A STEADY STATE STOICHIOMETRIC MODEL DESCRIBING THE ANAEROBIC DIGESTION OF BIOLOGICAL EXCESS PHOSPHORUS REMOVAL WASTE ACTIVATED SLUDGE

By

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LIST OF SYMBOLS AND ABREVIATIONS

AD	Anaerobic Digestion
AerD	Aerobic Digestion
Alk H_3CO_4	Phosphate Alkalinity (as mg$CaCO_3$)
AMD1	Anaerobic Digestion Model no.1
ANO	Autotrophic Nitrifying Organism
AS	Activated Sludge
ASM1	Activated Sludge Model no.1
BEPR	Biological Excess Phosphorus Removal
b_{G20}	Specific endogenous mass loss rate for PAOs (0.04/d)
b_{H20}	Specific endogenous mass loss rate for OHOs (0.24/d)
BPO(U)	BPO utilized
BPO	Biodegradable Particulate Organic
BSO	Biodegradable Soluble Organics
BSR	Biological Sulphate Reduction
C	Carbon
CBIM	Continuity-based interfacing model
CH_4	Methane
$C_5H_7O_2N$	Anaerobic Biomass (as used in this study)
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
CSTR	Continuously Stirrer Tank Reactor
C_t	weak acid/base system inorganic carbon
D_B	electrons per mole biomass (AD biomass)
D_s	electrons per mole biodegradable organics (substrate)
f	Value that related the pH and equilibrium (pK_{p2}) in AD model
f_{avPAO}	Active biomass of the PAOs (mgAVSS/mgVSS)
f_{avOHO}	Active biomass of the OHOs (mgAVSS/mgVSS)
f_C or α^C	TOC/VSS mass ratio

f_{cv} **or** α^{COD}	COD/VSS mass ratio
f_H **or** α^H	H/VSS mass ratio
f_{iPAO}	ISS fraction of the PAOs (mgISS/mgPAOTSS)
f_{iOHO}	ISS fraction of the OHOs (mgISS/mgOHOTSS)
f_m **,** f_d **and** f_t	Activity Coefficient (mono-, di- and tri-valent) Ionic species
f_N **or** α^N	N/VSS mass ratio
f_O **or** α^O	O/VSS mass ratio
f_P **or** α^P	P/VSS mass ratio
f**-RBCOD**	Fermentable Soluble Biodegradable Organic COD
FSA	Free and Saline Ammonia
$f_{up(AS)}$	UPO fraction of WAS in AS system
$f_{up(AS)}$	UPO fraction of WAS in AD system
f_{XBGPP}	Polyphosphate P fraction of the PAOs (0.38 mgP/mgActPAOVSS)
f_{XBGP}	P fraction of the PAOs (mgP/mgPAOVSS)
f_{XBHPBM}	P fraction of OHOs (mgP/mgOHOVSS)
f_{XBGPBM}	Biological cell P fraction of the PAOs (mgP/mgPAOVSS)
H	Hydrogen (e.g. H_2)
HCO_3^-	Bi-carbonate
$H_2CO_3^*$ **Alk**	Inorganic Carbon Alkalinity (as mg CaCO3)
ISS	Inorganic Suspended Solid
$J_ø$	Molar Flux (mol/d) {where ø
J_{BPO}	Molar fluxes for the total BPO (mol/d)
$J_{BPO(U)}$	Molar fluxes for the utilized BPO (mol/d)
K_H	Henry's law constant
K_{is}	Ionic Product
K_S	Half velocity coefficient
K_{spm}	Thermodynamic Solubility Product
Me	Counter-ion metals (includes cations of Mg, K and Ca)
$MePO_3$	Polyphosphate

