/96	20	36.0	36.2	12.31	12.31	291	20	24	33.9	2.00	2.00
08/07/96	20	37.2	37.2	13.90							
09/07/96	20	36.5	36.5	15.08	14.56	225	18	20	43.7	3.94	3.50
10/07/96	20	36.5	36.5	14.78	12.86	225	19	22			
11/07/96	20	36.5	36.5	13.15	12.77	223	18	19	36.9	2.00	2.00
12/07/96	20	36.7	36.7	11.88	12.98						
13/07/96	20	36.0	36.0	13.88	11.56						
14/07/96	20	36.7	36.2								
15/07/96	20	36.7	36.7	8.23	7.59	285	17	16			
16/07/96	20	37.0	36.0	8.24	7.64	247	16	17	25.8	2.00	2.00
17/07/96	20		35.8	8.20	7.70	209	14	17			
18/07/96	20	35.5	36.2	11.00	11.20	357	16	20	41.8	2.00	2.00
19/07/96	20	36.0	35.3	11.70	12.90						
20/07/96	20	36.2	36.7	12.20	13.10						
21/07/96	20	35.5	36.2	12.10	12.60	328	20	20	34.8	2.00	3.22
22/07/96	20	35.0	35.8	12.40	13.20	336	18	20			
23/07/96	20	34.8	36.2	12.50	12.90	225	16	15	29.6	3.16	2.00
24/07/96	20	35.8	37.7	13.10	13.70	316	14	18			
25/07/96	20	33.6	35.0	14.10	13.70	199	15	19	38.0	2.00	2.00
26/07/96	20	36.0	36.0	14.00	13.13						
Average:	20	36.0	36.0	12.31	11.91	278	19	20	34.1	2.33	2.28
Count:	45	42	45	43	41	29	29	29	18	18	18
Maximum:	20	37.2	37.7	23.00	14.56	400	29	25	43.7	3.94	3.50
Minimum:	20	33.6	31.2	8.20	7.59	125	13	12	25.8	2.00	2.00
Standard Deviation:	0	0.7	1.0	2.45	1.60	67	3	3	5.2	0.65	0.54

PERIOD 3.5.1
SUMMARY DATA 2
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P, LOW ACETATE

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
12/06/96							
13/06/96							
14/06/96							
15/06/96							
16/06/96							
17/06/96							
18/06/96							
19/06/96							
20/06/96	12.64	7.37	8.43	5.27	4.21	105.92	110.87
21/06/96							
22/06/96							
23/06/96	11.59	7.07	9.63	4.52	1.96	97.86	81.74
24/06/96	10.08	5.87	9.33	4.21	0.75	81.14	70.68
25/06/96	10.68	7.07	10.08	3.61	0.60	82.62	68.54
26/06/96	14.14	8.28	10.83	5.86	3.31	80.30	75.15
27/06/96	12.46	5.68	8.05	6.78	4.41	69.59	76.21
28/06/96							
29/06/96							
30/06/96							
01/07/96							
02/07/96	14.04	3.00	6.47	11.04	7.57	67.03	55.61
03/07/96	13.72	2.68	5.05	11.04	8.67	68.84	68.80
04/07/96	11.20	2.05	4.57	9.15	6.63	77.79	66.54
05/07/96	10.88	2.37	3.15	8.51	7.73	80.93	72.60
06/07/96	11.52	2.05	4.89	9.47	6.63	70.43	72.20
07/07/96	10.25	1.89	4.42	8.36	5.83	82.28	66.44
08/07/96							
09/07/96	8.05	4.10	6.31	3.95	1.74	73.23	62.13
10/07/96	9.31	5.36	8.05	3.95	1.26	77.07	64.52
11/07/96	7.23	3.53	6.59	3.70	0.64	73.07	56.24
12/07/96							
13/07/96							
14/07/96							
15/07/96	6.91	2.09	2.73	4.82	4.18	62.79	52.68
16/07/96	7.87	2.41	3.37	5.46	4.50	70.11	47.58
17/07/96	5.10	0.46	0.62	4.64	4.48	60.90	48.72
18/07/96	9.89	1.08	1.85	8.81	8.04	62.92	51.66
19/07/96							
20/07/96							
21/07/96	9.11	3.55	6.33	5.56	2.78	67.38	53.28
22/07/96	8.03	4.02	6.33	4.01	1.70	75.29	44.42
23/07/96	8.34	3.71	6.33	4.63	2.01	64.12	48.45
24/07/96	8.03	3.55	6.02	4.48	2.01	60.19	48.23
25/07/96	6.80	3.71	6.02	3.09	0.78	65.57	46.31
26/07/96							
Average:	9.91	3.87	6.06	6.04	3.85	74.06	62.90
Count:	24	24	24	24	24	24	24
Maximum:	14.14	8.28	10.83	11.04	8.67	105.92	110.87
Minimum:	5.10	0.46	0.62	3.09	0.60	60.19	44.42
Standard Deviation:	2.41	2.06	2.57	2.40	2.56	10.88	14.74

PERIOD 3.5.1
SUMMARY DATA 3
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P, LOW ACETATE

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
12/06/96										
13/06/96			2085	1298	1830	1177	62.3	64.3	91	142
14/06/96										
15/06/96										
16/06/96			1844	1212	1545	1093	65.7	70.7	87	155
17/06/96			1757	1139	1445	1034	64.8	71.6	91	152
18/06/96			1707	1110	1417	1013	65.0	71.5	91	155
19/06/96			1580	1014	1279	918	64.2	71.8	91	164
20/06/96	69.65	81.78	1577	1037	1288	950	65.8	73.8	86	155
21/06/96										
22/06/96										
23/06/96	67.08	63.53	1615	1107	1279	994	68.5	77.7	87	177
24/06/96	56.72	55.87	1512	1057	1212	958	69.9	79.0	90	182
25/06/96	56.64	53.52	1514	1038	1209	944	68.6	78.1	92	185
26/06/96	54.44	58.98	1534	1040	1199	941	67.8	78.5	91	192
27/06/96	47.88	59.95	1542	1061	942	741	68.8	78.7	91	234
28/06/96										
29/06/96										
30/06/96										
01/07/96										
02/07/96	46.11	44.30	1984	1365	1417	1129	68.8	79.7	74	155
03/07/96	46.47	49.59	1874	1265	1336	963	67.5	72.1	91	165
04/07/96	53.81	50.59	1894	1310	01397	1062	69.2	76.0	84	143
05/07/96	55.14	54.40	1808	1232	1392	1043	68.1	74.9	96	148
06/07/96	48.26	54.77	1935	1326	1417	1075	68.5	75.9	88	141
07/07/96	50.35	48.69	1817	1112	1445	1059	61.2	73.3	94	141
08/07/96										
09/07/96	50.01	46.43	1760	1202	1393	1041	68.3	74.7	91	144
10/07/96	51.62	49.67	1632	1093	1321	1017	67.0	77.0	96	151
11/07/96	47.91	43.76	1690	1108	1248	971	65.6	77.8	92	160
12/07/96										
13/07/96										
14/07/96										
15/07/96	43.18	41.32	1473	1013	1104	866	68.8	78.4	88	176
16/07/96	44.99	37.52	1471	944	1173	925	64.2	78.9	84	162
17/07/96	42.03	39.21	1426	984	1040	837	69.0	80.5	84	173
18/07/96	41.18	41.30	1418	928	1122	897	65.4	79.9	87	169
19/07/96										
20/07/96										
21/07/96	44.20	40.12	1363	894	1109	835	65.6	75.3	84	157
22/07/96	44.39	33.59	1350	796	1205	911	59.0	75.6	84	144
23/07/96	42.23	37.14	1368	901	1173	899	65.9	76.6	80	152
24/07/96	40.58	38.02	1317	888	1105	871	67.4	78.8	84	154
25/07/96	38.90	33.70	1350	801	1146	834	59.3	72.8	81	131
26/07/96										
Average:	49.32	48.24	1627	1078	1282	965	66.2	75.7	88	161
Count:	24	24	29	29	29	29	29	29	29	29
Maximum:	69.65	81.78	2085	1365	1830	1177	69.9	80.5	96	234
Minimum:	38.90	33.59	1317	796	942	741	59.0	64.3	74	131
Standard Deviation:	7.66	10.88	211	152	174	98	2.8	3.5	5	20

PERIOD 3.5.1
SUMMARY DATA 4
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P, LOW ACETATE

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
12/06/96							00	00		
13/06/96	7.47	7.45	7.41	7.39	7.50	7.61	00	00		
14/06/96							00	00		
15/06/96							00	00		
16/06/96							00	00	111.0	121.7
17/06/96	7.38	7.46	7.14	7.18	7.24	7.35	00	00		
18/06/96	7.47	7.44	7.10	7.20	7.22	7.36	00	00		
19/06/96	7.49	7.52	7.21	7.17	7.32	7.35	00	00	103.7	103.6
20/06/96	7.47	7.53	7.10	7.19	7.21	7.34	00	00		
21/06/96							00	00		
22/06/96							00	00		
23/06/96	7.67	7.72	7.55	7.59	7.81	7.90	00	00	95.0	115.9
24/06/96	7.52	7.55	7.17	7.17	7.31	7.34	00	00		
25/06/96	7.42	7.43	7.14	7.11	7.27	7.29	00	00		
26/06/96	7.52	7.54	7.35	7.26	7.47	7.44	00	00	101.6	112.0
27/06/96	7.50	7.52	7.39	7.36	7.49	7.55	00	00		
28/06/96							00	00		
29/06/96							00	00		
30/06/96							00	00		
01/07/96	7.27	7.32	7.33	7.33	7.48	7.53	00	00		
02/07/96	7.43	7.44	7.41	7.42	7.58	7.64	00	00		
03/07/96	7.31	7.36	7.30	7.35	7.47	7.59	00	00	148.3	153.4
04/07/96	7.35	7.35	7.43	7.44	7.48	7.54	00	00		
05/07/96							00	00		
06/07/96	7.54	7.55	7.28	7.30	7.46	7.46	00	00	134.3	144.9
07/07/96	7.48	7.48	7.27	7.29	7.41	7.47	00	00		
08/07/96	7.56	7.61	7.20	7.34	7.28	7.37	00	00		
09/07/96	7.53	7.53	7.13	7.15	7.28	7.28	00	00	98.2	114.7
10/07/96	7.56	7.60	7.09	7.15	7.23	7.29	00	00		
11/07/96	7.58	7.58	7.16	7.15	7.26	7.27	00	00		
12/07/96							00	00		
13/07/96							00	00		
14/07/96							00	00		
15/07/96	7.37	7.29	7.28	7.28	7.45	7.48	00	00	111.5	143.6
16/07/96	7.45	7.38	7.33	7.33	7.48	7.52	00	00		
17/07/96	7.49	7.47	7.31	7.30	7.42	7.43	00	00		
18/07/96	7.59	7.60	7.25	7.36	7.37	7.35	00	00	113.6	140.7
19/07/96							00	00		
20/07/96							00	00		
21/07/96	7.53	7.58	7.20	7.26	7.28	7.41	00	00	107.9	116.6
22/07/96	7.57	7.62	7.20	7.18	7.30	7.34	00	00		
23/07/96	7.53	7.59	7.10	7.16	7.21	7.27	00	00		
24/07/96	7.57	7.63	7.14	7.19	7.23	7.30	00	00	81.7	102.4
25/07/96	7.58	7.60	7.10	7.20	7.27	7.36	00	00		
26/07/96							00	00		
Average:	7.49	7.51	7.24	7.27	7.37	7.43	0	0	109.7	124.5
Count:	29	29	29	29	29	29	45	45	11	11
Maximum:	7.67	7.72	7.55	7.59	7.81	7.90	0	0	148.3	153.4
Minimum:	7.27	7.29	7.09	7.11	7.21	7.27	0	0	81.7	102.4
Standard Deviation:	0.09	0.10	0.12	0.11	0.14	0.14	0	0	17.5	17.1

APPENDIX 5

PERIOD 3.5.1
SUMMARY DATA 5
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P, LOW ACETATE

DATE	NH3 fR1	NH3 fR2	NO3 fR1	NO3 fR2	SRP fR1	SRP fR2
12/06/96						
13/06/96	0.17	0.55	9.01	7.24	0.40	1.15
14/06/96						
15/06/96						
16/06/96	0.24	0.19	11.12	10.75	6.85	8.52
17/06/96	0.19	0.20	10.33	10.78	6.60	8.96
18/06/96	0.22	0.24	10.66	11.00	6.21	8.58
19/06/96	0.21	1.53	10.63	10.03	5.20	8.08
20/06/96	0.25	0.28	12.08	12.54	5.38	6.61
21/06/96						
22/06/96						
23/06/96	0.18	0.18	12.20	10.36	4.73	7.24
24/06/96	0.18	0.07	12.08	11.22	5.10	7.90
25/06/96	0.10	0.10	12.42	11.29	5.32	8.28
26/06/96	0.20	0.16	11.90	10.71	6.33	9.00
27/06/96	0.31	0.20	8.49	7.73	4.91	7.37
28/06/96						
29/06/96						
30/06/96						
01/07/96						
02/07/96	0.22	0.24	3.44	5.60	2.31	5.51
03/07/96	0.16	0.14	4.46	5.40	1.47	3.99
04/07/96	0.05	0.31	5.08	5.13	1.27	3.70
05/07/96	0.26	0.14	5.05	5.46	1.41	2.00
06/07/96	0.13	0.13	6.20	5.94	0.91	3.54
07/07/96	0.13	0.12	6.80	6.10	1.09	3.49
08/07/96						
09/07/96	0.62	0.43	13.00	11.45	2.46	4.92
10/07/96	0.53	0.48	13.30	12.20	3.20	5.60
11/07/96	0.48	0.48	13.70	12.60	3.14	5.92
12/07/96						
13/07/96						
14/07/96						
15/07/96	0.55	0.50	6.65	6.13	0.37	1.11
16/07/96	0.45	0.40	6.43	5.62	0.69	1.11
17/07/96	0.00	0.00	6.85	5.51	0.24	0.42
18/07/96	0.00	0.00	10.86	9.42	0.79	1.53
19/07/96						
20/07/96						
21/07/96	0.05	0.06	14.93	13.70	3.07	6.17
22/07/96	0.08	0.12	15.79	15.05	3.33	6.19
23/07/96	0.08	0.12	16.64	15.66	3.07	5.87
24/07/96	0.10	0.09	17.25	15.72	3.05	5.66
25/07/96	0.09	0.08	17.54	16.33	2.83	5.54
26/07/96						
Average:	0.21	0.26	10.51	9.89	3.16	5.31
Count:	29	29	29	29	29	29
Maximum:	0.62	1.53	17.54	16.33	6.85	9.00
Minimum:	0.00	0.00	3.44	5.13	0.24	0.42
Standard Deviation:	0.16	0.28	3.93	3.49	2.07	2.60

PERIOD 3.5.1
SUMMARY DATA 6
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P, LOW ACETATE

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAE1	NO3 R1 fAE2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAE1	NO3 R2 fAE2
12/06/96								
13/06/96								
14/06/96								
15/06/96								
16/06/96								
17/06/96	0.37	6.36	10.12	9.82	0.25	8.27	11.33	11.27
18/06/96	0.04	6.57	10.12	10.15	0.09	6.57	9.49	10.00
19/06/96								
20/06/96	0.04	7.11	11.62	11.33	0.08	6.91	10.97	10.51
21/06/96								
22/06/96								
23/06/96	0.20	7.28	11.62	10.51	0.19	7.70	11.60	11.84
24/06/96	0.07	7.00	11.75	11.93	0.10	6.57	11.05	11.02
25/06/96								
26/06/96								
27/06/96	0.05	4.81	7.92	8.30	2.10	4.37	7.38	7.22
28/06/96								
29/06/96								
30/06/96								
01/07/96								
02/07/96	0.10	1.52	3.81	3.68	0.06	3.01	5.55	5.11
03/07/96								
04/07/96	0.05	2.59	5.34	5.31	0.04	3.04	5.56	5.31
05/07/96								
06/07/96	0.04	3.30	6.07	5.91	0.04	3.35	6.13	5.82
07/07/96								
08/07/96								
09/07/96	0.93	9.66	11.38	12.84	0.66	8.86	10.98	11.51
10/07/96								
11/07/96	0.83	10.59	12.84	13.63	1.02	9.26	12.31	12.97
12/07/96								
13/07/96								
14/07/96								
15/07/96								
16/07/96	0.11	4.02	5.43	5.43	0.17	3.04	4.23	4.30
17/07/96								
18/07/96	0.10	6.62	12.99	13.70	0.08	7.97	11.07	12.11
19/07/96								
20/07/96								
21/07/96	0.66	9.15	14.02	14.81	0.43	8.63	14.02	13.96
22/07/96								
23/07/96	2.04	10.77	16.04	16.87	2.00	9.64	15.49	16.53
24/07/96								
25/07/96	3.53	12.27	17.67	17.54	2.89	11.45	17.07	19.46
26/07/96								
Average:	0.57	6.85	10.55	10.74	0.64	6.79	10.26	10.56
Count:	16	16	16	16	16	16	16	16
Maximum:	3.53	12.27	17.67	17.54	2.89	11.45	17.07	19.46
Minimum:	0.04	1.52	3.81	3.68	0.04	3.01	4.23	4.30
Standard Deviation:	0.92	3.00	3.83	4.04	0.87	2.60	3.57	4.09

PERIOD 3.5.1
SUMMARY DATA 7
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P, LOW ACETATE

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
12/06/96								
13/06/96								
14/06/96								
15/06/96								
16/06/96								
17/06/96	8.23	6.32	6.47	7.22	11.28	8.88	9.03	8.88
18/06/96	18.81	8.28	7.97	9.93	20.31	9.93	9.78	9.78
19/06/96								
20/06/96	40.63	9.18	7.82	7.07	42.13	9.78	9.03	8.43
21/06/96								
22/06/96								
23/06/96	29.34	7.82	7.07	7.97	31.60	9.78	9.63	9.18
24/06/96	10.38	8.28	6.92	7.22	11.74	10.23	9.93	9.63
25/06/96								
26/06/96								
27/06/96	11.04	6.94	5.21	4.42	10.73	8.52	7.57	6.31
28/06/96								
29/06/96								
30/06/96								
01/07/96								
02/07/96	21.30	10.73	6.63	3.31	25.24	13.72	9.78	7.26
03/07/96								
04/07/96	19.72	8.68	4.42	2.05	20.82	10.73	7.41	4.89
05/07/96								
06/07/96	16.56	7.26	4.42	2.68	18.30	10.25	7.73	4.57
07/07/96	10.25	5.99	4.26	4.10	11.67	8.05	6.94	6.31
08/07/96								
09/07/96	7.57	5.99	5.36	5.21	8.52	7.89	7.41	4.73
10/07/96								
11/07/96	5.78	4.34	3.86	3.69	6.75	6.59	6.43	6.59
12/07/96								
13/07/96								
14/07/96								
15/07/96								
16/07/96	11.24	5.14	3.05	2.25	13.65	6.91	4.66	3.05
17/07/96								
18/07/96	6.33	3.40	2.32	1.85	7.11	4.48	3.86	3.09
19/07/96								
20/07/96								
21/07/96	5.56	4.33	4.02	3.71	7.11	6.80	7.11	6.80
22/07/96								
23/07/96	4.94	4.17	3.71	3.55	6.33	6.33	6.49	6.33
24/07/96								
25/07/96	6.18	5.10	4.79	4.63	7.41	7.41	7.41	7.41
26/07/96								
Average:	13.76	6.59	5.19	4.76	15.34	8.60	7.66	6.66
Count:	17	17	17	17	17	17	17	17
Maximum:	40.63	10.73	7.97	9.93	42.13	13.72	9.93	9.78
Minimum:	4.94	3.40	2.32	1.85	6.33	4.48	3.86	3.05
Standard Deviation:	9.45	1.99	1.63	2.27	9.73	2.10	1.70	2.05