Mg	Magnesium
$MgNH_4PO_4.6H_2O$	Struvite
MLE	Modified Ludzack–Ettinger
MM_x	Molar Mass (g/mol) {where x refer to the relevant element}
N	Nitrogen (e.g. N_2)
ND	Nitrification-denitrification
NDBEPR	Nitrification-denitrification Biological Excess Phosphorus Removal
NH_4^+	Ammonium
N_t	weak acid/base system ammonia
$n_{R(x)}$	mol {where x refer to the relevant element}
O	Oxygen (e.g. O_2)
OHO	Ordinary Heterotrophic Organism
OP	Ortho Phosphates or OrthoP (include HPO_4^{2-} and H_2PO_4 in this study)
P	Phosphorus
PAO	Phosphorus Accumulating Organism
pCO_2	partial pressure of CO_2
PHA	Poly-hydroxyalkanoates
PO	Particulate Organic
PST	Primary Settling Tank
PS	Primary Sludge
P_t	weak acid/base system phosphate
q_Φ	Linkage factor (where Φ the component its applied to)
Q_e	Effluent Volumetric flow rate
Q_i	Influent Volumetric flow rate
Q_w	Waste Volumetric flow rate
R	Generalised Stoichiometric Model
RBCOD	Readily Biodegradable COD
RWQM1	River Water Quality Model no.1
R_a	e^- Acceptor reaction catabolism

R_d or f_s	e^- donor reaction (catabolism) for the organics
R_c or f_e	synthesis reaction (anabolism)
r_h	hydrolysis rate
R_s	Sludge Age
S_{up}	UPO in COD conc. (mgCOD/l)
S_{bp}	BPO in COD conc. (mgCOD/l)
S_t	Total COD conc. (mgCOD/l)
S_{bpe}	residual BPO in AD system (mgCOD/l)
SCFA	Short Chain Fatty Acid
TKN	Total Kjeldahl Nitrogen
TP	Total Phosphorus
TOC	total organic carbon
UCT	University of Cape Town
USO	Unbiodegradable Soluble Organics
UPO	Unbiodegradable Particulate Organic
UASB	Upflow Anaerobic Sludge Bed
VFA	Volatile Fatty Acid
VSS	Volatile Suspended Solid or X_V
WWTP	Wastewater Treatment Plants
WAS	Waste Activated Sludge
WW	Wastewater
WRG	Water Research Group
X_{BH}	Active biomass of the OHOs (mgVSS/l)
X_{BG}	Active biomass of the PAOs (mgVSS/l)
X_{EH}	Endogenous mass of the OHOs (mgVSS/l)
X_{EG}	Endogenous mass of the PAOs (mgVSS/l)
X_{Io}	ISS mass (mgISS/l)
X_{inert}	Inert mass (mgVSS/l)

Y_h	Active mass yield coefficient (0.45 mgVSS/mgCOD)
Z_{AD}	Acidogen biomass concentration

SYNOPSIS

A. Background, Principle Objectives and Scope

Until the mid-1990's model-based studies on wastewater treatment plants (WWTPs) focussed on the development of models describing a single unit operation within the WWTP i.e. an activated sludge system, an anaerobic digester or some other WWTP unit operation. The focus of these model-based studies changed in the late 1990's due to limitations in linking different models in applications for multi unit operation or full scale plant-wide designs or process evaluations. The boundaries related to the focus of these model-based studies within the WWTP, was widened to develop models that describe more than one unit operation and ultimately the whole WWTP.

In line with these plant-wide model-based studies at University of Cape Town an steady state models coupling a primary settling tank (PST) unit coupled to an anaerobic digester (AD) was developed (Sötemann *et al.,* 2005). Furtermore a steady state model coupling an UCT biological excess phosphorus removal (BEPR) activated sludge (AS) system to an aerobic digester was also developed (Mebrutha *et al,* 2007). Furthermore, the Sötemann *et al*. (2005) model can also be used to couple the nitrification-denitrification (ND) AS system to an anaerobic digester. To extend the work of these studies, this study focuses on the development of a steady state model that couples an NDBEPR AS system to an anaerobic digester.

This study, with the support of a parallel study by Ikumi *et al.* (2009), aims at developing a steady state AD model that describes the anaerobic digestion of waste activated sludge (WAS) from a NDBEPR AS system and, secondly, comparing the unbiodegradable particulate organic (UPO) fraction determined for the AS and AD systems. The aim (primary objective) of this study was categorised into various secondary objectives to ensure that all aspects related to this study are achieved. The objectives of, and modelling approaches utilized in, this study are largely similar to those reported by Sötemann *et al.* (2005) in the development of the steady state model describing the anaerobic digestion of primary sludge (PS). Consequently, the steady state AD model of Sötemann *et al.* (2005) is extended in this study to include the phosphorus and counter-ion metal components contained by NDBEPR WAS. The development of this steady state AD model can be divided into two sections, which are:

(a) the characterization of the WAS from the NDBEPR AS system and,
(b) the extension and amendment of the Sötemann *et al.* (2005) steady state AD model to describe the anaerobic digestion of the NDBEPR WAS.