PERIOD 3.5.1
SUMMARY DATA 8
LOW FERROUS-FERRIC TO R1 AEROBIC, LOW P, LOW ACETATE

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
12/06/96				20.5	20.1
13/06/96	0.0			19.8	19.5
14/06/96				19.6	19.2
15/06/96				19.5	19.1
16/06/96				20.2	20.6
17/06/96	0.0			19.5	
18/06/96	0.0			19.9	20.5
19/06/96	0.0			19.5	19.3
20/06/96	0.0			20.5	20.0
21/06/96				20.4	19.8
22/06/96				20.0	19.9
23/06/96	0.0			20.3	19.9
24/06/96	0.0			19.2	19.6
25/06/96	0.0			20.2	19.7
26/06/96	0.0			20.3	19.7
27/06/96	0.0			20.1	19.6
28/06/96				20.1	19.2
29/06/96				20.2	19.8
30/06/96					
01/07/96	0.0			18.6	19.5
02/07/96	0.0			20.3	20.0
03/07/96	0.0			20.0	19.5
04/07/96	0.0			20.2	19.7
05/07/96				20.0	19.7
06/07/96	0.0			19.8	19.0
07/07/96	0.0	0.0		19.8	19.8
08/07/96	0.0	0.0		20.0	
09/07/96	0.0			19.9	19.2
10/07/96	0.0			20.2	19.7
11/07/96	0.0			19.9	19.6
12/07/96				19.1	19.5
13/07/96				19.3	18.9
14/07/96					
15/07/96	0.0			19.8	19.5
16/07/96	0.0			19.6	18.5
17/07/96	0.0			20.3	19.2
18/07/96	0.0			20.5	19.4
19/07/96				20.4	19.8
20/07/96				20.6	20.0
21/07/96	0.0			20.2	19.8
22/07/96	0.0			20.8	20.8
23/07/96	0.0			20.4	20.0
24/07/96	0.0			20.5	19.7
25/07/96	0.0			20.7	20.1
26/07/96				20.4	20.1
Average:				20.0	19.7
Count:	29	2	0	43	41
Maximum:	0.0	0.0		20.8	20.8
Minimum:	0.0	0.0		18.6	18.5
Standard Deviation:				0.5	0.4

APPENDIX 5

PERIOD 3.5.2
SUMMARY DATA 1
LOW FERROUS-FERRIC TO R1 ANAEROBIC, LOW P, LOW ACETATE

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
27/07/96	20	36.0	36.0	13.31	11.49						
28/07/96	20	37.2	36.5	11.13	11.04						
29/07/96	20	37.4	35.3	11.58	13.01	374	21	23			
30/07/96	20	37.4	36.7	12.79	14.00	385	23	25	30.8	2.00	2.00
31/07/96	20	35.8	36.2	13.07	13.28	323	20	28			
01/08/96	20	36.0	36.5	14.20	13.75	340	22	24	30.9	2.00	2.00
02/08/96	20	37.2	39.4	13.36	13.54						
03/08/96	20	36.0	35.5	13.25	12.37						
04/08/96	20	36.2	36.5	12.72	11.66	338	24	22	31.8	2.00	2.00
05/08/96	20	36.2	35.3	13.31	12.22	347	22	21			
06/08/96	20	36.0	35.0	12.16	11.63	281	21	22	46.2	5.99	4.65
07/08/96	20	35.5	36.5	13.33	12.93	274	20	23			
08/08/96	20	35.8	34.8	14.40	13.20	274	18	25			
09/08/96	20	36.7	36.7	13.40							
10/08/96	20	37.2	36.7	12.60	13.00						
11/08/96	20	37.2	36.0	13.00	12.50	320	19	21	37.6	4.00	2.00
12/08/96	20	36.7	35.8	13.10	12.30	283	21	21			
13/08/96	20	37.2	36.0	14.10	12.40	291	20	20	40.3	6.73	6.72
14/08/96	20	37.2	36.0	12.80	12.10	318	14	20			
15/08/96	20	36.5	36.5	14.33	12.58	391	21	20	37.6	2.00	2.00
16/08/96	20	37.9	37.9	15.80	13.80						
17/08/96	20	35.8		16.20	13.50						
18/08/96	20	36.0	35.0	16.31	12.88	418	22	22	37.4	3.26	3.62
19/08/96	20	35.8	36.2	14.99	13.29	398	23	22			
20/08/96	20	35.0	35.0	15.61	13.65	300	21	27	35.5	4.56	4.82
21/08/96	20	35.8	35.3	13.00	13.15	400	20	24			
22/08/96	20	34.8	36.7	12.48	14.20	434	20	24	37.9	5.82	4.13
23/08/96	20	36.2	34.8	14.59	13.80						
24/08/96	20	36.0	36.2	14.40	14.07						
25/08/96	20	37.2	37.9	14.18	15.30	420	22	22	38.7	4.57	3.73
26/08/96	20	36.7	38.6	14.00	14.80	204	20	23			
27/08/96	20	36.2		15.87		394	24		23.3	2.00	
Average:	20	36.4	36.3	13.73	13.05	341	21	23	35.7	3.74	3.42
Count:	32	32	30	32	30	22	22	21	12	12	11
Maximum:	20	37.9	39.4	16.31	15.30	434	24	28	46.2	6.73	6.72
Minimum:	20	34.8	34.8	11.13	11.04	204	14	20	23.3	2.00	2.00
Standard Deviation:	0	0.7	1.1	1.27	0.97	59	2	2	5.6	1.71	1.51

PERIOD 3.5.2
SUMMARY DATA 2
LOW FERROUS-FERRIC TO R1 ANAEROBIC, LOW P, LOW ACETATE

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	R1 ML TP mgP/gVSS	R2 ML TP mgP/gVSS
27/07/96							
28/07/96							
29/07/96	10.81	4.17	7.26	6.64	3.55	60.07	44.04
30/07/96	11.89	3.86	6.18	8.03	5.71	59.71	46.08
31/07/96	11.74	3.40	5.72	8.34	6.02	58.72	50.06
01/08/96	12.17	2.69	4.42	9.48	7.75	63.07	52.61
02/08/96							
03/08/96							
04/08/96	7.74	2.05	2.37	5.69	5.37	64.22	52.60
05/08/96	6.64	0.00	0.32		6.32	60.35	51.08
06/08/96	6.00	0.32	0.47	5.68	5.53	60.11	55.70
07/08/96	10.27	0.47	0.63	9.80	9.64	59.17	59.95
08/08/96	9.48	1.11	1.58	8.37	7.90	63.02	56.62
09/08/96							
10/08/96							
11/08/96	10.43	3.00	4.58	7.43	5.85	67.88	65.31
12/08/96	10.27	3.00	3.63	7.27	6.64	69.47	54.05
13/08/96	10.27	4.42	5.69	5.85	4.58	78.27	74.41
14/08/96	11.06	4.90	6.79	6.16	4.27	75.60	70.91
15/08/96	9.96	4.82	7.00	5.14	2.96	71.40	66.22
16/08/96							
17/08/96							
18/08/96	11.05	2.64	3.27	8.41	7.78	79.51	60.60
19/08/96	12.60	3.42	3.73	9.18	8.87	79.14	71.60
20/08/96	12.60	3.73	3.89	8.87	8.71	77.45	68.35
21/08/96	12.91	4.20	4.67	8.71	8.24	79.98	83.11
22/08/96	9.96	1.09	1.09	8.87	8.87	68.38	69.97
23/08/96							
24/08/96							
25/08/96	12.14	1.24	1.24	10.90	10.90	72.88	71.64
26/08/96	13.38	1.87	2.02	11.51	11.36	77.29	72.68
27/08/96	13.54	2.64		10.90		71.68	
Average:	10.77	2.68	3.65	8.15	6.99	68.97	61.79
Count:	22	22	21	21	21	22	21
Maximum:	13.54	4.90	7.26	11.51	11.36	79.98	83.11
Minimum:	6.00	0.00	0.32	5.14	2.96	58.72	44.04
Standard Deviation:	1.96	1.46	2.21	1.79	2.24	7.54	10.38

PERIOD 3.5.2
SUMMARY DATA 3
LOW FERROUS-FERRIC TO R1 ANAEROBIC, LOW P, LOW ACETATE

DATE	R1 mgP/gMLSS	R2 mgP/gMLSS	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
27/07/96										
28/07/96										
29/07/96	40.22	35.27	1398	936	1191	954	67.0	80.1	79	134
30/07/96	41.25	37.48	1468	1014	1228	999	69.1	81.4	85	130
31/07/96	41.20	39.78	1522	1068	1227	975	70.2	79.5	79	132
01/08/96	43.05	41.70	1468	1002	1220	967	68.3	79.3	82	141
02/08/96										
03/08/96										
04/08/96	43.85	41.03	1542	1053	1132	883	68.3	78.0	78	139
05/08/96	41.76	39.43	1536	1063	1210	934	69.2	77.2	81	132
06/08/96	40.26	43.76	1554	1041	1148	902	67.0	78.6	79	144
07/08/96	37.15	46.45	1599	1004	1204	933	62.8	77.5	77	137
08/08/96	43.21	43.96	1565	1073	1301	1010	68.6	77.6	77	131
09/08/96										
10/08/96										
11/08/96	45.46	50.80	1571	1052	1188	924	67.0	77.8	73	135
12/08/96	46.88	40.43	1584	1069	1266	947	67.5	74.8	76	126
13/08/96	51.99	56.50	1471	977	1180	896	66.4	75.9	75	136
14/08/96	50.40	53.97	1461	974	1218	927	66.7	76.1	75	131
15/08/96	47.48	50.18	1501	998	1197	907	66.5	75.8	80	134
16/08/96										
17/08/96										
18/08/96	52.85	45.61	1566	1041	1419	1068	66.5	75.3	77	109
19/08/96	52.03	54.23	1585	1042	1360	1030	65.7	75.7	77	119
20/08/96	51.40	52.56	1677	1113	1415	1088	66.4	76.9	73	110
21/08/96	53.89	58.59	1686	1136	1349	951	67.4	70.5	72	105
22/08/96	45.85	50.69	1751	1174	1455	1054	67.0	72.4	71	103
23/08/96										
24/08/96										
25/08/96	47.75	52.63	1714	1123	1496	1099	65.5	73.5	70	100
26/08/96	52.81	55.39	1809	1236	1618	1233	68.3	76.2	66	91
27/08/96	47.13		1743	1146			65.7		69	
Average:	46.27	47.16	1581	1061	1287	985	67.1	76.7	76	125
Count:	22	21	22	22	21	21	22	21	22	21
Maximum:	53.89	58.59	1809	1236	1618	1233	70.2	81.4	85	144
Minimum:	37.15	35.27	1398	936	1132	883	62.8	70.5	66	91
Standard Deviation:	4.82	6.77	106	70	127	84	1.5	2.5	4	15

PERIOD 3.5.2
SUMMARY DATA 4
LOW FERROUS-FERRIC TO R1 ANAEROBIC, LOW P, LOW ACETATE

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
27/07/96							0	0		
28/07/96	7.27	7.38	7.20	7.31	7.40	7.48	0	0		
29/07/96	7.37	7.43	7.33	7.39	7.50	7.53	0	0	127.4	148.6
30/07/96	7.36	7.40	7.38	7.37	7.53	7.55	0	0		
31/07/96	7.38	7.41	7.38	7.38	7.54	7.58	0	0	132.2	155.0
01/08/96	7.40	7.47	7.32	7.32	7.48	7.48	0	0		
02/08/96							0	0		
03/08/96							0	0		
04/08/96	7.17	7.18	7.20	7.28	7.34	7.43	0	0		
05/08/96	7.28	7.27	7.28	7.27	7.41	7.48	0	0	107.1	132.9
06/08/96	7.31	7.32	7.18	7.20	7.29	7.36	0	0		
07/08/96	7.40	7.44	7.18	7.16	7.23	7.26	0	0	95.8	121.3
08/08/96							0	0		
09/08/96							0	0		
10/08/96							0	0		
11/08/96	7.33	7.36	7.11	7.18	7.27	7.35	0	0	112.1	128.2
12/08/96	7.38	7.40	7.16	7.23	7.30	7.42	0	0		
13/08/96	7.44	7.52	7.19	7.28	7.27	7.41	0	0		
14/08/96	7.33	7.39	7.17	7.24	7.28	7.36	0	0	110.8	138.5
15/08/96	7.32	7.40	7.19	7.34	7.33	7.45	0	0		
16/08/96							0	0		
17/08/96							0	0		
18/08/96	7.31	7.32	7.28	7.36	7.42	7.53	0	0	126.8	138.0
19/08/96	7.27	7.30	7.21	7.31	7.33	7.45	0	0		
20/08/96	7.19	7.15	7.22	7.30	7.38	7.48	0	0		
21/08/96	7.22	7.20	7.22	7.30	7.34	7.48	0	0	129.1	151.1
22/08/96	7.23	7.24	7.33	7.32	7.43	7.48	0	0		
23/08/96							0	0		
24/08/96							0	0		
25/08/96	7.23	7.23	7.25	7.35	7.42	7.53	0	0	118.4	163.3
26/08/96	7.22	7.17	7.32	7.30	7.46	7.34	0	0		
27/08/96	7.24		7.24		7.35		0	0	141.6	
Average:	7.30	7.33	7.24	7.29	7.38	7.45	0	0	120.1	141.9
Count:	22	21	22	21	22	21	32	32	10	9
Maximum:	7.44	7.52	7.38	7.39	7.54	7.58	0	0	141.6	163.3
Minimum:	7.17	7.15	7.11	7.16	7.23	7.26	0	0	95.8	121.3
Standard Deviation:	0.07	0.10	0.07	0.06	0.09	0.08	0	0	13.0	12.8

PERIOD 3.5.2
SUMMARY DATA 5
LOW FERROUS-FERRIC TO R1 ANAEROBIC, LOW P, LOW ACETATE

DATE	NH3 fE1	NH3 fE2	NO3 fE1	NO3 fE2	SRP fE1	SRP fE2
27/07/96						
28/07/96						
29/07/96	0.13	0.12	6.82	6.16	2.49	5.42
30/07/96	0.13	0.13	5.83	5.36	2.33	4.71
31/07/96	0.18	0.18	5.79	5.61	1.74	3.82
01/08/96	0.36	0.32	6.86	7.26	1.93	3.47
02/08/96						
03/08/96						
04/08/96	0.32	0.30	6.72	7.39	0.40	0.94
05/08/96	0.32	0.32	7.12	7.38	0.25	0.50
06/08/96	0.23	0.19	8.90	8.77	0.20	0.33
07/08/96	0.23	0.23	13.50	12.20	0.20	0.30
08/08/96	0.27	0.23	15.40	15.10	0.35	1.01
09/08/96						
10/08/96						
11/08/96	0.23	0.23	13.20	11.30	2.38	3.74
12/08/96	0.23	0.23	11.40	11.70	1.62	2.48
13/08/96	0.42	0.37	12.10	11.80	3.03	5.11
14/08/96	0.17	0.15	12.32	12.45	3.26	4.67
15/08/96	0.20	0.18	12.57	12.20	3.88	6.39
16/08/96						
17/08/96						
18/08/96	0.23	0.15	9.71	9.52	1.25	1.88
19/08/96	0.20	0.20	10.10	9.71	0.71	1.19
20/08/96	0.22	0.21	5.88	7.02	0.38	0.30
21/08/96	0.21	0.21	5.48	5.09	0.46	0.86
22/08/96	0.26	0.25	5.61	5.35	0.36	0.61
23/08/96						
24/08/96						
25/08/96	0.31	0.29	6.20	5.09	0.30	0.36
26/08/96	0.27	0.29	6.68	5.06	0.29	0.34
27/08/96	0.40		6.68		0.56	
Average:	0.25	0.23	8.86	8.64	1.29	2.31
Count:	22	21	22	21	22	21
Maximum:	0.42	0.37	15.40	15.10	3.88	6.39
Minimum:	0.13	0.12	5.48	5.06	0.20	0.30
Standard Deviation:	0.08	0.07	3.09	3.03	1.14	2.00

PERIOD 3.5.2
SUMMARY DATA 6
LOW FERROUS-FERRIC TO R1 ANAEROBIC, LOW P, LOW ACETATE

DATE	NO3 R1 fAN	NO3 R1 fAX	NO3 R1 fAR1	NO3 R1 fAR2	NO3 R2 fAN	NO3 R2 fAX	NO3 R2 fAR1	NO3 R2 fAR2
27/07/96								
28/07/96								
29/07/96	0.24	2.68	6.70	6.82	0.12	1.98	5.88	5.48
30/07/96	0.03	0.90	5.07	4.94	0.05	0.38	4.31	4.46
31/07/96								
01/08/96	0.07	2.85	7.39	7.13	0.07	3.82	7.80	7.66
02/08/96								
03/08/96								
04/08/96	0.08	2.69	5.92	6.32	0.11	3.31	6.05	6.72
05/08/96								
06/08/96								
07/08/96	0.05	8.77	14.22	14.88	0.03	7.84	13.50	14.08
08/08/96								
09/08/96								
10/08/96								
11/08/96	0.09	6.38	10.82	12.20	0.09	6.11	10.44	11.70
12/08/96								
13/08/96	0.11	6.61	11.97	12.70	0.08	6.60	10.97	12.95
14/08/96								
15/08/96	0.05	5.10	9.73	11.51	0.07	5.87	11.59	11.51
16/08/96								
17/08/96								
18/08/96	0.05	4.50	8.32	9.71	0.10	5.10	9.46	9.46
19/08/96								
20/08/96								
21/08/96								
22/08/96	0.10	2.35	4.18	5.19	0.05	2.50	4.31	4.11
23/08/96								
24/08/96								
25/08/96	0.05	1.80	4.85	4.20	0.07	1.24	4.37	3.66
26/08/96								
27/08/96	0.07	2.48	3.00	3.53				
Average:	0.08	3.93	7.68	8.26	0.08	4.07	8.06	8.34
Count:	12	12	12	12	11	11	11	11
Maximum:	0.24	8.77	14.22	14.88	0.12	7.84	13.50	14.08
Minimum:	0.03	0.90	3.00	3.53	0.03	0.38	4.31	3.66
Standard Deviation:	0.05	2.25	3.28	3.63	0.03	2.30	3.14	3.60

PERIOD 3.5.2
SUMMARY DATA 7
LOW FERROUS-FERRIC TO R1 ANAEROBIC, LOW P, LOW ACETATE

DATE	TP R1 fAN	TP R1 fAX	TP R1 fAE1	TP R1 fAE2	TP R2 fAN	TP R2 fAX	TP R2 fAE1	TP R2 fAE2
27/07/96								
28/07/96								
29/07/96	10.50	6.95	5.41	4.63	13.59	9.27	8.03	7.11
30/07/96	11.43	6.80	4.79	3.71	14.06	9.58	7.57	5.87
31/07/96								
01/08/96	13.11	6.95	4.27	3.32	17.06	9.64	7.27	5.53
02/08/96								
03/08/96								
04/08/96	10.11	4.74	2.37	1.90	14.06	6.32	3.79	2.53
05/08/96								
06/08/96								
07/08/96	4.74	1.58	0.47	0.47	8.53	3.32	1.42	0.79
08/08/96								
09/08/96								
10/08/96								
11/08/96	12.64	6.79	4.74	3.63	19.43	10.59	7.90	5.69
12/08/96								
13/08/96	11.53	7.27	5.69	5.69	17.06	11.22	9.32	7.58
14/08/96								
15/08/96	14.00	7.62	5.60	4.20	20.23	11.36	8.71	6.85
16/08/96								
17/08/96								
18/08/96	12.45	5.60	3.58	2.18	18.05	8.09	4.36	2.49
19/08/96								
20/08/96								
21/08/96								
22/08/96	11.82	4.82	1.71	0.93	18.83	7.31	3.11	0.93
23/08/96								
24/08/96								
25/08/96	19.76	7.93	2.80	1.40	28.32	12.91	5.13	1.87
26/08/96								
27/08/96	21.16	9.65	4.67	2.49				
Average:	12.77	6.39	3.84	2.88	17.20	9.06	6.06	4.29
Count:	12	12	12	12	11	11	11	11
Maximum:	21.16	9.65	5.69	5.69	28.32	12.91	9.32	7.58
Minimum:	4.74	1.58	0.47	0.47	8.53	3.32	1.42	0.79
Standard Deviation:	4.10	1.94	1.60	1.52	4.76	2.56	2.48	2.47

PERIOD 3.5.2
SUMMARY DATA 8
LOW FERROUS-FERRIC TO R1 ANAEROBIC, LOW P, LOW ACETATE

DATE	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
27/07/96	0.0	0.0	6.2	20.3	20.0
28/07/96	0.0	0.0	6.2	20.4	20.2
29/07/96	0.0	0.0	6.2	20.0	19.8
30/07/96	0.0	0.0	6.2	20.2	19.6
31/07/96	0.0	0.0	6.2	20.4	20.1
01/08/96	0.0	0.0	6.2	20.5	20.3
02/08/96	0.0	0.0	6.2	20.3	19.8
03/08/96	0.0	0.0	6.2	20.3	20.0
04/08/96	0.0	0.0	6.2	20.0	19.7
05/08/96	0.0	0.0	6.2	19.8	19.6
06/08/96	0.0	0.0	6.2	19.7	19.7
07/08/96	0.0	0.0	6.2	19.8	19.9
08/08/96	0.0	0.0	6.2	19.5	19.4
09/08/96	0.0	0.0	6.2	19.8	
10/08/96	0.0	0.0	6.2	20.2	20.3
11/08/96	0.0	0.0	6.2	19.5	19.2
12/08/96	0.0	0.0	6.2	19.7	19.7
13/08/96	0.0	0.0	6.2	19.6	20.0
14/08/96	0.0	0.0	6.2	19.2	18.8
15/08/96	0.0	0.0	6.2	19.3	18.9
16/08/96	0.0	0.0	6.2	20.1	20.1
17/08/96	0.0	0.0	6.2	19.5	19.4
18/08/96	0.0	0.0	6.2	19.4	19.3
19/08/96	0.0	0.0	6.2	19.3	19.0
20/08/96	0.0	0.0	6.2	19.8	19.3
21/08/96	0.0	0.0	6.2	19.6	19.4
22/08/96	0.0	0.0	6.2	19.0	18.9
23/08/96	0.0	0.0	6.2	20.0	19.8
24/08/96	0.0	0.0	6.2	20.3	20.3
25/08/96	0.0	0.0	6.2	20.2	20.2
26/08/96	0.0	0.0	6.2	19.2	19.2
27/08/96	0.0	0.0	6.2	19.7	
Average:				19.8	19.7
Count:	32	32	32	32	30
Maximum:	0.0	0.0	6.2	20.5	20.3
Minimum:	0.0	0.0	6.2	19.0	18.8
Standard Deviation:				0.4	0.4

APPENDIX 5

UCT UNITS AT DARVILL
SUMMARY DATA 1
PERIOD 3.6.1. LOW FERRIC, AE1, LOW P, WITH BICARB.

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
21/08/97	100	35.8	36.2	13.84	15.64	475	49	53	26.70	5.39	2.00
22/08/97	100	36.2	36.2	14.45	16.05	468	45	47	19.50	3.49	2.00
23/08/97	100	35.8	35.8	14.80	14.90						
24/08/97	100	36.5	36.0	14.90	15.50						
25/08/97	100	35.5	35.0	16.47	14.89	401	23	48	22.40	2.00	2.00
26/08/97	100	35.5	36.5	16.80	15.31	392	37	24	26.40	2.00	2.00
27/08/97	100	36.7	35.3			379	34	37	28.10	2.00	2.00
28/08/97	100	37.2	36.7	13.34	13.35	324	28	49	34.40	2.00	2.00
29/08/97	100	36.7	35.8	13.41	14.87	392	64	64	22.20	5.53	2.00
30/08/97	100	35.5	36.5	13.10	15.20						
31/08/97	100	36.2									
01/09/97	100	36.2	36.5	13.56	14.12	389	25	38	28.40	2.00	2.00
02/09/97	100	36.2	34.6	13.28	13.85	393		52	28.70		2.00
03/09/97	100	36.0	36.5	13.51	13.55	288	34	28	21.80	2.00	2.00
04/09/97	100	37.0	36.2	14.81	15.41	517	82	63	37.80	3.11	3.13
05/09/97	100	36.0	36.0	13.60	15.66	145	34	101	43.30	3.69	3.67
06/09/97	100	35.8	35.8	15.00	16.90		34	46	39.40	3.90	4.67
07/09/97	100	36.0	36.2	14.69	15.89						
08/09/97	100	35.0	36.5	12.68	14.86						
09/09/97	100	37.4	35.8	12.46	14.85	382	17	36	38.80	2.00	2.00
10/09/97	100	35.8	36.5	12.70	14.99	392		40	33.50	2.00	2.00
11/09/97	100	35.3	35.8	12.00	14.63	341	25	40	36.30	2.00	2.00
12/09/97	100	36.0	36.5	12.40	12.62	293		86	35.40	2.00	2.00
13/09/97	100	36.0	35.0	11.20	12.70						
14/09/97	100	36.2	35.5	10.65	12.57						
15/09/97	100	35.5	34.8	11.34	13.17	319	99	86	26.60	2.00	2.00
16/09/97	100	36.5	36.7	10.62	11.54	280	83	85	23.60	2.00	2.00
17/09/97	100	36.0	36.5	9.66	11.45	345	78	41	29.00	2.00	2.00
18/09/97	100	36.0	36.5		12.22	409		62	18.10	2.00	2.00
19/09/97	100	36.2	36.2		13.56	373	89	88	34.60	2.00	2.00
20/09/97	100	31.7	36.2	12.06	14.08						
21/09/97	100	32.9	34.3	11.80	13.90						
22/09/97	100	34.6	36.0	11.76	14.32	422		85	33.50	2.00	2.00
23/09/97	100	34.1	33.6	11.30	12.30	360	68	72	32.90	2.00	2.00
24/09/97	100	35.0	34.3	11.13	12.47	370	69	76	33.00	2.00	2.00
25/09/97	100	35.3	34.6	11.46	13.44	333	68	75	30.80	2.00	2.00
26/09/97	100	36.5	36.5	12.39	13.81	531	48	56	36.70	2.00	2.00
27/09/97	100	36.2	35.5	12.20	13.50						
28/09/97	100	36.5	36.0	14.40	15.77						
29/09/97	100	36.5	37.0	14.66	14.89	537	48	90	38.90	2.00	2.00
30/09/97	100	35.0	35.5	13.76	13.98	483		47	31.30		2.00
01/10/97	100	35.5	34.8	13.54		450	38	41	36.20	2.00	2.00
02/10/97	100	35.8	36.2	14.01		706	65	37	33.00	2.00	3.25
03/10/97	100	35.8	34.8	15.60	16.40	617	65	65	33.70	2.00	2.00
04/10/97	100	36.5	35.5								
Average:	100	35.8	35.8	13.13	14.23	403	52	58	31.09	2.44	2.21
Count:	45	45	44	40	40	31	26	32	32	30	32
Maximum:	100	37.4	37.0	16.80	16.90	706	99	101	43.30	5.53	4.67
Minimum:	100	31.7	33.6	9.66	11.45	145	17	24	18.10	2.00	2.00
Standard Deviation:	0	1.0	0.8	1.61	1.33	105	23	20	6.19	0.97	0.60

UCT UNITS AT DARVILL
SUMMARY DATA 2
PERIOD 3.6.1

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	mgP/gVSS R1	mgP/gVSS R2
21/08/97	10.77	0.25	0.57	10.52	10.20	88.37	91.81
22/08/97	10.90	0.26	0.58	10.64	10.32	89.18	95.93
23/08/97							
24/08/97							
25/08/97	10.97	0.25	0.25	10.72	10.72	74.76	81.78
26/08/97	10.71	0.25	0.25	10.46	10.46	84.61	88.19
27/08/97	10.38	0.25	0.25	10.13	10.13	82.99	97.44
28/08/97	8.09	0.25	0.25	7.84	7.84	81.36	89.41
29/08/97	11.17	0.25	0.25	10.92	10.92	74.22	91.11
30/08/97							
31/08/97							
01/09/97	11.47		1.62		9.85	74.77	83.67
02/09/97	10.63		0.25		10.38		101.58
03/09/97	10.57	0.70	0.25	9.87	10.32	78.52	100.97
04/09/97	8.52	0.25	0.25	8.27	8.27	84.56	96.17
05/09/97	7.58	0.25	0.25	7.33	7.33	76.24	85.98
06/09/97	7.30	0.25	0.25	7.05	7.05	77.37	86.90
07/09/97							
08/09/97							
09/09/97	7.68	0.25	0.25	7.43	7.43	76.89	87.07
10/09/97	7.00	0.25	0.25	6.75	6.75	73.31	85.72
11/09/97	7.90	0.25	0.25	7.65	7.65	83.88	90.42
12/09/97	11.79		0.25		11.54	81.88	92.32
13/09/97							
14/09/97							
15/09/97	11.02	0.60	0.25	10.42	10.77	77.67	91.42
16/09/97	10.70	0.75	0.25	9.95	10.45	85.28	102.49
17/09/97	11.12	1.08	0.55	10.04	10.57	93.21	98.80
18/09/97	9.20		0.61		8.59	86.48	95.51
19/09/97	10.24	0.59	0.25	9.65	9.99	80.78	95.20
20/09/97							
21/09/97							
22/09/97	9.99	0.25	0.25	9.74	9.74	80.02	89.75
23/09/97	9.56	0.25	0.25	9.31	9.31	79.17	88.34
24/09/97	9.55	0.25	0.25	9.30	9.30	79.16	89.55
25/09/97	9.40	0.56	0.52	8.84	8.88	85.15	97.29
26/09/97	8.87	0.53	0.73	8.34	8.14	79.65	89.62
27/09/97							
28/09/97							
29/09/97	13.41	0.25	0.25	13.16	13.16	74.94	84.24
30/09/97	12.96		0.53		12.43	71.19	83.45
01/10/97	12.79	0.53	0.25	12.26	12.54	75.06	82.86
02/10/97	16.25	2.00	2.35	14.25	13.90	72.64	86.19
03/10/97	15.77	0.55	0.25	15.22	15.52	79.79	95.23
04/10/97							
Average:	10.45	0.45	0.43	9.85	10.01	80.10	91.14
Count:	32	27	32	27	32	31	32
Maximum:	16.25	2.00	2.35	15.22	15.52	93.21	102.49
Minimum:	7.00	0.25	0.25	6.75	6.75	71.19	81.78
Standard Deviation:	2.15	0.37	0.43	2.05	2.00	5.24	5.68

UCT UNITS AT DARVILL
SUMMARY DATA 3
PERIOD 3.6.1

DATE	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
21/08/97	2135	1423	1996	1455	66.7	72.9		
22/08/97	2098	1434	1772	1296	68.4	73.1		
23/08/97								
24/08/97								
25/08/97	2329	1577	1733	1276	67.7	73.6		
26/08/97	2085	1360	1764	1269	65.2	71.9	67	68
27/08/97	1988	1356	1598	1210	68.2	75.7	66	75
28/08/97	2034	1360	1745	1294	66.9	74.2	68	70
29/08/97	2069	1423	1720	1256	68.8	73.0		
30/08/97								
31/08/97								
01/09/97	2047	1362	1893	1394	66.5	73.6	68	74
02/09/97			1833	1288		70.3		
03/09/97	1964	1321	1695	1149	67.3	67.8	66	77
04/09/97	1848	1222	1521	1166	66.1	76.7		
05/09/97	1972	1351	1666	1251	68.5	75.1	64	87
06/09/97	1995	1344	1708	1249	67.4	73.1		
07/09/97								
08/09/97								
09/09/97	1917	1259	1637	1183	65.7	72.3		
10/09/97	1935	1245	1673	1270	64.3	75.9	62	90
11/09/97	1744	1123	1521	1150	64.4	75.6	69	99
12/09/97	1901	1234	1457	1098	64.9	75.4	68	106
13/09/97								
14/09/97								
15/09/97	1911	1277	1618	1167	66.8	72.1	60	111
16/09/97	1861	1209	1556	1095	65.0	70.4	59	109
17/09/97	1764	1120	1563	1093	63.5	69.9	62	109
18/09/97	1840	1177	1635	1158	64.0	70.8	60	110
19/09/97	1860	1236	1674	1203	66.5	71.9		
20/09/97								
21/09/97								
22/09/97	1772	1158	1581	1156	65.3	73.1		
23/09/97	1772	1158	1581	1156	65.3	73.1	62	104
24/09/97	1787	1220	1546	1144	68.3	74.0	62	103
25/09/97	1723	1115	1450	1043	64.7	71.9	64	103
26/09/97	1791	1188	1465	1125	66.3	76.8	67	119
27/09/97								
28/09/97								
29/09/97	1929	1321	1685	1261	68.5	74.8	67	142
30/09/97	1890	1312	1705	1273	69.4	74.7	71	70
01/10/97	1920	1332	1752	1282	69.4	73.2	73	143
02/10/97	2052	1467	1737	1305	71.5	75.1	68	161
03/10/97	1995	1352	1705	1257	67.8	73.7	35	147
04/10/97								
Average:	1933	1291	1662	1218	66.8	73.3	64	104
Count:	31	31	32	32	31	32	22	22
Maximum:	2329	1577	1996	1455	71.5	76.8	73	161
Minimum:	1723	1115	1450	1043	63.5	67.8	35	68
Standard Deviation:	133	110	122	89	1.8	2.0	7	26

CT UNITS AT DARVILL
SUMMARY DATA 4
PERIOD 3.6.1

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
21/08/97	7.41	7.36	7.60	7.68	7.78	7.86	0.5	0.0		
22/08/97							0.5	0.0		
23/08/97							0.5	0.0		
24/08/97							0.5	0.0		
25/08/97	7.35	7.33	7.50	7.61	7.61	7.78	0.5	0.0	192.7	232.7
26/08/97	7.36	7.29	7.48	7.54	7.64	7.73	0.5	0.0		
27/08/97	7.33	7.23	7.47	7.59	7.63	7.79	0.5	0.0	203.9	242.8
28/08/97	7.43	7.33	7.60	7.61	7.75	7.80	0.5	0.0		
29/08/97							0.5	0.0		
30/08/97							0.5	0.0		
31/08/97	7.52	7.36	7.55	7.69	7.71	7.80	0.5	0.0		
01/09/97	7.02	6.98	7.12	7.15	7.26	7.32	0.5	0.0	208.3	252.1
02/09/97	7.64	7.52	7.62	7.70	7.74	7.82	0.5	0.0		
03/09/97	7.53	7.45	7.62	7.66	7.77	7.77	0.5	0.0	208.4	249.8
04/09/97	7.51	7.36	7.54	7.68	7.68	7.79	0.5	0.0		
05/09/97							0.5	0.0		
06/09/97							0.5	0.0	159.0	209.6
07/09/97	7.12	7.02	7.06	7.18	7.20	7.31	0.5	0.0		
08/09/97	7.15	7.02	7.12	7.15	7.24	7.30	0.5	0.0		
09/09/97	7.02	7.02	7.02	7.13	7.13	7.20	0.5	0.0		
10/09/97	7.02	7.02	7.01	7.09	7.16	7.24	0.5	0.0	162.1	218.6
11/09/97	7.45	7.31	7.67	7.56	7.70	7.78	0.5	0.0		
12/09/97							0.5	0.0		
13/09/97							0.5	0.0		
14/09/97	7.02	7.02	7.02	7.24	7.15	7.43	0.5	0.0		
15/09/97	7.02	7.02	7.02	7.28	7.17	7.51	0.5	0.0	200.3	241.4
16/09/97	7.02	7.03	7.10	7.24	7.22	7.45	0.5	0.0		
17/09/97	7.03	7.03	7.05	7.25	7.22	7.45	0.5	0.0	196.9	230.2
18/09/97	7.45	7.29	7.49	7.49	7.60	7.69	0.5	0.0		
19/09/97							0.5	0.0		
20/09/97							0.5	0.0		
21/09/97	7.50	7.33	7.51	7.63	7.67	7.80	0.5	0.0		
22/09/97							0.5	0.0	263.0	151.6
23/09/97	7.52	7.32	7.60	7.53	7.65	7.70	0.5	0.0		
24/09/97	7.48	7.36	7.48	7.50	7.59	7.71	0.5	0.0	205.1	225.3
25/09/97	7.44	7.25	7.54	7.53	7.70	7.75	0.5	0.0		
26/09/97							0.5	0.0		
27/09/97							0.5	0.0		
28/09/97	7.02	7.02	7.15	7.36	7.29	7.54	0.5	0.0		
29/09/97	7.03	7.02	7.16	7.38	7.31	7.57	0.5	0.0	206.8	238.4
30/09/97	7.02	7.02	7.13	7.35	7.25	7.52	0.5	0.0		
01/10/97	7.12	7.01	7.25	7.56	7.39	7.87	0.5	0.0	201.8	210.4
02/10/97	7.20	7.01	7.25	7.30	7.39	7.45	0.5	0.0		
03/10/97	7.14	7.02	7.33	7.33	7.42	7.53	0.5	0.0		
04/10/97							0.5	0.0		
Average:	7.26	7.18	7.34	7.43	7.47	7.61	0.5	0.0	200.7	225.2
Count:	30	30	30	30	30	30	45	45	12	12
Maximum:	7.64	7.52	7.67	7.70	7.78	7.87	0.5	0.0	263.0	252.1
Minimum:	7.02	6.98	7.01	7.09	7.13	7.20	0.5	0.0	159.0	151.6
Standard Deviation:	0.21	0.17	0.23	0.19	0.23	0.20	0.0	0.0	24.8	25.9