Each of these sections can then be divided further into secondary sections or parts. Figure 1 is a diagrammatical representation of these different stages in the development of the steady state AD model and directions to the chapters of this work dealing with the specific topics.

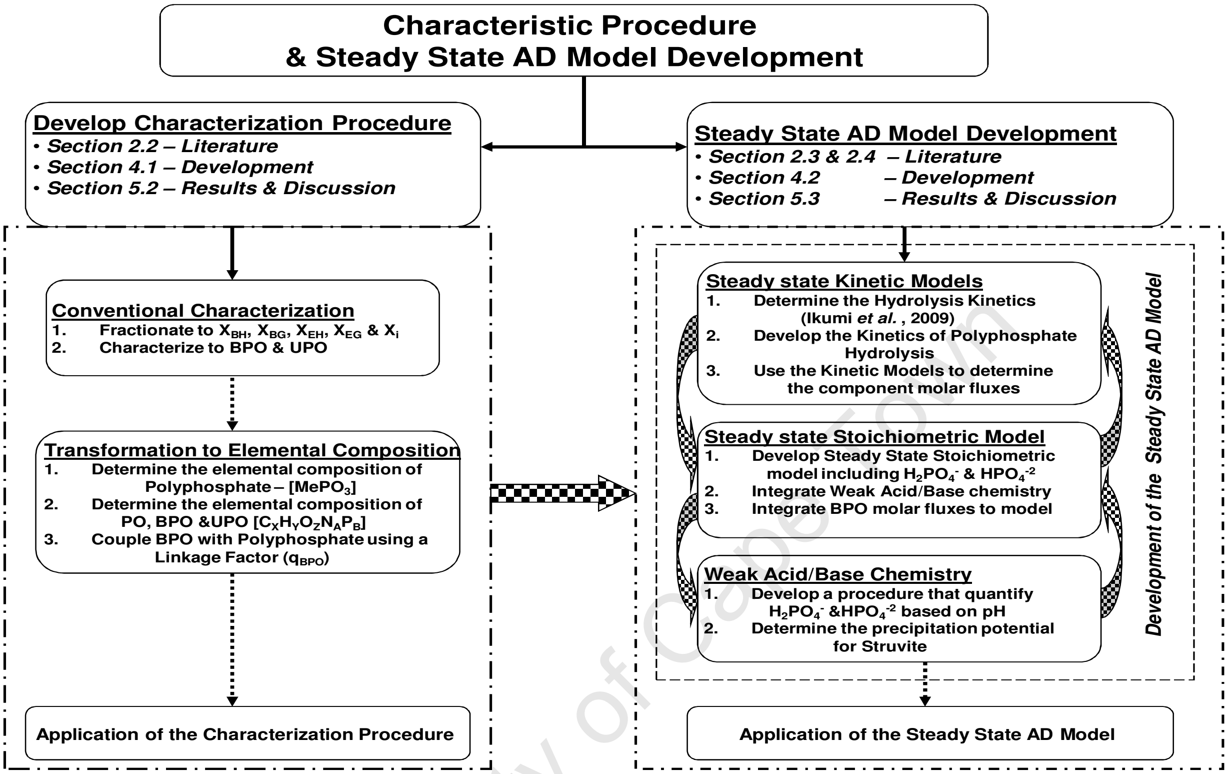

Figure 1: General Structure of the Study

A characterization procedure was developed in this study that characterizes NDBEPR WAS to its elemental composition, which is the required form of the input variable to the stoichiometric part of the steady state AD model. This characterization procedure consists of two steps. (1) The fractionation of NDBEPR WAS into its active mass (OHO and PAO), endogenous mass (OHO and PAO) and inert organic mass content using the steady state AS model of Wentzel *et al.* (1990) and ISS (Ekama and Wentzel, 2004) model. These AS models require measured data from the experimental UCT MBR AS system as input variables. The VSS concentration from the fractionation of NDBEPR WAS is then divided into its biodegradable particulate organic (BPO) and unbiodegradable particulate organic (UPO) components of the VSS (or equivalently particulate organic (PO) component). (2) The characterization procedure centres on transforming the PO, UPO and BPO components determined in the first step to molar elemental composition in terms of carbon (C), nitrogen (N), hydrogen (H), oxygen (O), phosphorus (P) and counter-ion metals (Me) content using their COD/VSS, OrgN/VSS and OrgP/VSS mass ratios. The organic part of WAS is characterized in the form $C_XH_YO_ZN_AP_B$ while the inorganic polyphosphate stored in the PAOs is characterized as an additional $MePO_3$ compound linked to the PAOs.

Although the polyphosphate part is not essentially biodegradable, it is hydrolysable and so its transformation during the AD process mimics that of the organic part of the BPO component in that it changes from a stored or seemingly particulate form (based on analytical measurements) to a dissolved form in the AD system liquor. The kinetics that describes the hydrolysis rate of the organic part and polyphosphate part during AD is different. For this reason polyphosphate is characterized as separate part of the BPO component but linked to it with a linkage factor (q_{BPO}) resulting in the elemental composition $C_XH_YO_ZN_AP_B$. q_{BPO} [$MePO_3$]. This elemental composition is also applied to the PO component because it contains the BPO component but with decreased linkage factor (q_{PO}) to account for the dilution of the polyphosphate concentration in relation to the larger organic concentration of the PO (PO = BPO + UPO where UPO contains no polyphosphate). The molar elemental composition is the required form of the input feed composition to the steady state AD model that was developed.

The steady state AD model development includes the extension and modification, as required, of the three parts of the Sötemann *et al.* (2005) model describing the AD of PS to include biomass phosphorus and the polyphosphate and the counter-ion metal components related to NDBEPR WAS. The three parts of the Sötemann *et al.* (2005) AD models are (i) a COD based hydrolysis kinetic part, (ii) a CHONP stoichiometric part and (iii) a weak acid/base chemistry part. The kinetic part of this AD model deals with the determination of the kinetic rate describing the hydrolysis of the BPO component and was developed in the parallel study by Ikumi *et al.* (2009). This kinetic part of the AD model is used to quantify the extent of digestion of the feed WAS BPO and, thus, the residual BPO at different sludge ages. In addition, the kinetics for polyphosphate hydrolysis was determined in this study.

The stoichiometric part of the AD model focuses on determining the stoichiometry for the biochemical reactions that describe the anaerobic digestion of NDBEPR WAS including phosphate accumulating organisms (PAOs). This reaction stoichiometry, used in the Sötemann *et al.* (2005) AD model, was initially developed by McCarty (1974) and is extended in this study to accommodate biomass P and PAO polyphosphate with its counter-ion metals. The AD products therefore are methane (CH_4), carbon dioxide (CO_2), ammonium (NH_4^+), bi-carbonate (HCO_3^-), anaerobic biomass (assumed at $C_5H_7O_2NP_{0.114}$), Mg, K and Ca counter-ion metals and phosphate in the $H_2PO_4^-$ and HPO_4^{2-} forms depending on the charge balance. The method used in extending this reaction stoichiometry is that described by McCarty *et al.* (1975). In adding P, cognizance needed to be taken of the $H_2PO_4^-$ / HPO_4^{2-} pK value (~7.0) near the operating pH range of the experimental AD system. This results in complexities concerning the phosphorus species, both $H_2PO_4^-$ and HPO_4^{2-} concentrations being present, within the AD system because these concentrations change with change in system pH. This problem is solved by using a factor f that relates the aqueous phase phosphates species to the system pH (and vice versa), splitting the phosphates generated into f x $H_2PO_4^-$ and (1-f) HPO_4^{2-}, which defines the pH depending on the f value. The gaseous CO_2 and CH_4 set the pCO_2, which together with the dissolved CO_2 (HCO_3^- or $H_2CO_3^*$ Alk.) define the AD pH for the inorganic carbon system. The pCO_2 and HCO_3^- concentration are also affected by the f value. The pH that meets the requirements for both the inorganic carbon and ortho-P subsystems defines the f value and establishes the pH in the digester.