UCT UNITS AT DARVILL
SUMMARY DATA 5
PERIOD 3.6.2a

DATE	NO3 IN	NO3 E1	NO3 E2	NH4 IN	NH4 E1	NH4 E2	SRP IN	SRP E1	SRP E2
21/08/97	0.25	6.25	5.33	21.20	0.25	0.69	9.80	0.15	0.56
22/08/97	0.25	6.73	5.72	19.40	1.19	0.25	7.74	0.23	0.39
23/08/97									
24/08/97									
25/08/97	0.25	6.45	5.31	17.40	1.27	0.25	7.30	0.17	0.20
26/08/97	0.25	6.60	5.89	23.80	2.08	0.25	9.22	0.22	0.17
27/08/97	0.25	6.90	5.82	19.60	0.83	0.25	8.04	0.12	0.14
28/08/97	0.25	6.46	5.01	22.30	0.25	0.25	7.98	0.10	0.13
29/08/97	0.25	6.35	5.03	15.40		0.25	7.66	0.46	0.14
30/08/97									
31/08/97									
01/09/97	0.25	8.33	6.46	22.20		0.25	7.94	0.60	1.35
02/09/97	0.25		6.74	19.40		1.19	7.60		0.15
03/09/97	0.25	8.54	7.35	21.10	0.62	0.72	7.34	0.38	0.10
04/09/97	0.25	9.00	7.90	24.30	0.71	0.25	5.22	0.11	0.13
05/09/97	0.25	11.40	10.50	24.70	0.25	0.25	5.30	0.05	0.05
06/09/97	0.25	11.60	11.40	26.40	0.25	1.60	5.62	0.05	0.05
07/09/97									
08/09/97									
09/09/97	0.25	11.80	11.60	24.00	1.06	0.25	5.40	0.18	0.05
10/09/97	0.25	11.10	10.90	25.60	1.15	0.25	5.58	0.18	0.05
11/09/97	0.25	10.40	10.20	30.40	0.25	1.89	5.64	0.14	0.05
12/09/97	0.25	8.51	8.31	16.10		0.25	8.16		0.20
13/09/97									
14/09/97									
15/09/97	0.25	5.91	4.70	15.50	1.46	0.25	7.78	0.31	0.17
16/09/97	0.25	6.61	5.61	15.50	0.66	0.25	7.90	0.32	0.16
17/09/97	0.25	7.09	5.80	14.20	0.53	0.25	7.88	0.65	0.21
18/09/97	0.25	8.14	6.41	20.10		0.25	6.20		0.30
19/09/97	0.25	8.40	7.03	27.20		0.25	7.46	0.34	0.19
20/09/97									
21/09/97									
22/09/97	0.25	6.80	6.35	20.20		0.25	7.20	0.20	0.17
23/09/97	0.25	6.44	6.51	18.60	3.20	1.17	7.02	0.27	0.18
24/09/97	0.25	6.69	6.56	21.20	0.25	0.25	7.20	0.16	0.19
25/09/97	0.25	6.57	6.19	22.10	2.32	0.25	6.52	0.34	0.21
26/09/97	0.25	3.77	3.15	17.10	2.11	0.57	5.90	0.32	0.68
27/09/97									
28/09/97									
29/09/97	0.25	1.93	1.81	24.10	0.25	0.25	8.84	0.14	0.05
30/09/97	0.25		1.87	24.60		2.08	9.84		0.20
01/10/97	0.25	2.14	1.73	23.70	0.54	0.25	9.46	0.11	0.05
02/10/97	0.25	2.61	2.79	18.70	1.67	0.25	10.44	0.15	0.14
03/10/97	0.25	2.92	3.56	21.00	1.89	0.25	10.82	0.19	0.05
04/10/97									
========	====	=====	=====	=====	====	====	=====	====	====
Average:	0.25	7.08	6.24	21.16	1.04	0.50	7.56	0.24	0.21
Count:	32	30	32	32	24	32	32	28	32
Maximum:	0.25	11.80	11.60	30.40	3.20	2.08	10.82	0.65	1.35
Minimum:	0.25	1.93	1.73	14.20	0.25	0.25	5.22	0.05	0.05
Standard Deviation:	0.00	2.61	2.60	3.80	0.80	0.50	1.49	0.15	0.25

UCT UNITS AT DARVILL
SUMMARY DATA 6
PERIOD 3.6.1

DATE	fAN NO3 R1	fAX NO3 R1	fAR1 NO3 R1	fAR2 NO3 R1	fAN NO3 R2	fAX NO3 R2	fAR1 NO3 R2	fAR2 NO3 R2
21/08/97	0.25	3.87	6.52	6.97	0.25	2.22	5.48	6.12
22/08/97								
23/08/97								
24/08/97								
25/08/97	0.25	2.67	5.61	6.60	0.25	1.71	5.21	6.33
26/08/97	0.25	2.88	5.76	6.60	0.25	0.25		
27/08/97								
28/08/97								
29/08/97								
30/08/97								
31/08/97								
01/09/97					0.25	2.07	7.91	6.37
02/09/97					0.25	3.22	7.28	7.33
03/09/97								
04/09/97	0.25	4.95	9.24	10.20	0.25	2.76	7.58	9.27
05/09/97	0.25	4.45	7.75	8.49				
06/09/97	0.25	6.31	11.60	11.80	0.25	6.33	10.70	11.70
07/09/97								
08/09/97								
09/09/97	0.25	6.15	10.90	11.70	0.25	6.54	10.50	11.50
10/09/97								
11/09/97	0.25	5.85	10.50	10.60	0.25	5.55	9.17	10.40
12/09/97								
13/09/97								
14/09/97								
15/09/97	0.25	3.74	6.48	6.45	0.25	2.28	5.17	5.01
16/09/97	0.25	3.62	6.68	6.69	0.25	2.94	5.82	5.70
17/09/97								
18/09/97	0.25	4.02	8.47	8.57	0.25	3.24	6.36	7.05
19/09/97								
20/09/97								
21/09/97								
22/09/97	0.25	3.46	6.80	7.05	0.25	3.38	6.15	6.49
23/09/97								
24/09/97	0.25	3.68	6.74	6.68	0.25	3.72	6.72	6.51
25/09/97	0.25	3.66	6.86	6.71	0.25	3.36	6.38	6.21
26/09/97								
27/09/97								
28/09/97								
29/09/97	0.25	0.25	2.25	2.03	0.25	0.25	2.27	1.93
30/09/97	0.25	0.25	2.35	2.01	0.25	0.25	2.21	1.93
01/10/97								
02/10/97	0.25	1.46	3.47	3.29	0.25	1.78	3.94	3.76
03/10/97								
04/10/97								
Average:	0.25	3.60	6.94	7.20	0.25	2.88	6.40	6.68
Count:	17	17	17	17	18	18	17	17
Maximum:	0.25	6.31	11.60	11.80	0.25	6.54	10.70	11.70
Minimum:	0.25	0.25	2.25	2.01	0.25	0.25	2.21	1.93
Standard Deviation:	0.00	1.72	2.63	2.83	0.00	1.81	2.33	2.74

UCT UNITS AT DARVILL
SUMMARY DATA 6.1
PERIOD 3.6.1

DATE	fAN NH4 R1	fAX NH4 R1	fAE1 NH4 R1	fAE2 NH4 R1	fAN NH4 R2	fAX NH4 R2	fAE1 NH4 R2	fAE2 NH4 R2
21/08/97	10.10	2.85	2.05	0.68	9.00	4.83	1.62	0.25
22/08/97								
23/08/97								
24/08/97								
25/08/97	11.90	3.99	1.49	0.25	9.90	4.56	1.65	0.25
26/08/97	8.34	4.23	1.10	0.25	9.84	4.62		
27/08/97								
28/08/97								
29/08/97								
30/08/97								
31/08/97								
01/09/97	6.95	3.06	0.25	0.25	6.84	4.20	0.63	0.65
02/09/97					7.20	6.60	1.74	1.01
03/09/97								
04/09/97	12.70	6.96	2.10	1.18	10.90	6.69	2.51	1.07
05/09/97	13.60	6.71	1.83	1.04				
06/09/97	13.30	5.61	0.60	0.25	10.30	4.71	0.69	0.25
07/09/97								
08/09/97								
09/09/97	9.93	4.65	0.93	0.25	12.30	5.49	0.88	0.25
10/09/97								
11/09/97	9.42	3.48	0.25	0.25	10.50	3.48	0.73	0.25
12/09/97								
13/09/97								
14/09/97								
15/09/97	5.85	3.38	0.25	0.25	5.46	3.44	0.58	0.80
16/09/97	7.05	3.30	1.50	0.25	6.63	2.78	0.25	0.25
17/09/97								
18/09/97	15.60	4.94	0.65	0.25	7.30	3.44	0.89	0.25
19/09/97								
20/09/97								
21/09/97								
22/09/97	13.20	4.38	0.87	0.25	6.55	4.16	1.00	0.25
23/09/97								
24/09/97	14.60	3.76	0.54	0.25	7.45	4.76	0.72	0.25
25/09/97	8.15	3.74	0.25	0.25	7.75	3.62	0.25	0.25
26/09/97								
27/09/97								
28/09/97								
29/09/97	15.00	5.34	0.95	2.54	9.10	4.26	0.85	0.25
30/09/97	8.00	4.40	0.72	0.25	8.80	4.30	0.69	0.94
01/10/97								
02/10/97	7.10	5.90	0.80	0.25	6.30	3.70	0.66	0.25
03/10/97								
04/10/97								
Average:	10.60	4.48	0.95	0.50	8.45	4.42	0.96	0.44
Count:	18	18	18	18	18	18	17	17
Maximum:	15.60	6.96	2.10	2.54	12.30	6.69	2.51	1.07
Minimum:	5.85	2.85	0.25	0.25	5.46	2.78	0.25	0.25
Standard Deviation:	3.08	1.18	0.59	0.57	1.84	1.01	0.57	0.30

CT UNITS AT DARVILL
JMMARY DATA 7
ERIOD 3.6.1

DATE	fAN TP R1	fAX TP R1	fAB1 TP R1	fAB2 TP R1	fAN TP R2	fAX TP R2	fAB1 TP R2	fAB2 TP R2
21/08/97	32.10	5.81	2.53	1.15	35.12	16.52	4.40	0.80
22/08/97								
23/08/97								
24/08/97								
25/08/97	32.50	11.08	1.22	0.25	44.05	19.35	3.80	0.95
26/08/97	29.48	10.68	1.49	0.25	47.80	20.38		
27/08/97								
28/08/97								
29/08/97								
30/08/97								
31/08/97								
01/09/97					37.46	17.31	1.01	0.25
02/09/97					36.45	17.66	2.31	0.25
03/09/97								
04/09/97	24.06	8.02	0.84	0.83	35.62	18.83	2.48	0.25
05/09/97	18.90	4.90	0.25	0.25				
06/09/97	23.64	7.39	0.74	0.25	33.26	11.03	10.20	0.25
07/09/97								
08/09/97								
09/09/97	18.43	5.40	0.59	0.25	29.76	9.59	0.77	0.25
10/09/97								
11/09/97	15.24	4.43	0.61	0.54	26.28	8.67	1.13	0.25
12/09/97								
13/09/97								
14/09/97								
15/09/97	23.98	8.01	1.86	0.74	38.16	13.46	2.44	0.25
16/09/97	26.60	8.35	1.79	0.63	41.84	13.77	2.66	0.25
17/09/97								
18/09/97	30.14	9.92	1.63	0.25	43.00	15.41	4.28	0.25
19/09/97								
20/09/97								
21/09/97								
22/09/97	25.26	7.84	2.41	0.25	44.72	16.78	3.41	0.25
23/09/97								
24/09/97	23.44	7.02	1.34	0.25	41.30	15.31	3.34	0.25
25/09/97	18.92	5.88	0.98	0.25	33.20	11.37	2.44	0.55
26/09/97								
27/09/97								
28/09/97								
29/09/97	26.96	8.99	0.87	0.25	47.50	18.23	1.88	0.25
30/09/97	29.74	10.59	0.99	0.25	52.85		1.39	0.25
01/10/97								
02/10/97	32.02	11.57	1.39	0.25	53.70	19.88	2.63	0.81
03/10/97								
04/10/97								
========	=====	=====	====	====	=====	=====	=====	====
Average:	25.38	7.99	1.27	0.41	40.12	15.50	2.97	0.37
Count:	17	17	17	17	18	17	17	17
Maximum:	32.50	11.57	2.53	1.15	53.70	20.38	10.20	0.95
Minimum:	15.24	4.43	0.25	0.25	26.28	8.67	0.77	0.25
Standard Deviation:	5.13	2.18	0.62	0.27	7.35	3.54	2.09	0.23

UCT UNITS AT DARVILL
SUMMARY DATA 7.1
PERIOD 3.6.1

DATE	fAN SRP R1	fAX SRP R1	fAB1 SRP R1	fAB2 SRP R1	fAN SRP R2	fAX SRP R2	fAB1 SRP R2	fAB2 SRP R2
21/08/97	25.50	5.08	2.33	1.15	32.88	15.06	4.41	0.75
22/08/97								
23/08/97								
24/08/97								
25/08/97	28.20	8.67	1.08	0.14	42.35	15.48	3.28	0.95
26/08/97	28.92	9.84	0.93	0.48	45.80	20.22		
27/08/97								
28/08/97								
29/08/97								
30/08/97								
31/08/97								
01/09/97					30.81	14.52	0.33	0.25
02/09/97					35.95	17.05	2.07	0.19
03/09/97								
04/09/97	22.05	7.20	0.64	0.55	35.58	16.47	2.33	0.26
05/09/97	17.14	3.90	0.25	0.12				
06/09/97	21.66	7.23	0.70	0.25	32.61	10.86		0.21
07/09/97								
08/09/97								
09/09/97	17.46	5.07	0.41	0.10	25.11	9.24	0.71	0.10
10/09/97								
11/09/97	14.34	4.29	0.51	0.18	23.25	8.19	1.13	0.11
12/09/97								
13/09/97								
14/09/97								
15/09/97	18.99	7.36	1.48	0.42	32.28	13.16	2.43	0.27
16/09/97	22.74	7.96	1.64	0.42	40.12	12.90	2.39	0.37
17/09/97								
18/09/97	24.20	8.24	1.44	0.31	39.10	13.60	3.83	0.29
19/09/97								
20/09/97								
21/09/97								
22/09/97	22.00	6.98	1.20	0.23	43.90	15.66	2.92	0.25
23/09/97								
24/09/97	21.65	6.08	1.11	0.27	37.00	12.76	2.55	0.57
25/09/97	16.90	5.00	0.77	0.21	31.50	9.90	2.25	0.36
26/09/97								
27/09/97								
28/09/97								
29/09/97	26.60	8.08	0.71	0.17	45.90	15.92	1.70	0.17
30/09/97	24.55	9.34	0.73	0.16	48.95	18.54	1.38	0.05
01/10/97								
02/10/97	29.65	9.40	1.28	0.18	47.50	18.10	2.63	0.63
03/10/97								
04/10/97								
Average:	22.50	7.04	1.01	0.31	37.26	14.31	2.27	0.34
Count:	17	17	17	17	18	18	16	17
Maximum:	29.65	9.84	2.33	1.15	48.95	20.22	4.41	0.95
Minimum:	14.34	3.90	0.25	0.10	23.25	8.19	0.33	0.05
Standard Deviation:	4.37	1.80	0.50	0.25	7.30	3.22	1.04	0.24

T UNITS DARVILL
MMARY DATA 8
RIOD 3.6.1

DATE	MAMAIS SOLUBLE COD IN	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
21/08/97	214		6.65		19.5	19.4
22/08/97	224		6.65		20.2	20.3
23/08/97			6.65		19.6	19.6
24/08/97			6.65		18.8	19.9
25/08/97	208		6.65		20.7	21.2
26/08/97	195		6.65		20.2	20.4
27/08/97	193		6.65			
28/08/97	176		6.65		20.6	20.9
29/08/97	233		6.65		19.8	20.0
30/08/97			6.65		19.5	19.5
31/08/97			6.65			
01/09/97	159		6.65		18.9	18.6
02/09/97	183		6.65		19.8	19.9
03/09/97	165		6.65		19.9	20.0
04/09/97	232		6.65		19.5	19.7
05/09/97	194		6.65		19.8	20.0
06/09/97			6.65		19.8	20.0
07/09/97			6.65		19.3	19.1
08/09/97			6.65		19.7	19.1
09/09/97	191		6.65		19.5	19.2
10/09/97	188		6.65		19.7	19.6
11/09/97	176		6.65		19.9	20.0
12/09/97	84		6.65		19.3	19.5
13/09/97			6.65		19.4	19.7
14/09/97			6.65		19.6	19.9
15/09/97	90		6.65		20.0	20.3
16/09/97	187		6.65		19.2	19.4
17/09/97	161		6.65		18.6	18.5
18/09/97	213		6.65		18.4	18.2
19/09/97	201		6.65			18.3
20/09/97			6.65		19.3	19.6
21/09/97			6.65		18.9	19.0
22/09/97	162		6.65		19.6	20.0
23/09/97	214		6.65		19.4	19.7
24/09/97	450		6.65		19.2	19.6
25/09/97	407		6.65		20.3	20.9
26/09/97	367		6.65		21.6	1.5
27/09/97			6.65		20.6	20.9
28/09/97			6.65		21.4	21.9
29/09/97	353		6.65		20.0	20.4
30/09/97	325		6.65		18.9	19.2
01/10/97	290		6.65		19.5	
02/10/97	284		6.65		20.3	
03/10/97	412		6.65		21.6	22.0
04/10/97			6.65			
Average:	230				19.8	19.4
Count:	31	0	45	0	41	40
Maximum:	450		6.65		21.6	22.0
Minimum:	84		6.65		18.4	1.5
Standard Deviation:	88				0.7	3.0

UCT UNITS AT DARVILL
SUMMARY DATA 1
PERIOD 3.6.2a. LOW FERRIC. AE1. LOW P. NO BICARB.