In weak acid/base part of the AD model, the predicted results from the stoichiometric part are evaluated to determine the likelihood of mineral precipitation within the digester. Literature from Loewenthal *et al.* (1994) and Musvoto *et al*. (2000) suggest that stuvite is the most likely precipitant with the AD of NDBEPR WAS. To evaluate the likelihood for struvite precipitation the ionic product of the aqueous phase ions are compared with the thermodynamic solubility product (K_{spm}) of struvite. However, this method does not quantify the struvite formed but models developed by Loewenthal *et al.* (1994) and Musvoto *et al.* (2000) and software like Stasoft 4 (Morrison *et al.,* 2000), can be applied for this purpose. The development and inclusion of a third solid phase that describes and quantifies the mineral precipitation are beyond the scope of this study.

B. Methods

The experimental setup used in this research consists of a membrane (MBR) UCT NDBEPR AS system and a completely mixed AD system that was fed the AS system WAS.

The NDBEPR UCT AS system was fed a basic 600 mgCOD/l settled wastewater with 200 mgCOD/l acetate added to increase the BEPR capacity of this AS system. Also, to avoid P limitation di-potassium hydrogen orthophosphate (K_2HPO_4) was added to the feed, to provide potassium and to increase the phosphorous concentration to 40mgP/l and when required NH_4Cl

was added to increase the TKN/COD ratio to 0.1 (before acetate addition). The reactor (zone) volumes of the NDBEPR UCT AS system were 19 l anaerobic, 21 l anoxic and a 35 l aerobic. The aerobic zone comprised two reactors – a 32 l membrane reactor and a 3 litre side stream aeration tank for OUR measurements. The membrane tank was fitted with Kubota ^{TM} A4 size membranes through which the final effluent was produced. The membrane panels were fitted vertically in the bottom section of the main aerobic tank. Continuous coarse bubble aeration was supplied at the base of the reactor. The air bubbles were forced to rise between the membrane panels to provide scour and minimize fouling. The 3 litre side stream aeration reactor was fitted with a DO controller/ OUR meter to measure the OUR. The flow rate from the anoxic reactor to side stream reactor was set to give the same actual retention time as in the MBR reactor. The solids concentrations in the side stream aerobic reactor was same as that in the anoxic reactor, hence the effective volume of the aerobic reactor at its higher solids concentration was lower than 35 l. This was taken into account when calculating the total sludge mass in the system and the anaerobic, anoxic and aerobic sludge mass fractions.

The UCT system was operated with one peristaltic pump set to deliver the influent feed volume of 150 l in 23.5 to 24 h The mixed liquor recycles were set at 3:1 (3 channels) for the as-recycle from the aerobic to the anoxic and 1:1 (1 channel) for the r-recycle from the anoxic to the anaerobic reactors. For the fixed volume reactors the anaerobic, anoxic and aerobic mass fractions are set by the recycle ratios. The relationships between the mass and volume fractions in terms of the recycle ratios are given by Ramphao *et al*. (2004). The anaerobic, anoxic and side stream aeration tanks were fitted with stirrers for mixing while the main aerobic MBR reactor was mixed by continuous coarse bubble aeration.

The AD was fed the WAS from the UCT-MBR AS system (~ 10g TSS/l) on a daily batch feeding basis. The AD was a flow through continuously stirred tank reactor (CSTR) with a total reactor volume of 20 litres and an operating volume of 16 litres. A feeding port was fitted on the side at the base of the tank and gas outlet and metering ports on the top lid. The gas metering pipe was connected to a wall-mounted gas meter. The AD was operated at a temperature of approximately 35 ˚C, optimal for Mesophilic organisms. This temperature was controlled by means of heating coils wrapped around the outside of the digester walls and connected to temperature controller with a temperature probe in the reactor mixed liquor. The AD was completely sealed except for the provision of the gas outlet pipe and the access port, which was closed during normal operation. The access port was opened only once daily to measure the pH. The sludge inlet/ outlet pipe at the base of the AD, controlled by a valve, was only opened during feeding process when waste sludge was with drawn and new feed sludge added. The AD system was operated at 7 different sludge ages i.e. 10, 12, 18, 20, 25, 40 and 60 days. The results of the 10, 18, 25, 40 and 60 day sludge ages are used to calibrate the steady state AD model while the 12 and 20 day sludge age results used to validate the AD model.

C. Summarize Results

The samples taken from the experimental UCT MBR AS system were averaged over a Sewage Batch and named after the Sewage Batch number fed to the AS system. The experimental AD system was operated at different steady state AD sludge ages of 10, 12, 18, 20, 25, 40 and 60 days and the samples measured over a particular sludge age were averaged and named after the sludge age. The average results collected from the experimental AS and AD system were evaluated by performing COD, N, P and counter-ion metals (Mg, K and Ca) mass balances over these experimental systems. Also, carbon mass balances were performed at the different sludge ages for the AD system based on an assumed carbon content (f_C, gC/gVSS) allocated to the VSS (PO) and UPO components of 0.52 and 0.51 respectively from which the f_C of BPO component was calculated. These mass balances were performed for the 11 Sewage Batches (Sewage Batches 3 to 14) of the AS system and the 7 AD steady state sludge ages.

1. The COD mass balances for all the sewage batches of the AS system remained within 10% of the 100% balance and the AD system remained within 3% of the 100% for the COD. The accuracy of the COD mass balance is important in this study because COD it is used to calibrate the steady state AD model. The mass balances achieved throughout this study were very good, in fact better than those achieved in several previous ADs and AD studies at UCT and so are acceptable for use in this study

2. The phosphorus (P) is important in this study as it differentiates this steady state AD model from that previously developed by Sötemann *et al.* (2005). The phosphorus mass balance also varies within 10% of the 100% balance for both the AS and AD systems for almost all balances. It was concluded that the P mass balances of the measured data from both systems were acceptable for use in this study.

3. The nitrogen (N) mass balances the measured data of both systems varies over a wider range (80% - 100%) than that of the COD and P. However, these variations did not significantly influence the results obtained from the use of the measured data because most of the N balance error arise from estimating the nitrate removal in the AS system, which does not affect the AD.

4. The C mass balance over the AD system averaged 92.7% (excluding about 3% for the AD biomass) and so deviates less than 10% from the target 100%. These good mass balance results for the C content validate the assumed C content (f_C) for the PO and UPO from which the f_C of the BPO was calculated by difference.

5. The mass balances for the polyphosphate counter-ion metals (Mg, K and Ca) varied within 20% of 100%. A possible source of error for these metals is the high dilution required in their analysis. Nevertheless, they are deemed acceptable for this study.

The quality of the data collected from the UCT membrane AS system during the experimental stage of this research were found to be consistent for the COD, TP and TC and acceptable for the TKN and counter-ion metals.

The overall objective of the characterization procedure developed and applied in this study is to determine the elemental compositions for the VSS (PO), UPO and BPO components of NDBEPR WAS as this is the required form of the input variables for use in the stoichiometric part of the steady state AD model. The wastewater characteristics and reactor VSS fractions obtained from the characterization and fractionation step of procedure conformed to other studies on the UCT MBR AS system applying the steady state AS model of Wentzel *et al.* (1990) and the ISS model (Ekama and Wentzel, 2004).

The different VSS fractions of the NDBEPR WAS are grouped to determine the BPO and UPO components the VSS (PO) concentrations for AD. This was done because the UPO component of the WAS, ideally (one of the objectives is to confirm this for AS and AD system), remains unchanged during the AD and, consequently, only the BPO components takes part in the reactions within the AD process. The UPO content ($S_{up(AS))}$) of the WAS was determined as the sum of its (i) inert mass (X_{inert}) which enters with the influent and accumulates in the AS system, (ii) the endogenous residue mass of the OHOs and PAOs (X_{EH} and X_{EG}) and (iii) the unbiodegradable part of the active mass of the OHOs and PAOs (X_{BH} and X_{BG}), which in terms of the death regeneration model is 8%. The UPO fraction (f_{upWAS}) of NDBEPR WAS was found to be 0.535 (on average) which is significantly larger than PS and the 10 day sludge age ND system WAS operated in the parallel to this investigation by Ikumi *et al.* (2009), at 0.33 to 0.36 (on average for PS and ND WAS). The BPO content of the WAS was determined from the difference of the PO and UPO components.

The second step of the characterization procedure transforms the COD/VSS (f_{cv}), OrgN/VSS (f_N) and OrgP/VSS (f_P) mass ratios and the polyphosphate content of the PAOs of NDBEPR WAS to the required elemental compositions. The elemental compositions were determined for the PO (VSS) and BPO components in the forms $C_XH_YO_ZN_AP_B.\boldsymbol{q_\Phi}[MePO_3]$ and for the UPO component in the form $C_XH_YO_ZN_AP_B$ where Φ is replaced by OP or BPO depending on the component.