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
05/10/97	100	35.5	35.8	14.23							
06/10/97	100	36.7	36.0	15.06	17.55	592	71	79	33.90	2.00	2.00
07/10/97	100	36.0	35.8	11.73	13.23	457	54	43	32.10	2.00	2.00
08/10/97	100	36.5	36.7	11.55	13.18	470	54	47	33.80	2.00	2.00
09/10/97	100	35.8	36.2	11.08	18.60	421	51	37	32.30	2.00	2.00
10/10/97	100	35.5	36.2	11.20	14.67	548	60	63	31.90	2.00	2.00
11/10/97	100	36.5	36.0	10.73	13.82						
12/10/97	100	37.0	37.4	10.59	13.49						
13/10/97	100	36.5	36.7	9.77		455	63	60	29.40	2.00	2.00
14/10/97	100	36.0	36.5	10.98	13.84	415	60	60	37.00	2.00	2.00
15/10/97	100	35.3	34.8	9.50	11.80	349	60	56	35.50	2.00	2.00
16/10/97	100	35.5	36.0	9.90	12.50	423	37	37	35.00	2.00	2.00
17/10/97	100	35.0	35.0	10.20	12.70	299	40	37	32.90	2.00	2.00
18/10/97	100	36.0	36.0	11.10	13.40						
19/10/97	100	34.8	35.3	11.05	13.06						
20/10/97	100	36.0	36.5	12.10	14.40	410	38	47	35.40	2.00	2.00
21/10/97	100	35.5	36.0	11.80	14.30	384	33	40	33.80	2.00	2.00
22/10/97	100	37.2	36.5	11.45	13.24	427	30	34	35.90	2.00	2.00
23/10/97	100	36.0	35.3	10.20	10.97	406	34	39	39.10	2.00	2.00
24/10/97	100	36.5	35.8	10.17	11.65	402	40	49	32.60	2.00	2.00
25/10/97	100	35.8	35.8	9.42	10.54						
26/10/97	100	35.0	35.0	10.60	11.30						
27/10/97	100	35.8	35.0	8.30	9.20	512	165	35	37.60	2.00	2.00
28/10/97	100	36.2	35.5	10.90	12.50	486	41	44	36.80	2.00	2.00
29/10/97	100	35.3	34.6	13.20	15.00	533	50	53	33.60	2.00	2.00
30/10/97	100	36.0	36.5	13.02	14.25	356	28	35	33.00	2.00	2.00
31/10/97	100	34.6	35.0	12.00	13.30						
01/11/97	100	35.5	35.5	11.60	13.30						
02/11/97	100	34.8	34.3	12.49	15.45	465	26	23	30.80	2.00	2.00
03/11/97	100	35.8	36.2	11.30	13.20	506	41	41	32.80	2.00	2.00
04/11/97	100	35.0	36.7	13.20	13.90	646	41	39	32.20	2.00	2.00
05/11/97	100	36.5	37.0	11.40	15.90	505	39	42	32.40	2.00	2.00
06/11/97	100	35.0	35.3	11.50	14.01	508	45	55	35.20	2.00	2.00
07/11/97	100	36.5	36.5	12.37	12.95	484	45	49	35.80	2.00	2.00
08/11/97	100	36.2	35.8	13.80	14.12						
09/11/97	100	36.5	36.0		12.70						
10/11/97	100			10.30	10.83	306	30	37	30.30	2.00	2.00
11/11/97	100			11.92	11.94	406	33	36	28.90	2.00	2.00
12/11/97	100			10.60	11.30	374	50	40	29.00	2.00	2.00
13/11/97	100	34.8	36.2	12.50	14.00	465	36	44	36.00	2.00	3.14
14/11/97	100	36.2	35.0	10.80	15.10						
15/11/97	100	40.3	35.3	12.70	13.70						
16/11/97	100	38.6	33.8	12.50	14.20						
17/11/97	100	46.1	34.1	13.50	11.30	356	35	33	34.30	2.00	2.00
18/11/97	100	36.5	33.8	14.40	13.30	369	56	33	31.30	3.27	3.47
19/11/97	100	36.7	35.3			422	26	33	31.50	3.24	3.17
20/11/97	100	36.0	35.5								
21/11/97	100	35.5	36.0	15.60	15.50	442	36	43	25.50	2.00	2.00
22/11/97	100	35.3	35.3	11.10	12.80						
23/11/97	100	35.5	36.2	12.70	21.40						
24/11/97	100	33.8	32.6		12.00	371	37	34	26.90	2.00	2.00
25/11/97	100	33.4	31.9	10.90	10.60	420	26	24	29.10	2.00	2.00
26/11/97	100	32.2	31.4	10.50	10.90	404	42	43	31.30	2.00	2.00
27/11/97	100	33.4	32.2	10.30	11.00	369	30	31	32.80	2.00	2.00
28/11/97	100	33.1	28.6	10.90	9.20	340	20	30	29.10	2.00	2.00
29/11/97	100	32.9	26.6	10.00	8.80						
30/11/97	100	35.0	39.6	9.30	10.80						

UCT UNITS AT DARVILL
SUMMARY DATA 2
PERIOD 3.6.2a

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	mgP/gVSS R1	mgP/gVSS R2
05/10/97							
06/10/97	18.40	1.10	0.56	17.30	17.84	83.78	91.37
07/10/97	17.51	0.79	0.25	16.72	17.26	82.56	99.61
08/10/97	16.49	0.79	0.25	15.70	16.24	91.87	98.67
09/10/97	16.72	0.70	0.25	16.02	16.47	93.38	106.80
10/10/97	11.32	0.57	0.25	10.75	11.07	100.34	100.43
11/10/97							
12/10/97							
13/10/97	10.01	0.25	0.25	9.76	9.76	97.06	104.23
14/10/97	8.58	0.25	0.25	8.33	8.33	89.92	101.79
15/10/97	7.64	0.25	0.25	7.39	7.39	97.90	101.38
16/10/97	11.24	0.25	0.25	10.99	10.99	93.97	103.22
17/10/97	10.55	0.25	0.25	10.30	10.30	91.86	102.98
18/10/97							
19/10/97							
20/10/97	10.95	0.25	0.25	10.70	10.70	88.93	98.80
21/10/97	10.27	0.25	0.25	10.02	10.02	89.69	98.53
22/10/97	8.76	0.25	0.25	8.51	8.51		
23/10/97	8.50	0.25	0.25	8.25	8.25		
24/10/97	8.26	0.25	0.25	8.01	8.01	88.44	97.87
25/10/97							
26/10/97							
27/10/97	12.72	0.25	0.25	12.47	12.47	89.72	96.94
28/10/97	11.40	0.25	0.25	11.15	11.15	88.86	98.42
29/10/97	11.40	0.25	0.25	11.15	11.15	91.87	98.44
30/10/97	11.33	0.25	0.25	11.08	11.08	87.98	103.27
31/10/97							
01/11/97							
02/11/97	12.69	0.25	0.25	12.44	12.44	89.57	110.48
03/11/97	12.74	0.54	0.25	12.20	12.49	85.61	99.12
04/11/97	12.73	0.58	0.25	12.15	12.48	91.52	101.82
05/11/97	13.01	0.60	0.25	12.41	12.76	92.55	105.61
06/11/97	12.93	0.68	0.25	12.25	12.68	91.87	99.00
07/11/97	10.91	0.65	0.25	10.26	10.66	90.97	106.53
08/11/97							
09/11/97							
10/11/97	9.71	0.61	0.25	9.10	9.46	83.39	97.15
11/11/97	9.69	0.25	0.25	9.44	9.44	87.47	99.37
12/11/97	9.36	0.65	0.25	8.71	9.11	93.43	104.19
13/11/97	10.50	0.53	0.25	9.97	10.25	94.78	110.64
14/11/97							
15/11/97							
16/11/97							
17/11/97	10.44	1.62	2.64	8.82	7.80	89.73	107.61
18/11/97	11.47	2.85	0.73	8.62	10.74	92.68	105.20
19/11/97	9.57	0.56	4.08	9.01	5.49	94.57	105.64
20/11/97							
21/11/97	10.01	0.62	4.72	9.39	5.29	87.71	94.24
22/11/97							
23/11/97							
24/11/97	9.54	0.76	1.24	8.78	8.30	150.77	94.76
25/11/97	9.61	0.66	1.34	8.95	8.27	81.19	80.35
26/11/97	9.94	0.51	1.01	9.43	8.93	81.98	85.89
27/11/97	6.85	0.25	0.78	6.60	6.07	85.05	88.72
28/11/97	6.92	0.25	0.25	6.67	6.67	85.27	85.58
29/11/97							
30/11/97							

UCT UNITS AT DARVILL
SUMMARY DATA 1
PERIOD 3.6.2a, LOW FERRIC, AE1, LOW P, NO BICARB.

	DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
	01/12/97	100	33.1	34.8	12.30	11.80	340	39	36	31.00	2.00	2.00
	02/12/97	100	36.0	39.8	12.40	14.40	584	40	40	32.40	2.00	2.00
	03/12/97	100	37.4	36.7	8.30	9.00	368	42	43	21.10	2.00	2.00
	04/12/97	100	34.8	36.5			313	42	32	17.40	2.00	2.00
	05/12/97	100	37.9	36.5	8.88	9.38	270	26	26	17.60	2.00	2.00
	06/12/97	100	36.0	36.0	8.78	8.97						
	07/12/97	100	36.7	36.7	9.58	9.23						
Average:		100	35.9	35.4	11.36	12.87	427	44	41	31.77	2.06	2.09
Count:		64	61	61	59	59	43	43	43	43	43	43
Maximum:		100	46.1	39.8	15.60	21.40	646	165	79	39.10	3.27	3.47
Minimum:		100	32.2	26.6	8.30	8.80	270	20	23	17.40	2.00	2.00
Standard Deviation:		0	1.9	2.0	1.57	2.35	82	22	11	4.56	0.26	0.32

-CT UNITS AT DARVILL
UMMARY DATA 2
ERIOD 3.6.2a

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	mgP/gVSS R1	mgP/gVSS R2
01/12/97	6.39	0.58	0.65	5.81	5.74	76.15	83.99
02/12/97	7.32	0.25	0.25	7.07	7.07	75.87	79.90
03/12/97	5.22	0.25	0.25	4.97	4.97	76.27	77.46
04/12/97	5.13	0.56	0.70	4.57	4.43	75.99	73.16
05/12/97	4.96	0.25	0.25	4.71	4.71	73.16	74.22
06/12/97							
07/12/97							
.verage:	10.46	0.53	0.62	9.93	9.84	89.65	96.91
!ount:	43	43	43	43	43	41	41
!aximum:	18.40	2.85	4.72	17.30	17.84	150.77	110.64
!inimum:	4.96	0.25	0.25	4.57	4.43	73.16	73.16
-Standard Deviation:	3.02	0.45	0.94	2.92	3.25	11.53	9.61

UCT UNITS AT DARVILL
SUMMARY DATA 3
PERIOD 3.6.2a

DATE	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
05/10/97								
06/10/97	2082	1370	1810	1303	65.8	72.0	62	144
07/10/97	2057	1466	1883	1347	71.3	71.5	63	143
08/10/97	2084	1371	1950	1350	65.8	69.2	62	144
09/10/97	2071	1363	1922	1355	65.8	70.5	63	135
10/10/97	1962	1298	1879	1382	66.2	73.5		
11/10/97								
12/10/97								
13/10/97	1952	1230	1765	1240	63.0	70.3	67	136
14/10/97	1988	1313	1781	1260	66.0	70.7	65	124
15/10/97	1878	1216	1710	1223	64.7	71.5	69	129
16/10/97	1849	1218	1660	1198	65.9	72.2	70	133
17/10/97	1845	1228	1625	1188	66.6	73.1	70	135
18/10/97								
19/10/97								
20/10/97	1844	1165	1723	1205	63.2	69.9	70	128
21/10/97	1839	1199	1696	1215	65.2	71.6	65	118
22/10/97								
23/10/97								
24/10/97	1809	1190	1598	1167	65.8	73.0	69	125
25/10/97								
26/10/97								
27/10/97	1822	1193	1650	1194	65.5	72.4	71	121
28/10/97	1758	1177	1628	1162	67.0	71.4	74	123
29/10/97	1897	1241	1620	1183	65.4	73.0	63	123
30/10/97	1924	1272	1700	1212	66.1	71.3	65	124
31/10/97								
01/11/97								
02/11/97	1951	1304	1738	1256	66.8	72.3	70	127
03/11/97	2094	1413	1876	1345	67.5	71.7	67	117
04/11/97	2093	1418	1869	1344	67.7	71.9	67	118
05/11/97	2106	1429	1828	1309	67.9	71.6	66	120
06/11/97	2060	1382	1873	1368	67.1	73.0	68	117
07/11/97	2085	1388	1881	1344	66.6	71.5	64	114
08/11/97								
09/11/97								
10/11/97	2076	1408	1796	1300	67.8	72.4	65	122
11/11/97	1961	1346	1726	1218	68.6	70.6	66	127
12/11/97	1919	1232	1654	1168	64.2	70.6	68	127
13/11/97	1835	1211	1552	1085	66.0	69.9	71	129
14/11/97								
15/11/97								
16/11/97								
17/11/97	1375	894	1566	1076	65.0	68.7	73	128
18/11/97	1964	1282	1514	1056	65.3	69.7	71	132
19/11/97	1992	1299	1435	1004	65.2	70.0	70	139
20/11/97								
21/11/97	1569	1060	1381	1072	67.6	77.6	80	152
22/11/97								
23/11/97								
24/11/97	1083	650	1420	1020	60.0	71.8	120	148
25/11/97	1741	1174	1536	1178	67.4	76.7	75	130
26/11/97	1839	1220	1476	1102	66.3	74.7	76	136
27/11/97	1771	1176	1422	1082	66.4	76.1	79	141
28/11/97	1792	1173	1324	1004	65.5	75.8	78	136

UCT UNITS AT DARVILL
SUMMARY DATA 3
PERIOD 3.6.2a

	DATE	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
	29/11/97								
	30/11/97								
	01/12/97	1677	1124	1324	995	67.0	75.2	83	151
	02/12/97	1621	1044	1321	1004	64.4	76.0	80	136
	03/12/97	1514	999	1475	1105	66.0	74.9	86	108
	04/12/97	1528	1007	1297	991	65.9	76.4	82	123
	05/12/97	1511	991	1291	1013	65.6	78.5	86	124
	06/12/97								
	07/12/97								
Average:		1849	1223	1638	1186	66.0	72.6	72	130
Count:		41	41	41	41	41	41	40	40
Maximum:		2106	1466	1950	1382	71.3	78.5	120	152
Minimum:		1083	650	1291	991	60.0	68.7	62	108
Standard Deviation:		220	160	192	121	1.7	2.4	10	10

UCT UNITS AT DARVILL
SUMMARY DATA 4
PERIOD 3.6.2a

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
05/10/97	7.22	7.09	7.32	7.43	7.52	7.61	0.5	0.0		
06/10/97	7.15	7.06	7.18	7.26	7.37	7.44	0.5	0.0	142.4	198.8
07/10/97	7.11	7.03	7.10	7.29	7.28	7.43	0.5	0.0		
08/10/97	7.12	7.02	7.14	7.23	7.26	7.38	0.5	0.0	130.8	150.6
09/10/97	7.11	7.04	7.24	7.22	7.35	7.43	0.5	0.0		
10/10/97	7.03	6.90	7.00	7.09	7.20	7.29	0.5	0.0		
11/10/97							0.5	0.0		
12/10/97	7.11	7.02	7.05	7.14	7.18	7.36	0.5	0.0		
13/10/97	7.05	7.00	7.12	7.12	7.24	7.29	0.5	0.0	28.4	31.4
14/10/97	7.02	7.05	7.04	7.06	7.18	7.19	0.5	0.0		
15/10/97	7.03	7.02	7.06	7.08	7.18	7.22	0.5	0.0	85.9	115.0
16/10/97	7.02	7.02	7.04	7.11	7.15	7.27	0.5	0.0		
17/10/97							0.5	0.0		
18/10/97							0.5	0.0		
19/10/97	7.31	7.11	7.21	7.33	7.37	7.55	0.5	0.0		
20/10/97	7.10	7.02	7.14	7.22	7.32	7.39	0.5	0.0	86.5	126.9
21/10/97	7.02	7.00	7.01	7.15	7.15	7.38	0.5	0.0		
22/10/97							0.5	0.0	104.7	130.6
23/10/97	7.11	6.95	6.95	7.08	7.15	7.27	0.5	0.0		
24/10/97							0.5	0.0		
25/10/97							0.5	0.0		
26/10/97	7.19	6.98	7.01	7.13	7.13	7.33	0.5	0.0		
27/10/97	6.62	6.50	6.59	6.67	6.78	6.90	0.5	0.0	94.3	126.1
28/10/97	7.14	6.92	7.20	7.17	7.35	7.40	0.5	0.0		
29/10/97	7.08	6.91	7.16	7.22	7.31	7.46	0.5	0.0	119.2	132.1
30/10/97	7.04	6.93	7.02	7.18	7.21	7.42	0.5	0.0		
31/10/97							0.5	0.0		
01/11/97							0.5	0.0		
02/11/97	7.10	6.91	7.13	7.21	7.31	7.41	0.5	0.0		
03/11/97	7.13	6.97	7.09	7.22	7.21	7.40	0.5	0.0	108.7	159.0
04/11/97	7.09	6.94	7.35	7.25	7.48	7.45	0.5	0.0		
05/11/97	7.26	7.11	7.27	7.38	7.40	7.55	0.5	0.0	119.4	153.0
06/11/97	7.24	7.07	7.20	7.26	7.37	7.43	0.5	0.0		
07/11/97							0.5	0.0		
08/11/97							0.5	0.0		
09/11/97	7.24	7.09	7.08	7.25	7.27	7.45	0.5	0.0		
10/11/97	6.70	6.53	6.64	6.69	6.80	6.86	0.5	0.0	65.1	126.2
11/11/97	7.07	6.92	6.85	7.05	7.09	7.28	0.5	0.0		
12/11/97	7.21	6.95	7.02	7.14	7.20	7.39	0.5	0.0	95.4	131.3
13/11/97	7.01	6.95	7.01	7.19	7.22	7.45	0.5	0.0		
14/11/97							0.5	0.0		
15/11/97							0.5	0.0		
16/11/97							0.5	0.0		
17/11/97	7.02	7.03	7.02	7.09	7.18	7.31	0.5	0.0	89.2	137.5
18/11/97	7.01	7.01	7.00	7.13	7.30	7.40	0.5	0.0		
19/11/97	7.01	7.01	7.01	7.01	7.01	7.01	0.5	0.0	82.1	121.9
20/11/97	7.01	7.01	7.01	7.01	7.17	7.24	0.5	0.0		
21/11/97							0.5	0.0		
22/11/97							0.5	0.0		
23/11/97	7.01	7.01	7.01	7.01	7.00	7.00	0.5	0.0		
24/11/97	7.14	6.97	6.98	7.02	7.15	7.31	0.5	0.0	105.2	138.1
25/11/97	7.02	6.96	6.83	7.03	7.21	7.34	0.5	0.0		
26/11/97	7.05	6.96	6.90	6.99	7.10	7.27	0.5	0.0	106.2	134.2
27/11/97	7.06	7.00	6.89	6.99	7.12	7.24	0.5	0.0		
28/11/97							0.5	0.0		

JCT UNITS AT DARVILL
SUMMARY DATA 4
PERIOD 3.6.2a

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
29/11/97							0.5	0.0		
30/11/97	7.10	7.03	6.88	7.09	7.07	7.33	0.5	0.0		
01/12/97	7.10	7.00	6.97	7.03	7.16	7.24	0.5	0.0	87.0	120.7
02/12/97	7.12	6.94	6.95	6.99	7.12	7.20	0.5	0.0		
03/12/97	7.18	7.00	7.07	7.26	7.31	7.48	0.5	0.0	100.0	134.1
04/12/97	7.17	6.97	7.00	7.22	7.19	7.43	0.5	0.0		
05/12/97							0.5	0.0		
06/12/97							0.5	0.0		
07/12/97	7.14	6.94	7.05	7.14	7.34	7.29	0.5	0.0		
Average:	7.08	6.97	7.04	7.13	7.21	7.33	0.5	0.0	97.3	131.5
Count:	45	45	45	45	45	45	64	64	18	18
Maximum:	7.31	7.11	7.35	7.43	7.52	7.61	0.5	0.0	142.4	198.8
Minimum:	6.62	6.50	6.59	6.67	6.78	6.86	0.5	0.0	28.4	31.4
Standard Deviation:	0.12	0.11	0.15	0.14	0.14	0.15	0.0	0.0	24.6	30.5