This study compares various elemental compositions for PS and ND WAS determined from studies within the WRG as well as that found from studies in the literature. This is done to determine the possible range for elemental composition and as such place the results of this investigation within the context of other findings. No values for the elemental composition for UPO and BPO of NDBEPR WAS were found in the literature so it was compared with those of PS and ND WAS.

1. Within this study the elemental composition for all the components were based on the molar composition of 7 for hydrogen (Y=7) in $C_XH_YO_ZN_AP_B$. If the molar composition required based on Carbon X=1, then the molar compositions of the H, O, N and P became $CH_{Y/X}O_{Z/X}N_{A/X}P_{B/X}$. The results for the PO VSS (BPO + UPO) composition of NDBEPR WAS ranges from $C_{5.00}H_7O_{2.11}N_{0.76}P_{0.12}.0.29[MePO_3]$ to $C_{5.33}H_7O_{2.34}N_{0.74}P_{0.14}.0.36[MePO_3]$, which is slightly higher in terms of carbon and oxygen molar content than that found by Ekama *et al.* (2006) from the van Haandel *et al.* (1998) ND WAS data, reported at $C_{4.96}H_7O_2N_{0.773}$.

2. The results for the BPO composition ranged from $C_{4.90}H_7O_{1.61}N_{1.09}P_{0.12}.0.61[MePO_3]$ to $C_{5.58}H_7O_{1.91}N_{1.18}P_{0.13}.\ 0.75[MePO_3]$. The BPO compositions of WAS was found to range from $C_{4.8}H_7O_2N_{0.77}$ (Dold *et al.*, 1980) to $C_{5.67}H_7O_2N_{0.865}$ (Ekama *et al.,* 2006b). The organic phosphorus content reported by Volcke *et al.* (2006), in the composition $C_{5.02}H_7O_{2.04}N_{0.95}P_{0.113}$, was found to be similar to that found in this study. Generally, the elemental compositions of

the organic parts of the BPO determined in this study compare well with those found for ND WAS in other studies.

3. In this investigation the UPO composition was determined from measurements on the effluent from the 60 day AD and ranged from $C_{5.11}H_7O_{2.63}N_{0.44}P_{0.12}$ to $C_{5.21}H_7O_{2.65}N_{0.45}P_{0.14}$. These show significantly lower AS biomass nitrogen and phosphorus compositions than that reported by Volcke *et al.* (2006) as $C_{5.44}H_7O_{2.04}N_{0.75}P_{0.038}$. This may be due to the influent UPO composition being significantly different in this study. However, the composition of the UPO from this study is reasonably similar to that obtained from the PS studies reported by Wentzel *et al.* (2006) i.e. low N and P content.

Generally, the elemental compositions determined in this study are similar to those found from comparative studies. This provides some confidence in the quality of elemental composition results obtain for the NDBEPR WAS in this study.

Results from the application of the three part steady state AD model developed in this research, i.e. (i) the kinetic part describing the organic and polyphosphate hydrolysis, (ii) the stoichiometry part describing the AD products produced from NDBEPR WAS AD and (iii) the mixed (inorganic carbon and phosphate) weak acid/base chemistry part, and compared to the measured results are presented below.

1. The hydrolysis rate (kinetic part of the AD model) of the organic part of BPO component (in this study) were determined by Ikumi *et al.* (2009). The kinetic equations used to describe the BPO concentration utilisation are the Monod kinetics at sludge ages < 25 days and Saturation kinetics at sludge ages ≥ 25 days. These kinetic models were calibrated using the AD influent and effluent COD measured data

2. Literature indicated that all the P contained by polyphosphate was released at sludge ages < 7 days and this was validated by batches tests in this study. Five AD Batch tests over 11 days at different dilutions to limit precipitation showed that P was released in less than 5 days. In the continuous ADs the extent of polyphosphate P release could not be observed directly because P mineral precipitation took place during the AD of NDBEPR WAS. Instead the potassium (K) contained in polyphosphate that is linearly related to P content and does not precipitate was used to determine the extent of polyphosphate P release. This K concentration

release indicated that all the polyphosphate was released at a sludge age ≥ 10 days. Because 10 days was the shortest sludge age considered in this study all the polyphosphate P content of the WAS was released at all sludge ages (10-60d) considered. The kinetic rate of polyphosphate hydrolysis therefore is much faster than that of the biodegradable particulate organics of the NDBEPR WAS.