UCT UNITS AT DARVILL
SUMMARY DATA 5
PERIOD 3.6.2a

DATE	NO3 IN	NO3 E1	NO3 E2	NH4 IN	NH4 E1	NH4 E2	SRP IN	SRP E1	SRP E2
05/10/97									
06/10/97	0.25	3.99	2.89	21.80	2.31	0.25	12.60	0.53	0.12
07/10/97	0.25	2.57	2.06	20.90	2.76	1.60	12.30	0.34	0.05
08/10/97	0.25	4.95	4.14	23.80	4.09	2.01	14.26	0.46	0.05
09/10/97	0.25	4.89	4.28	20.50	2.04	0.98	13.00	0.55	0.15
10/10/97	0.25	6.98	5.47	21.00	0.98	0.25	7.32	0.34	0.05
11/10/97									
12/10/97									
13/10/97	0.25	6.98	5.69	20.20	1.44	0.54	7.32	0.25	0.05
14/10/97	0.25	7.58	9.32	20.60	2.36	1.05	5.98	0.31	0.18
15/10/97	0.25	9.32	8.78	24.00	1.05	0.25	5.82	0.18	0.05
16/10/97	0.25	8.35	7.75	24.70	1.60	0.25	8.66	0.23	0.22
17/10/97	0.25	7.65	6.27	22.20	0.25	0.25	8.18	0.11	0.05
18/10/97									
19/10/97									
20/10/97	0.25	7.40	6.12	21.10	0.25	0.25	8.70	0.37	0.13
21/10/97	0.25	6.31	4.93	19.00	1.53	1.90	8.08	0.30	0.24
22/10/97	0.25	6.26	5.30	22.00	1.82	0.25	6.74	0.40	0.24
23/10/97	0.25	5.51	4.95	23.70	0.64	0.92	6.56	0.34	0.12
24/10/97	0.25	5.98	5.43	24.30	1.77	0.25	6.51	0.16	0.11
25/10/97									
26/10/97									
27/10/97	0.25	4.67	3.97	20.40	1.30	0.64	8.34	0.24	0.05
28/10/97	0.25	6.48	5.50	20.80	0.25	0.25	8.80	0.16	0.10
29/10/97	0.25	4.96	3.47	19.90	0.25	0.25	8.84	0.23	0.19
30/10/97	0.25	4.98	3.61	20.00	0.25	0.25	9.58	0.20	0.05
31/10/97									
01/11/97									
02/11/97	0.25	5.09	3.23	20.80	1.00	0.25	9.52	0.20	0.05
03/11/97	0.25	5.78	4.11	18.20	1.81	0.25	10.64	0.29	0.05
04/11/97	0.25	4.77	3.66	18.30	1.70	1.55	9.20	0.12	0.05
05/11/97	0.25	5.11	3.50	19.00	0.25	0.25	10.00	0.17	0.05
06/11/97	0.25	5.38	4.27	18.10	1.44	0.25	11.16	0.25	0.05
07/11/97	0.25	5.48	4.82	18.70	0.25	0.25	8.84	0.17	0.05
08/11/97									
09/11/97									
10/11/97	0.25	5.59	5.18	23.60	2.12	0.25	8.42	0.19	0.05
11/11/97	0.25	4.48	4.26	18.40	0.25	0.25	8.06	0.14	0.05
12/11/97	0.25	4.62	4.29	18.60	0.25	0.25	8.28	0.13	0.05
13/11/97	0.25	4.70	4.38	25.90	1.27	0.25	8.78	0.40	0.19
14/11/97									
15/11/97									
16/11/97									
17/11/97	0.25	4.74	5.57	23.60	0.86	0.25	8.78	1.26	2.20
18/11/97	0.25	5.14	4.78	20.80	0.25	0.25	7.00	2.15	0.79
19/11/97	0.25	4.54	4.64	19.80	0.25	0.25	5.48	0.37	3.26
20/11/97									
21/11/97	0.25	4.65	4.61	18.10	1.07	1.06	6.42	0.49	4.35
22/11/97									
23/11/97									
24/11/97	1.22	3.94	3.48	17.20	1.06	1.04	6.76	0.39	0.85
25/11/97	0.25	4.52	4.37	18.70	1.04	1.04	7.38	0.30	1.18
26/11/97	0.25	5.33	5.15	17.40	0.73	0.25	6.38	0.40	0.80
27/11/97	0.25	5.24	4.85	21.40	0.25	0.25	5.06	0.23	0.54
28/11/97	0.25	5.35	5.10	20.90	0.25	0.25	4.69	0.15	0.23
29/11/97									

JCT UNITS AT DARVILL
SUMMARY DATA 5
PERIOD 3.6.2a

DATE	NO3 IN	NO3 E1	NO3 E2	NH4 IN	NH4 E1	NH4 E2	SRP IN	SRP E1	SRP E2
30/11/97									
01/12/97	0.25	5.03	5.20	22.90	1.00	0.25	4.87	0.17	0.41
02/12/97	0.25	5.11	5.10	20.20	1.75	1.27	4.73	0.20	0.28
03/12/97	0.25	3.96	3.93	11.60	1.33	1.23	3.27	0.18	0.23
04/12/97	0.25	2.64	2.51	11.50	1.17	0.25	2.87	0.56	0.69
05/12/97	0.25	2.38	2.75	11.70	0.25	1.56	3.15	0.40	0.34
06/12/97									
07/12/97									
Average:	0.27	5.33	4.74	20.15	1.13	0.59	7.84	0.35	0.44
Count:	43	43	43	43	43	43	43	43	43
Maximum:	1.22	9.32	9.32	25.90	4.09	2.01	14.26	2.15	4.35
Minimum:	0.25	2.38	2.06	11.50	0.25	0.25	2.87	0.11	0.05
Standard Deviation:	0.15	1.39	1.42	3.14	0.84	0.52	2.54	0.34	0.85

UCT UNITS AT DARVILL
SUMMARY DATA 6
PERIOD 3.6.2a

DATE	fAN NO3 R1	fAX NO3 R1	fAE1 NO3 R1	fAE2 NO3 R1	fAN NO3 R2	fAX NO3 R2	fAE1 NO3 R2	fAE2 NO3 R2
05/10/97								
06/10/97	0.25	1.92	4.40	4.07	0.25	1.20	0.60	2.89
07/10/97	0.25	1.40	2.54	2.73	0.25	0.25	2.10	2.11
08/10/97								
09/10/97	0.25	2.46	4.75	4.81	0.25	1.98	3.95	3.92
10/10/97								
11/10/97								
12/10/97								
13/10/97	0.25	3.38	6.92	7.08	0.25	2.60	5.53	5.57
14/10/97	0.25	4.66	8.82	8.99	0.25	3.86	7.97	8.18
15/10/97								
16/10/97	0.25	3.88	7.56	7.80	0.25	3.62	6.73	6.84
17/10/97								
18/10/97								
19/10/97								
20/10/97	0.25	4.20	7.68	7.64	0.25	3.04	6.02	6.04
21/10/97	0.25	3.62	6.45	6.75	0.25	2.32	5.05	5.16
22/10/97								
23/10/97	0.25	2.92	5.34	5.42	0.25	2.38	4.76	4.69
24/10/97								
25/10/97								
26/10/97								
27/10/97	0.25	2.32	4.36	4.42	0.25	1.94	3.69	3.73
28/10/97	0.25	2.44	5.80	5.73	0.25	1.72	4.80	4.67
29/10/97								
30/10/97	0.25	2.48	5.54	5.61	0.25	1.68	4.37	4.30
31/10/97								
01/11/97								
02/11/97								
03/11/97	0.25	3.42	5.75	5.78	0.25	1.64	4.30	4.11
04/11/97	0.25	2.32	4.72	4.73	0.25	1.64	4.12	3.76
05/11/97								
06/11/97	0.25	2.80	5.72	5.84	0.25	2.10	4.74	4.67
07/11/97								
08/11/97								
09/11/97								
10/11/97	0.25	3.06	5.29	5.44	0.25	2.70	4.86	4.96
11/11/97	0.25	2.30	4.41	4.52	0.25	2.06	4.28	4.38
12/11/97								
13/11/97	0.25	2.92	5.42	5.40	0.25	2.44	5.10	4.97
14/11/97								
15/11/97								
16/11/97								
17/11/97	0.25	2.58	5.26	5.82	0.25	3.02	5.61	5.81
18/11/97	0.25	2.68	4.78	4.76	0.25	2.84	4.93	4.92
19/11/97								
20/11/97								
21/11/97								
22/11/97								
23/11/97								
24/11/97	0.25	2.16	4.23	4.22	0.25	1.96	4.11	3.92
25/11/97	0.25	2.32	4.55	4.90	0.25	2.18	4.39	4.32
26/11/97								
27/11/97	0.25	3.18	5.71	5.65	0.25	3.10	5.31	5.28
28/11/97								

UCT UNITS AT DARVILL
SUMMARY DATA 6
PERIOD 3.6.2a

	DATE	fAN NO3 R1	fAX NO3 R1	fAE1 NO3 R1	fAE2 NO3 R1	fAN NO3 R2	fAX NO3 R2	fAE1 NO3 R2	fAE2 NO3 R2
	29/11/97								
	30/11/97								
	01/12/97	0.25	3.00	5.22	5.27	0.25	3.17	5.33	5.30
	02/12/97	0.25	2.93	4.84	4.98	0.25	2.82	0.25	5.06
	03/12/97								
	04/12/97	0.25	2.13	2.66	2.75	0.25	1.68	2.56	2.57
	05/12/97								
	06/12/97								
	07/12/97								
Average:		0.25	2.83	5.34	5.43	0.25	2.31	4.44	4.70
Count:		26	26	26	26	26	26	26	26
Maximum:		0.25	4.66	8.82	8.99	0.25	3.86	7.97	8.18
Minimum:		0.25	1.40	2.54	2.73	0.25	0.25	0.25	2.11
Standard Deviation:		0.00	0.71	1.36	1.38	0.00	0.77	1.62	1.24

UCT UNITS AT DARVILL
SUMMARY DATA 6.1
PERIOD 3.6.2a

DATE	fAN NH4 R1	fAX NH4 R1	fAE1 NH4 R1	fAE2 NH4 R1	fAN NH4 R2	fAX NH4 R2	fAE1 NH4 R2	fAE2 NH4 R2
05/10/97								
06/10/97	7.00	3.98	2.62	0.25	8.55	4.32	2.19	0.72
07/10/97	13.90	6.86	2.18	1.94	13.20	5.95	2.03	2.95
08/10/97								
09/10/97	11.20	5.62	1.20	1.17	14.10	5.54	2.29	1.03
10/10/97								
11/10/97								
12/10/97								
13/10/97	8.15	4.00	0.25	0.25	13.20	4.52	0.25	0.25
14/10/97	8.10	5.28	0.55	0.25	6.95	4.12	0.25	0.25
15/10/97								
16/10/97	12.60	5.16	0.96	0.25	8.00	4.16	0.25	0.25
17/10/97								
18/10/97								
19/10/97								
20/10/97	7.05	4.40	0.25	0.25	10.80	6.88	0.25	0.25
21/10/97	10.80	5.36	0.51	0.25	10.10	5.00	0.50	0.25
22/10/97								
23/10/97	12.80	6.08	0.82	0.25	11.00	4.95	0.73	1.54
24/10/97								
25/10/97								
26/10/97								
27/10/97	14.00	4.64	0.86	0.73	10.80	3.94	0.82	0.57
28/10/97	12.00	4.14	0.99	0.25	9.90	4.06	0.25	0.25
29/10/97								
30/10/97	9.05	4.08	0.25	0.25	8.70	4.60	0.25	0.25
31/10/97								
01/11/97								
02/11/97								
03/11/97	7.85	4.16	0.25	0.25	12.00	4.28	0.25	0.25
04/11/97	14.60	6.76	1.62	1.54	14.80	7.20	1.56	1.49
05/11/97								
06/11/97	9.35	3.90	0.25	1.83	10.40	3.66	0.25	0.25
07/11/97								
08/11/97								
09/11/97								
10/11/97	8.40	4.76	0.25	0.25	8.65	4.16	0.25	1.68
11/11/97	13.40	4.54	3.90	0.53	12.00	4.78	0.25	0.25
12/11/97								
13/11/97	12.10	5.20	0.55	0.25	11.80	4.36	1.15	0.25
14/11/97								
15/11/97								
16/11/97								
17/11/97	13.90	6.36	1.09	0.25	15.40	5.38	1.30	0.25
18/11/97	10.70	4.78	0.25	0.25	10.20	5.56	0.61	0.25
19/11/97								
20/11/97								
21/11/97								
22/11/97								
23/11/97								
24/11/97	12.40	5.12	1.26	1.12	11.40	4.50	1.16	1.67
25/11/97	13.90	5.92	1.49	1.11	13.40	4.96	1.35	1.12
26/11/97								
27/11/97	9.93	3.77	0.25	0.25	7.23	3.19	0.25	0.25
28/11/97								

UCT UNITS AT DARVILL
SUMMARY DATA 6.1
PERIOD 3.6.2a

DATE	fAN NH4 R1	fAX NH4 R1	fAE1 NH4 R1	fAE2 NH4 R1	fAN NH4 R2	fAX NH4 R2	fAE1 NH4 R2	fAE2 NH4 R2
29/11/97								
30/11/97								
01/12/97	9.68	3.97	0.25	0.25	11.00	3.93	0.25	0.25
02/12/97	10.20	4.60	1.31	1.21	8.26	5.52	1.36	1.30
03/12/97								
04/12/97	5.48	1.37	0.25	0.25	2.06	2.01	0.25	0.25
05/12/97								
06/12/97								
07/12/97								
Average:	10.71	4.80	0.94	0.59	10.53	4.67	0.78	0.70
Count:	26	26	26	26	26	26	26	26
Maximum:	14.60	6.88	3.90	1.94	15.40	7.20	2.29	2.95
Minimum:	5.48	1.37	0.25	0.25	2.06	2.01	0.25	0.25
Standard Deviation:	2.53	1.12	0.87	0.54	2.79	1.06	0.66	0.68

UCT UNITS AT DARVILL
SUMMARY DATA 7
PERIOD 3.6.2a

DATE	fAN TP R1	fAX TP R1	fAE1 TP R1	fAE2 TP R1	fAN TP R2	fAX TP R2	fAE1 TP R2	fAE2 TP R2
05/10/97								
06/10/97	38.98	14.09	2.95	0.67	50.20	18.89	1.86	0.25
07/10/97	34.06	12.31	2.70	0.25	44.35	17.04	1.44	0.25
08/10/97								
09/10/97	34.44	11.50	2.10	1.03	49.05	17.76	1.93	0.25
10/10/97								
11/10/97								
12/10/97								
13/10/97	25.32	7.46	0.72	0.25	40.50	13.40	1.00	0.25
14/10/97	25.58	7.61	0.61	0.25	38.78	13.27	1.07	0.25
15/10/97								
16/10/97	30.94	10.26	1.69	0.73	45.56	16.84	3.48	0.69
17/10/97								
18/10/97								
19/10/97								
20/10/97	30.42	9.61	0.98	0.25	45.62	16.63	1.67	0.25
21/10/97	22.56	7.17	1.41	0.25	39.04	12.72	2.74	0.25
22/10/97								
23/10/97	25.42	7.55	0.86	0.73	40.40	13.51	1.11	0.25
24/10/97								
25/10/97								
26/10/97								
27/10/97	20.54	5.07	0.54	0.25	33.98	9.49	0.81	0.25
28/10/97	30.62	11.01	2.20	0.25	46.14	18.14	2.46	0.25
29/10/97								
30/10/97	30.94	11.22	1.71	0.25	48.70	18.21	1.65	0.25
31/10/97								
01/11/97								
02/11/97								
03/11/97	31.98	11.48	2.11	0.70	50.50	18.11	1.53	0.25
04/11/97	30.64	11.01	1.69	0.25	46.30	17.33	1.11	0.25
05/11/97								
06/11/97	28.90	10.35	2.22	0.25	44.72	16.85	1.24	0.25
07/11/97								
08/11/97								
09/11/97								
10/11/97	23.64	7.79	1.52	0.25	37.00	12.68	1.08	0.25
11/11/97	27.62	9.35	1.93	0.55	44.30	15.71	1.86	0.25
12/11/97								
13/11/97	25.72	9.01	2.28	0.56	50.24	16.07	3.42	0.25
14/11/97								
15/11/97								
16/11/97								
17/11/97	21.36	7.68	3.19	1.13	42.08	18.08	8.68	3.25
18/11/97	20.66	6.20	1.13	0.25	37.10	14.02	6.70	2.72
19/11/97								
20/11/97								
21/11/97								
22/11/97								
23/11/97								
24/11/97	21.56	6.96	1.27	0.25	36.16	14.22	5.76	1.63
25/11/97	23.38	7.43	1.43	0.25	39.10	14.00	6.00	1.44
26/11/97								
27/11/97	20.54	5.83	0.70	0.25	33.74	11.76	3.88	0.91
28/11/97								

UCT UNITS AT DARVILL
SUMMARY DATA 7
PERIOD 3.6.2a

DATE	fAN TP R1	fAX TP R1	fAR1 TP R1	fAR2 TP R1	fAN TP R2	fAX TP R2	fAR1 TP R2	fAR2 TP R2
29/11/97								
30/11/97								
01/12/97	18.26	4.92	0.61	0.25	16.48	11.54	3.10	0.71
02/12/97	12.72	3.38	0.53	0.25	32.10	10.75	3.32	0.63
03/12/97								
04/12/97	12.30	3.29	0.25	0.25	21.45	6.81	1.57	0.25
05/12/97								
06/12/97								
07/12/97								
Average:	25.73	8.44	1.51	0.41	40.52	14.76	2.71	0.63
Count:	26	26	26	26	26	26	26	26
Maximum:	38.98	14.09	3.19	1.13	50.50	18.89	8.68	3.25
Minimum:	12.30	3.29	0.25	0.25	16.48	6.81	0.81	0.25
Standard Deviation:	6.32	2.72	0.79	0.26	8.19	3.04	1.99	0.77

UCT UNITS AT DARVILL
SUMMARY DATA 7.1
PERIOD 3.6.2a

DATE	fAN SRP R1	fAX SRP R1	fAE1 SRP R1	fAE2 SRP R1	fAN SRP R2	fAX SRP R2	fAE1 SRP R2	fAE2 SRP R2
05/10/97								
06/10/97	34.30	11.06	2.33	0.44	48.50	17.34	1.59	0.18
07/10/97	29.45	11.10	2.23	0.29	42.75	14.76	1.31	0.05
08/10/97								
09/10/97	29.00	10.24	1.84	1.03	49.05	15.78	1.50	0.17
10/10/97								
11/10/97								
12/10/97								
13/10/97	22.80	6.56	0.68	0.19	40.20	12.46	1.00	0.15
14/10/97	20.30	6.64	0.98	0.26	34.75	11.96	1.27	0.10
15/10/97								
16/10/97	29.30	9.38	1.69	0.54	43.40	16.32	3.18	0.60
17/10/97								
18/10/97								
19/10/97								
20/10/97	26.75	9.00	0.86	0.25	43.80	15.28	1.49	0.17
21/10/97	21.00	6.90	1.31	0.30	35.90	11.86	2.34	0.32
22/10/97								
23/10/97	25.25	7.54	0.75	0.12	39.85	12.94	1.24	0.10
24/10/97								
25/10/97								
26/10/97								
27/10/97	17.95	4.36	0.52	0.16	29.85	7.40	0.77	0.10
28/10/97	22.00	9.90	1.86	0.49	42.82	16.40	2.08	0.13
29/10/97								
30/10/97	30.40	9.90	1.64	0.26	45.35	17.14	1.52	0.05
31/10/97								
01/11/97								
02/11/97								
03/11/97	30.90	11.34	1.85	0.29	46.85	16.80	1.09	0.15
04/11/97	26.40	9.52	1.03	0.13	44.75	15.02	0.59	0.05
05/11/97								
06/11/97	24.85	7.80	1.35	0.25	43.40	13.56	0.66	0.05
07/11/97								
08/11/97								
09/11/97								
10/11/97	21.50	7.20	0.95	0.17	35.70	12.00	0.67	0.05
11/11/97	27.60	8.68	1.60	0.29	43.85	15.02	1.53	0.05
12/11/97								
13/11/97	25.20	8.70	2.14	0.52	45.50	14.92	3.31	0.38
14/11/97								
15/11/97								
16/11/97								
17/11/97	20.45	7.50	2.90	1.09	42.00	16.66	8.27	3.02
18/11/97	18.00	5.56	0.79	0.22	30.10	11.36	6.41	2.44
19/11/97								
20/11/97								
21/11/97								
22/11/97								
23/11/97								
24/11/97	19.25	6.14	1.07	0.23	32.70	11.36	5.36	1.59
25/11/97	22.75	6.10	1.43	0.18	39.10	12.78	6.00	1.40
26/11/97								
27/11/97	17.43	5.04	0.57	0.16	30.78	10.71	3.47	0.69
28/11/97								

UCT UNITS AT DARVILL
SUMMARY DATA 7.1
PERIOD 3.6.2a

DATE	fAN SRP R1	fAX SRP R1	fAB1 SRP R1	fAB2 SRP R1	fAN SRP R2	fAX SRP R2	fAB1 SRP R2	fAB2 SRP R2
29/11/97								
30/11/97								
01/12/97	16.48	4.21	0.43	0.20	33.75	10.79	2.60	0.57
02/12/97	12.36	2.96	0.39	0.16	30.60	9.80	2.76	0.47
03/12/97								
04/12/97	11.36	2.55	0.37	0.21	21.45	6.60	1.50	0.46
05/12/97								
06/12/97								
07/12/97								
Average:	23.19	7.53	1.29	0.32	39.11	13.35	2.44	0.52
Count:	26	26	26	26	26	26	26	26
Maximum:	34.30	11.34	2.90	1.09	49.05	17.34	8.27	3.02
Minimum:	11.36	2.55	0.37	0.12	21.45	6.60	0.59	0.05
Standard Deviation:	5.65	2.43	0.67	0.24	6.82	2.86	1.95	0.75

UCT UNITS DARVILL
SUMMARY DATA 8
PERIOD 3.6.2a

DATE	MAMAIS SOLUBLE COD IN	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
05/10/97			6.65		20.9	
06/10/97	360		6.65		22.6	22.8
07/10/97	269		6.65		19.0	18.9
08/10/97	255		6.65		18.3	17.9
09/10/97	262		6.65		13.2	18.9
10/10/97	261		6.65		20.1	20.5
11/10/97			6.65		19.3	19.5
12/10/97			6.65		19.0	18.9
13/10/97	306		6.65		18.7	
14/10/97	201		6.65		20.1	20.3
15/10/97	201		6.65		18.8	18.5
16/10/97	257		6.65		18.7	18.4
17/10/97			6.65		19.7	19.6
18/10/97			6.65		20.0	20.0
19/10/97			6.65		20.4	20.4
20/10/97	192		6.65		21.8	21.9
21/10/97	167		6.65		23.1	23.4
22/10/97	192		6.65		20.7	21.0
23/10/97	179		6.65		18.7	18.8
24/10/97	198		6.65		19.0	18.8
25/10/97			6.65		18.6	18.6
26/10/97			6.65		21.7	21.9
27/10/97	231		6.65		18.7	18.6
28/10/97	242		6.65		18.7	18.6
29/10/97	216		6.65		21.6	21.8
30/10/97	226		6.65		22.0	22.2
31/10/97			6.65		21.8	22.1
01/11/97			6.65		21.4	21.7
02/11/97	191		6.65		22.3	23.0
03/11/97	251		6.65		18.9	19.0
04/11/97	257		6.65		19.9	20.0
05/11/97	258		6.65		21.2	22.2
06/11/97	273		6.65		20.6	20.9
07/11/97	309		6.65		18.7	18.7
08/11/97			6.65		22.0	22.1
09/11/97			6.65			20.9
10/11/97	209		6.65		17.1	17.1
11/11/97	234		6.65		18.9	18.7
12/11/97	369		6.65		19.1	18.7
13/11/97	247		6.65		20.7	20.8
14/11/97			6.65		22.3	22.5
15/11/97			6.65		21.9	22.2
16/11/97			6.65		22.8	23.1
17/11/97	219		6.65		19.3	19.4
18/11/97	228		6.65		19.0	18.8
19/11/97	177		6.65			
20/11/97			6.65			
21/11/97	189		6.65		21.3	21.3
22/11/97			6.65		19.9	19.9
23/11/97			6.65		13.8	21.6
24/11/97	160		6.65			21.6
25/11/97	182		6.65		19.1	18.7
26/11/97	171		6.65		19.0	18.6
27/11/97	170		6.65		19.0	18.5
28/11/97	121		6.65		19.1	18.7

UCT UNITS DARVILL
SUMMARY DATA 8
PERIOD 3.6.2a

	DATE	MAMAIS SOLUBLE COD IN	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
	29/11/97			6.65		19.0	18.5
	30/11/97			6.65		19.2	18.8
	01/12/97	165		6.65		21.8	21.8
	02/12/97	145		6.65		23.5	23.7
	03/12/97	154		6.65		19.0	19.0
	04/12/97	135		6.65			
	05/12/97	154		6.65		20.7	20.9
	06/12/97			6.65		21.5	21.7
	07/12/97			6.65		19.2	19.2
Average:		219				19.9	20.2
Count:		42	0	64	0	59	59
Maximum:		369		6.65		23.5	23.7
Minimum:		121		6.65		13.2	17.1
Standard Deviation:		55				1.9	1.6

UCT UNITS AT DARVILL
SUMMARY DATA 1
PERIOD 3.6.2b. LOW FERRIC. AE1. ADDED P. NO BICARB.

DATE	Sbsai	R1 L/d	R2 L/d	R1 OUR	R2 OUR	COD IN	COD E1	COD E2	TKN IN	TKN E1	TKN E2
07/12/97	100	36.7	36.7	9.58	9.23						
08/12/97	100	36.5	36.0	9.94	9.61	291	34	41	23.20	2.00	2.00
09/12/97	100	36.5	36.2		13.74	398	43	40	28.50	2.00	2.00
10/12/97	100	37.2	36.5	11.50	11.20	396	39	63	27.90	2.00	2.00
11/12/97	100	36.0	35.5	10.57	10.98	328	46	38	29.80	2.00	2.00
12/12/97	100	36.0	35.0	11.45	11.76	365	43	41	25.50	2.00	2.00
13/12/97	100	36.2	37.0	13.29	14.50						
14/12/97	100	36.7	36.2	10.12	11.41						
15/12/97	100	36.7	36.7	11.87	12.63	333	34	32	26.30	2.00	2.00
16/12/97	100	36.5	36.0	14.40	14.70	281	29	31	24.50	2.00	2.00
17/12/97	100	37.2	36.7	10.42	9.66	338	10	10	22.30	2.00	2.00
18/12/97	100	36.0	37.0			290	23	35	19.60	2.00	2.00
19/12/97	100	36.5	36.5		12.84	222	10	10	31.60	2.00	2.00
Average:	100	36.5	36.3	11.31	11.86	324	31	34	25.92	2.00	2.00
Count:	13	13	13	10	12	10	10	10	10	10	10
Maximum:	100	37.2	37.0	14.40	14.70	398	46	63	31.60	2.00	2.00
Minimum:	100	36.0	35.0	9.58	9.23	222	10	10	19.60	2.00	2.00
Standard Deviation:	0	0.4	0.6	1.47	1.79	52	12	15	3.47	0.00	0.00

UCT UNITS AT DARVILL
SUMMARY DATA 2
PERIOD 3.6.2b

DATE	INFLUENT TP mgP/L	R1 EFFL. TP mgP/L	R2 EFFL. TP mgP/L	TP REM. R1 mgP/L	TP REM. R2 mgP/L	mgP/gVSS R1	mgP/gVSS R2
07/12/97							
08/12/97	6.28	0.25	0.25	6.03	6.03	73.52	76.34
09/12/97	29.72	2.77	0.95	26.95	28.77	95.12	108.00
10/12/97	29.43	8.51	7.33	20.92	22.10	108.54	117.91
11/12/97	29.81	11.77	11.66	18.04	18.15	115.15	125.40
12/12/97	27.17	14.56	13.95	12.61	13.22	125.33	138.30
13/12/97							
14/12/97							
15/12/97	29.49	11.81	13.33	17.68	16.16	140.75	141.68
16/12/97	29.34	11.95	13.11	17.39	16.23	144.99	153.10
17/12/97	25.47	17.73	20.62	7.74	4.85	143.74	147.33
18/12/97	23.59	12.78	16.43	10.81	7.16	150.19	148.93
19/12/97	28.24	12.09	13.90	16.15	14.34	142.47	151.94
Average:	25.85	10.42	11.15	15.43	14.70	123.98	130.89
Count:	10	10	10	10	10	10	10
Maximum:	29.81	17.73	20.62	26.95	28.77	150.19	153.10
Minimum:	6.28	0.25	0.25	6.03	4.85	73.52	76.34
Standard Deviation:	6.82	5.01	6.16	5.97	7.07	24.16	23.24

UCT UNITS AT DARVILL
SUMMARY DATA 3
PERIOD 3.6.2b

	DATE	MLSS(1)	VSS(1)	MLSS(2)	VSS(2)	%VSS(1)	%VSS(2)	DSVI R1 ml/g	DSVI R2 ml/g
	07/12/97								
	08/12/97	1488	977	1207	932	65.7	77.2	81	124
	09/12/97	1510	981	1274	923	65.0	72.4	79	118
	10/12/97	1636	1039	1375	965	63.5	70.2	76	116
	11/12/97	1669	1061	1385	993	63.6	71.7	78	116
	12/12/97	1652	1023	1404	978	61.9	69.7	79	123
	13/12/97								
	14/12/97								
	15/12/97	1666	1035	1365	1005	62.1	73.6	83	122
	16/12/97	1656	1032	1325	958	62.3	72.3	82	113
	17/12/97	1674	1041	1292	962	62.2	74.5	81	116
	18/12/97	1642	1016	1354	934	61.9	69.0	79	111
	19/12/97	1741	1101	1295	961	63.2	74.2	76	124
Average:		1633	1031	1328	961	63.1	72.5	79	118
Count:		10	10	10	10	10	10	10	10
Maximum:		1741	1101	1404	1005	65.7	77.2	83	124
Minimum:		1488	977	1207	923	61.9	69.0	76	111
Standard Deviation:		73	34	58	25	1.3	2.4	2	4

ICT UNITS AT DARVILL
;UMMARY DATA 4
'ERIOD 3.6.2b

DATE	pH R1 AN	pH R2 AN	pH R1 AE1	pH R2 AE1	pH R1 AE2	pH R2 AE2	ACID DOSE R1 mmol/d	ACID DOSE R2 mmol/d	H2CO3* Alk E1	H2CO3* Alk E2
07/12/97	7.14	6.94	7.05	7.14	7.34	7.29	0.5	0.0		
08/12/97	7.18	7.08	7.29	7.21	7.58	7.47	0.5	0.0	60.5	128.6
09/12/97	7.11	6.94	7.02	7.19	7.18	7.48	0.5	0.0		
10/12/97	7.12	6.98	7.04	7.15	7.28	7.43	0.5	0.0	122.0	155.1
11/12/97	7.11	6.95	7.07	7.14	7.29	7.41	0.5	0.0		
12/12/97							0.5	0.0		
13/12/97							0.5	0.0		
14/12/97	7.07	6.98	7.11	7.25	7.38	7.59	0.5	0.0		
15/12/97							0.5	0.0	118.7	146.3
16/12/97	7.13	7.02	7.04	7.13	7.24	7.41	0.5	0.0		
17/12/97	7.25	7.17	7.39	7.66	7.72	8.08	0.5	0.0	122.9	151.2
18/12/97	7.10	7.04	7.12	7.31	7.43	7.53	0.5	0.0		
19/12/97	7.27	7.05	7.37	7.23	7.61	7.47	0.5	0.0		
■Average:	7.15	7.02	7.15	7.24	7.41	7.52	0.5	0.0	106.0	145.3
Count:	10	10	10	10	10	10	13	13	4	4
■Maximum:	7.27	7.17	7.39	7.66	7.72	8.08	0.5	0.0	122.9	155.1
■Minimum:	7.07	6.94	7.02	7.13	7.18	7.29	0.5	0.0	60.5	128.6
=Standard Deviation:	0.06	0.07	0.14	0.15	0.17	0.20	0.0	0.0	26.3	10.1

UCT UNITS AT DARVILL
SUMMARY DATA 5
PERIOD 3.6.2b

	DATE	NO3 IN	NO3 E1	NO3 E2	NH4 IN	NH4 E1	NH4 E2	SRP IN	SRP E1	SRP E2
	07/12/97									
	08/12/97	0.25	4.14	4.14	17.90	0.25	0.25	4.63	0.40	0.38
	09/12/97	0.25	3.81	3.64	17.00	1.19	0.25	28.30	2.77	0.95
	10/12/97	0.25	3.26	3.57	15.90	1.65	0.25	27.70	8.48	7.14
	11/12/97	0.25	3.05	3.36	18.60	1.42	1.09	27.55	10.46	10.46
	12/12/97	0.25	4.45	4.80	17.40	0.52	0.25	25.80	11.64	11.30
	13/12/97									
	14/12/97									
	15/12/97	0.25	3.45	3.78	17.60	0.25	0.25	21.75	9.59	9.77
	16/12/97	0.25	3.47	4.27	16.40	0.53	1.52	21.30	9.07	9.39
	17/12/97	0.25	4.87	5.50	16.80	0.25	0.25	22.65	13.28	16.12
	18/12/97	0.25	5.06	5.33	15.20	0.25	0.25	22.05	11.10	14.60
	19/12/97	0.25	4.40	4.46	19.40	0.25	0.25	23.45	11.14	12.22
Average:		0.25	4.00	4.29	17.22	0.66	0.46	22.52	8.79	9.23
Count:		10	10	10	10	10	10	10	10	10
Maximum:		0.25	5.06	5.50	19.40	1.65	1.52	28.30	13.28	16.12
Minimum:		0.25	3.05	3.36	15.20	0.25	0.25	4.63	0.40	0.38
Standard Deviation:		0.00	0.66	0.70	1.18	0.52	0.43	6.48	3.86	4.93

UCT UNITS AT DARVILL
SUMMARY DATA 6
PERIOD 3.6.2b

DATE	fAN NO3 R1	fAX NO3 R1	fAB1 NO3 R1	fAB2 NO3 R1	fAN NO3 R2	fAX NO3 R2	fAB1 NO3 R2	fAB2 NO3 R2
07/12/97								
08/12/97	0.25	2.68	4.34	4.34	0.25	3.14	4.27	4.32
09/12/97	1.12	2.15	3.88	4.06	1.20	1.74	3.31	3.42
10/12/97								
11/12/97	0.25	2.00	3.40	3.00	0.25	2.13	3.84	3.26
12/12/97								
13/12/97								
14/12/97								
15/12/97	0.25	0.50	3.68	3.72	0.25	2.22	3.87	3.99
16/12/97	0.25	2.33	3.73	3.71	0.25	2.66	4.36	4.50
17/12/97								
18/12/97	0.25	3.36	5.13	5.29	0.25	3.34	5.19	5.27
19/12/97								
Average:	0.40	2.17	4.03	4.02	0.41	2.54	4.14	4.13
Count:	6	6	6	6	6	6	6	6
Maximum:	1.12	3.36	5.13	5.29	1.20	3.34	5.19	5.27
Minimum:	0.25	0.50	3.40	3.00	0.25	1.74	3.31	3.26
Standard Deviation:	0.32	0.87	0.57	0.70	0.35	0.57	0.58	0.68

UCT UNITS AT DARVILL
SUMMARY DATA 6.1
PERIOD 3.6.2b

DATE	fAN NH4 R1	fAX NH4 R1	fAE1 NH4 R1	fAE2 NH4 R1	fAN NH4 R2	fAX NH4 R2	fAE1 NH4 R2	fAE2 NH4 R2
07/12/97								
08/12/97	8.64	5.14	0.78	0.25	5.91	2.72	0.25	0.25
09/12/97	6.86	3.63	0.25	0.25	12.70	3.16	0.25	0.25
10/12/97								
11/12/97	8.42	3.36	0.25	1.04	7.84	2.99	0.25	0.82
12/12/97								
13/12/97								
14/12/97								
15/12/97	9.33	3.41	0.25	0.25	8.47	3.45	0.25	0.25
16/12/97	7.70	1.94	0.25	0.75	8.75	3.08	0.25	0.68
17/12/97								
18/12/97	9.16	2.20	0.25	0.25	7.40	2.42	0.25	0.25
19/12/97								
Average:	8.35	3.28	0.34	0.47	8.51	2.97	0.25	0.42
Count:	6	6	6	6	6	6	6	6
Maximum:	9.33	5.14	0.78	1.04	12.70	3.45	0.25	0.82
Minimum:	6.86	1.94	0.25	0.25	5.91	2.42	0.25	0.25
Standard Deviation:	0.85	1.05	0.20	0.32	2.08	0.33	0.00	0.24

"ICT UNITS AT DARVILL
SUMMARY DATA 7
'ERIOD 3.6.2b

DATE	fAN TP R1	fAX TP R1	fAE1 TP R1	fAE2 TP R1	fAN TP R2	fAX TP R2	fAE1 TP R2	fAE2 TP R2
07/12/97								
08/12/97	11.66	2.81	0.59	0.25		7.12	1.15	0.25
09/12/97	36.22	18.01	10.84	6.72	51.94	21.63	11.26	4.73
10/12/97								
11/12/97	44.00	24.07	17.26	12.53	60.36	31.40	19.35	10.05
12/12/97								
13/12/97								
14/12/97								
15/12/97	55.80	25.96	19.78	13.35	59.10	31.38	21.43	13.13
16/12/97	46.86	20.99	15.70	12.12	51.26	25.97	18.84	14.02
17/12/97								
18/12/97	35.06	19.27	14.86	11.15	44.16	22.92	18.25	14.34
19/12/97								
Average:	38.27	18.52	13.17	9.35	53.36	23.40	15.05	9.42
Count:	6	6	6	6	5	6	6	6
Maximum:	55.80	25.96	19.78	13.35	60.36	31.40	21.43	14.34
Minimum:	11.66	2.81	0.59	0.25	44.16	7.12	1.15	0.25
Standard Deviation:	13.76	7.53	6.24	4.60	5.88	8.19	6.97	5.25

UCT UNITS AT DARVILL
SUMMARY DATA 7.1
PERIOD 3.6.2b

DATE	fAN SRP R1	fAX SRP R1	fAE1 SRP R1	fAE2 SRP R1	fAN SRP R2	fAX SRP R2	fAE1 SRP R2	fAE2 SRP R2
07/12/97								
08/12/97	11.26	2.73	0.59	0.41	21.51	7.04	1.15	0.45
09/12/97	34.00	16.50	10.19	6.69	50.40	21.39	10.36	4.68
10/12/97								
11/12/97	41.70	22.80	15.92	10.80	56.30	27.85	17.58	12.70
12/12/97								
13/12/97								
14/12/97								
15/12/97	43.30	22.60	15.62	11.30	55.50	28.40	17.56	10.94
16/12/97	38.20	19.95	14.10	10.84	49.90	25.10	16.66	12.20
17/12/97								
18/12/97	34.95	18.08	13.40	9.92	40.75	21.55	15.98	12.66
19/12/97								
Average:	33.90	17.11	11.64	8.33	45.73	21.89	13.22	8.94
Count:	6	6	6	6	6	6	6	6
Maximum:	43.30	22.80	15.92	11.30	56.30	28.40	17.58	12.70
Minimum:	11.26	2.73	0.59	0.41	21.51	7.04	1.15	0.45
Standard Deviation:	10.66	6.82	5.28	3.85	11.96	7.18	5.93	4.71

UCT UNITS DARVILL
SUMMARY DATA 8
PERIOD 3.6.2b

DATE	MAMAIS SOLUBLE COD IN	ALUM R1 mmolAl/d	FERRIC R1 mmolFe/d	FERROUS R1 mmolFe/d	T1 °C	T2 °C
07/12/97			6.65		19.2	19.2
08/12/97	128		6.65		21.2	21.3
09/12/97	198		6.65			25.3
10/12/97	184		6.65		20.2	20.5
11/12/97	204		6.65		19.2	19.2
12/12/97	170		6.65		19.4	19.4
13/12/97			6.65		23.3	23.7
14/12/97			6.65		19.5	19.5
15/12/97	162		6.65		21.6	21.7
16/12/97	150		6.65		26.2	26.4
17/12/97	157		6.65		19.0	19.1
18/12/97	122		6.65			
19/12/97	268		6.65			20.8
Average:	174				20.9	21.3
Count:	10	0	13	0	10	12
Maximum:	268		6.65		26.2	26.4
Minimum:	122		6.65		19.0	19.1
Standard Deviation:	40				2.2	2.4

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting enhanced biological phosphate removal.

Appendix 6

Photographic record of Nocardia *scum and foam problems at Darvill WWW during ferrous-ferric chloride plant trial*

DW de Haas

Figure 6.5 : Use of stainless tensile rigid sheeting with edging to be encased in
deep tie beam and sand as separation barrier.

Figure 6.6: Foam emerging from buckling box on mixed liquor diverting to secondary settling tank. The foam ceased as aeration and odour problem and had to be mechanically removed.

Photo 6.9: Oily scum carryover from secondary clarifier into effluent launder. *Nocardia* problem compounded by high influent concentrations of vegetable oil emulsions (trade waste).

Photo 6.10: Detail of scum carryover problem at secondary clarifier overflow weir. The effluent itself is very clear but lumps of scum break off and pass over into the effluent launder.

APPENDIX 6
Photogaphic record of *Nocardia* scum and foam problems at Darvill WWW during ferrous-ferric chloride plant trial

Photo 6.1: Anaerobic basin showing accumulation of scum. Whitish patches are granular HTH distrubuted on surface in an (unsuccessful) attempt to kill the *Nocardia* microorganisms.

Photo 6.2: Anaerobic basin in foreground with *Drizit*® floating boom in place during attempts to remove scum manually or using trash pumps.

Photo 6.3: *Nocardia* -type foam forming in an aeration basin and accumulating between succesive aerators.

Photo 6.4: Foam covering an aeration basin with an aerator switched off.

Photo 6.5 : Use of aeration basin high pressure water sprays in an attempt to break up foam and scum on aeration basins.

Photo 6.6: Foam emerging from junction box on mixed liquor pipeline to secondary settling tank. The foam created an eyesore and odour problem and had to be manually removed.

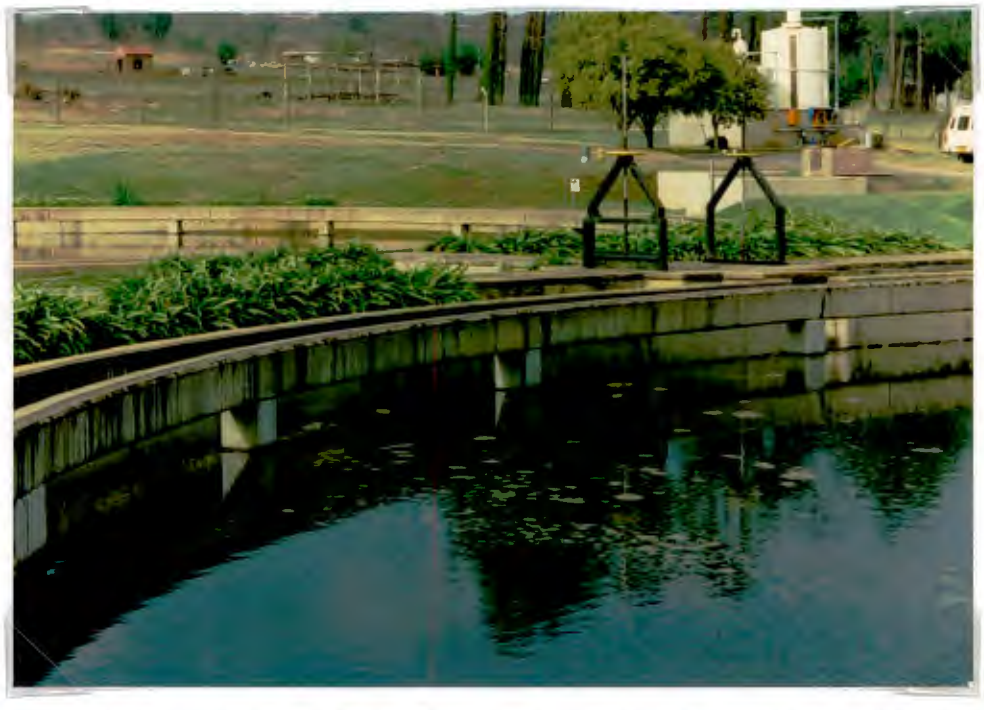


Photo 6.7: Scum carryover. Solids floating out over the surface of one of the secondary settling tanks (SST A) and contributing to the secondary effluent solids and pathogen load.

Photo 6.8: The central skirt baffle retrofitted to old SSTs (A, D and E) served to improve clarifier performance by expanding the central flocculation well. Despite being approx. 10 mm below top water level, the baffle set up flow conditions which trapped *Nocardia* scum. Hosing with water
helped to dislodge the scum but this aggravated the solids carryover problem.

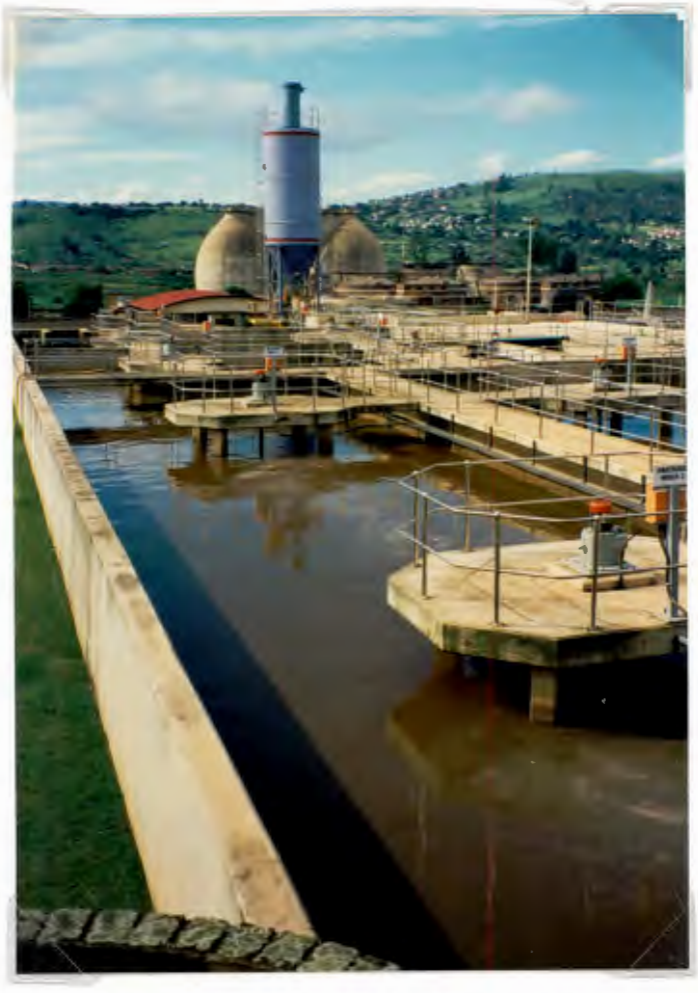


Photo 6.11: Anaerobic basin virtually free of scum approximately six weeks after alum dosing was resumed following ferrous-ferric plant trial. This photo was taken on 14/1/97. Few vegetable oil-related incidents were recorded in Dec. 1996 through to early Jan. 1997.

Photo 6.12: "New" secondary clarifier (SST B) virtually free of scum on 14/1/97. The return activated sludge pumphouse is situated in the background.

Photo 6.13: Junction box on mixed liquor pipeline to secondary clarifiers was completely free of foam on 14/1/97, six weeks after a resumption of alum dosing (compare with Photo 6.6).

Photo 6.14: "Old" secondary clarifier (SST E) virtually free of scum on 14/1/97. Note: experimental water sprays were fitted as an experiment to this SST at the time of the *Nocardia* problem and may be seen here from the circular surface spray pattern on the far side of the clarifier bridge.

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting enhanced biological phosphate removal.

Appendix 7

Photographic record of problems during full-scale stress testing of secondary clarifier performance at Darvill WWW

DW de Haas

APPENDIX 7

Photogaphic record of problems encountered during full-scale stress testing of secondary clarifier performance at Darvill WWW.

Photo 7.1: *Nocardia* foam/ scum travelling down channel from aeration basins to mixed liquor splitter box.

Photo 7.2: Mixed liquor splitter box showing one of three 500mm square of scum holes, considered to be too large due to tendency to bias flow in the direction of the nearest weir splitting flow to one secondary clarifier.Temporary baffles are shown, used to reduce flow via scum holes and equalise split to clarifers. This practice tended to trap *Nocardia* upstream.

Photo 7.3: Preferential flow and Nocradia foam/scum travelling toward one weir of the mixed liquor splitter box (refer to Photo 7.2).

Photo 7.4: SST A showing scum trapped by the central skirt baffles and tending to carry-over into the effluent with the prevailing wind direction.

Photo 7.5: Detail of scum carry-over from SST A in the direction of prevailing wind.

Photo 7.6: Detail of scum carry-over from SST A in the direction of prevailing wind making it difficult to obtain a representative sample of effluent suspended solids (see also Photo 6.9).

The use of simultaneous chemical precipitation in modified activated sludge systems exhibiting enhanced biological phosphate removal.

Appendix 8

List of symbols

DW de Haas

APPENDIX 8

DEFINITION OF SYMBOLS

Symbol	Definition
% ile	Percentile
Δ	Delta, meaning "difference in" or "change in" (e.g. $\Delta M, P_{rem}$ - see also below)
AE1 or 2	Aerobic zone or reactor
Al:P	Aluminium to phosphate ratio (usually molar ratio of mol Al/ mol P)
Al~P~O	Aluminium phosphate/ oxide precipitate (theoretical) after ashing of aluminium hydroxy phosphate
Al~P~OH	Aluminium hydroxy phosphate
Alk.	Alkalinity (unless otherwise stated: *bicarbonate* alkalinity)
AM	Atomic mass of some specified element
AN	Anaerobic zone or reactor
AX	Anoxic zone or reactor
Bicarb.	Bicarbonate (or sodium bicarbonate)
c_{Fe}	Concentration of Fe (III) ions in solution
c_{Fe}^{**}	Maximum residual concentration Fe (III) ions in solution *at equilibrium via precipitation/ redissolution/ complexation processes in the presence of both ferric (hydroxy) phosphate and ferric hydroxide precipitates* (Luedecke *et al.*, 1989)
CLAR	Clarifier (settling tank)
COD	Chemical oxygen demand
c_P	Concentration of dissolved orthophosphate
c_P^{**}	Maximum residual orthophosphate concentration in solution *at equilibrium via precipitation/ redissolution/ complexation processes in the presence of both ferric (hydroxy) phosphate and ferric hydroxide precipitates* (Luedecke *et al.*, 1989)
$c_{P,ads}$	Concentration of orthophosphate adsorbed to precipitate
$c_{P,eq}$	Concentration of dissolved orthophosphate in equilibrium via adsorption processes (= $c_{P,ads} + c_{P,res}$) (Luedecke *et al.*, 1989)
$c_{P,in}$	Influent concentration of orthophosphate
$c_{P,res}$	Residual orthophosphate concentration normally determined analytically (i.e. $c_{P,eq} - c_{P,ads}$) (Luedecke *et al.*, 1989)
d.s.	Dry solids
DSVI	Dilute sludge volume index
Eqn	Equation
f	*Italics:* denotes *filtered* (e.g. fP_t implies *filtered* total phosphate)
f_{ac}	Fraction of readily biodegradable COD which is acetate
f_{bs}	Fraction of biodegradable COD which is readily biodegradable
Fe:P	Iron to phosphate ratio (usually molar ratio of mol Fe: mol P)
Fe~P	Ferric phosphate precipitate (of uncertain formula)
Fe~P~O	Ferric phosphate/ oxide (theoretical) after ashing of iron hydroxy phosphate
Fe~P~OH	Ferric hydroxy phosphate (iron hydroxy phosphate)
FeOOH	Amorphous ferric hydroxide
f_{na}	Fraction of (influent) TKN which is ammonia
$f_{nob,p}$	Fraction of organic biodegradable nitrogen which is particulate
$f_{nou,s}$	Fraction of organic biodegradable nitrogen which is soluble
*f*PCA	Filtered PCA extract (in chemical fractionation studies) - see Chapter 2
fP_t	Filtered total phosphate
$fP_{t,a}$	Filtered total phosphate, anaerobic zone or reactor
$fP_{t,b1 \text{ or } b2}$	Filtered total phosphate, first or second aerobic zone or reactor, respectively
$fP_{t,d}$	Filtered total phosphate, second anoxic zone or reactor
*f*SUP	Filtered supernatant (in chemical fractionation studies) - see Chapter 2

f_{up}	Fraction of unbiodegradable particulate COD
f_{us}	Fraction of unbiodegradable soluble COD
g	grams
h	hours
i_{NBM}	N content of biomass (i.e. N content of X_H, X_{PAO}, X_{AUT})
i_{NSF}	N content of soluble (biodegradable) fermentable COD
i_{NSI}	N content of soluble inert (unbiodegradable) COD
i_{NXI}	N content of particulate inert (unbiodegradable) COD
i_{NXS}	N content of particulate (biodegradable) substrate COD
ISS	Inorganic suspended solids
Jhb or JHB	Johannesburg (e.g. Johannesburg process configuration of activated sludge plants)
K'_{sp}	Apparent solubility product
k_a	Adsorption coefficient
K_{fp}	Equilibrium constant for iron phosphate complex (ion pair): $FeH_2PO_4^{2+}$ (Luedecke et al., 1989)
K_{MeH}	Solubility product for metal hydroxide (Briggs, 1995)
K_{MeP}	Solubility product for metal (hydroxy) phosphate (Briggs, 1995)
k_{MHP}	Equilibrium constant for metal phosphate complex (ion pair): $MeH_2PO_4^{2+}$
k_{PRE}	Kinetic (rate) constant for precipitation (IAWQ, 1995)
k_{RED}	Kinetic (rate) constant for redissolution (IAWQ, 1995)
K_{sp}	Solubility product
ℓ	litre(s)
M	molar
M,P_{rem}	Mass of phosphate removed (mgP/d)
m/m	mass for mass (in chemistry for expression of concentration)
m/v	mass for volume (in chemistry for expression of concentration)
Max.	Maximum
Me	Metal (trivalent metal ion in the context of this study: Fe^{3+} or Al^{3+})
MeOH	Metal hydroxide (nominally $Fe(OH)_3$ or $Al(OH)_3$)
MeP	Metal (hydroxy) phosphate ($Me_rPO_4(OH)_{3r-3}$, or $FePO_4$ or $AlPO_4$)
meq	milli-equivalents
Me_T	Total metal ion concentration
mg	milligrams
Min.	Minimum
min.	minutes
MLSS	Mixed liquor suspended solids
mM	millimolar
mmol	millimoles
mol	moles
MW	molecular weight
n	Flux theory constant (volume per unit sludge mass)
N_{ae}	Concentration of ammonia in the effluent
N_{ai}	Concentration of ammonia in the influent
NaOH	Sodium hydroxide (fractionation studies)
nm	nanometres
No_3 or No3	Concentration of nitrate
$No_{3,a}$	Concentration of nitrate in the anaerobic zone/ reactor
$No_{3,b1\ or\ b2}$	Concentration of nitrate in the first and second zone/ reactor, respectively
$No_{3,d}$	Concentration of nitrate in the anoxic zone/ reactor
$No_{3,e}$	Concentration of nitrate in the effluent
$N_{ob,p}$	Concentration of organic, biodegradable, particulate nitrogen
N_{obi}	Influent concentration of organic, biodegradable nitrogen (particulate + soluble)
$N_{ou,p}$	Concentration of organic, unbiodegradable, particulate nitrogen
$N_{ou,s}$	Concentration of organic, unbiodegradable, soluble nitrogen
N_{oupi}	Influent concentration of organic, unbiodegradable, particulate nitrogen
N_{ousi}	Influent concentration of organic, unbiodegradable, soluble nitrogen

University of Cape Town

N_{te}	Effluent TKN concentration
N_{ti}	Influent TKN concentration
ortho P	orthophosphate
O_t	Oxygen uptake rate (in mg/[ℓ.h])
PAO or PAOs	Polyphosphate accumulating organisms (or poly P organisms)
PCA	Perchloric acid (fractionation studies)
pK	-log K (where K is a given equilibrium constant)
pK'_{sp}	-log K'_{sp} (see K'_{sp} above)
pK'	-log K' (where K' is a given *apparent* equilibrium constant)
pK_{fp}	-log K_{fp} (see K_{fp} above)
pK_{sp}	-log K_{sp} (see K_{sp} above)
poly P	polyphosphate
$P_{P\ res}$	Maximum residual orthophosphate concentration in solution *at equilibrium via precipitation/ redissolution/ complexation* reactions in the presence of both metal (hydroxy) phosphate and metal hydroxide precipitates (Briggs, 1995)
P_P*	Residual orthophosphate concentration in solution (Briggs, 1995)
P_{pi}	Influent ortho P concentration (Briggs, 1995)
P_{pp}	Concentration of poly P
prec	Precipitate
P_{rel}	Concentration of P released (biologically)
P_{rem}	Concentration of P removed
PSTs	Primary settling tanks (or primary sedimentation tanks)
P_{ti}	Influent total P concentration
P_{trem}	Total P concentration removed
P_{ui}	Phosphate component of influent unbiodegradable (inert) soluble organic material
P_{upt}	Concentration of P taken up (biological uptake)
P_{xi}	Phosphate component of influent unbiodegradable (inert) particulate organic material
Q_i	Influent flow rate
Q_r	RAS (or s) recycle flow rate
r	RAS (or s) recycle ratio, relative to influent flow (Q_i)
r as in Me_r	Stoichiometric ratio of Me:P (where Me is a trivalent metal ion and P is ortho P)
R^2	Correlation coefficient squared (statistical parameter)
RAS	Return activated sludge
rem	Removal/ removed
RES	Residue (in fractionation studies)
res	Residual (e.g. ortho P) concentration
R_s	Sludge age (or solids retention time)
S_{bpi}	Influent particulate biodegradable substrate (COD) concentration
S_{bs}	Readily biodegradable (soluble) substrate (COD) concentration
$S_{bs,ai}$	Influent readily biodegradable (soluble) substrate (COD) concentration *which is acetate*
$S_{bs,ci}$	Influent readily biodegradable (soluble) substrate (COD) concentration *which is can be converted to acetate by fermentation*
S_{bsi}	Influent readily biodegradable (soluble) substrate (COD) concentration
S_{PO4}	Soluble orthophosphate concentration IAWQ, 1995)
S_{te}	Effluent (total) COD concentration
S_{ti}	Influent (total) COD concentration
SUP	Supernatant (in fractionation studies)
S_{upi}	Influent unbiodegradable (inert) particulate COD concentration
S_{us}	Unbiodegradable (inert) soluble COD concentration
S_{usi}	Influent unbiodegradable (inert) soluble COD concentration
TKN	Total Kjeldahl Nitrogen
TSS	Total suspended solids
v/v	volume for volume (in chemistry for expression of concentration)

University of Cape Town

V_o	Flux theory constant (settling velocity of sludge at infinite dilution)
VSS	Volatile suspended solids
X_a	Concentration of active mass (biomass)
X_{AUT}	Concentration of active mass of autotrophs (IAWQ, 1995)
$X_{B,G}$	Concentration of active mass of (heterotrophic) poly P accumulating organisms (PAOs)
X_H	Concentration of active mass of heterotrophs (IAWQ, 1995)
X_{ii}	Influent unbiodegradable (inert) particulate COD (Briggs, 1995)
X_{MeH}	Concentration of metal hydroxide (Briggs, 1995)
X_{MeOH}	Concentration of metal hydroxide (IAWQ, 1995)
X_{MeP}	Concentration of metal (hydroxy) phosphate (IAWQ, 1995)
X_o	Reactor MLSS concentration
X_{PAO}	Concentration of PAOs (IAWQ, 1995)
X_r	Concentration of solids (TSS) in the RAS stream

University of Cape Town