3. To deal with the different kinetic rates for the organic and polyphosphate hydrolysis in the steady state AD model, the total BPO and utilized BPO concentrations relating to the different sludge ages were converted to molar fluxes and the entire PAO PP content linked to these. The molar fluxes for the influent BPO (J_{BPO}) and utilized BPO ($J_{BPO(U)}$) concentration were incorporated into the stoichiometry part of the AD model to ensure that the AD products were related to the hydrolysis kinetics that govern the utilization of BPO. The volumetric fluxes (l/d) determined for this study were 1.6, 1.333, 0.889, 0.8, 0.64, 0.4 and 0.267 at the different sludge ages of 10, 12, 18, 20, 25, 40 and 60 days respectively. The influent BPO fluxes (J_{BPO} – gCOD/d) were 39.4, 32.5, 25.4, 21.2, 18.8, 11.1 and 7.6 and the utilized BPO fluxes ($J_{BPO(U)}$, gCOD/d) were 17.6, 15.1, 14.3, 13.2, 12.5, 9.0 and 7.1 at the above stated sludge ages, respectively.

4. The application of the stoichiometry part of the steady state AD model predicted the concentration for the AD products at the different sludge ages i.e. results for the methane (CH_4) and carbon dioxide (CO_2) gas generated, ammonium (NH_4^+), bi-carbonate (HCO_3^-), counter-ion metals (Mg^{2+}, K^+ and Ca^{2+}), phosphates ($H_2PO_4^-$ and HPO_4^{2-}, dependent on AD system pH) and biomass. The predicted concentrations not affected by mineral precipitation (mainly struvite), i.e. methane gas, potassium and CO_2 (aqueous (HCO_3^-) plus gaseous) compared well with measurements. The predicted CH_4 gas was 50.7 mmol/d compared with 45.1 mmol/d measured at the 10 day sludge age and 17.8 mmol/d (predicted) versus 17.9 mmol/d (measured) at the 60 day sludge age. All the CH_4 gas fluxes are predicted within 10% of the measured fluxes. On comparison the predicted and measured K it was found that K was under predicted to about 15%. The reason for this could be that the measured counter-ion metal ratios i.e. Mg: K: Ca of 1: 0.289: 0.305: 0.028 might be to low.

5. However, the CO_2 gas was under predicted for all sludge ages but this result was accompanied by the over prediction of the HCO_3^- concentration. The variance in the measured and predicted CO_2 gas and aqueous HCO_3^- could be explained with mixed weak acid/base

chemistry, which shows the interdependency of the CO_2 gas, H_2CO_3* Alkalinity (closely equal to the HCO_3^- concentration in the range pH 7 to 8) and pH. Because mineral precipitation changed the digester pH, the steady state AD model over predicted the CO_2 in the gaseous phase and under predicted the CO_2 in the aqueous phase (HCO_3^-) measured as the system H_2CO_3* alkalinity.

6. The measured and predicted carbon concentrations were determined for each of the component of the influent and effluent that contain carbon by using the assumed f_C values of 0.52 and 0.51 for the influent VSS (PO) and UPO components respectively. The f_C value for the BPO component was determined by difference from the assumed f_C for the PO and UPO. For the feed WAS, the PO (VSS) carbon content contributed more than 98% of the total influent carbon concentration with the less than 2% contained by the influent H_2CO_3* alkalinity. The C concentration of the UPO remains unchanged from the influent to the effluent, as it is not affected by the AD processes and accounts for 53% of the C concentration exiting the AD system for both the measured and predicted results. The effluent residual BPO accounts for 24% of the exiting C concentration at the 10 day sludge age but decreases to only 4% at the 60 day sludge age. In contrast, the C concentration of the CH_4 and CO_2 exiting the AD system were 11% and 7% respectively at the 10 sludge age but increased to about 22% and 11% respectively at the 60 day sludge age. This shows the increase in the transfer of BPO carbon to the AD gaseous products, CH_4 and CO_2. The effluent C concentration contributed by the HCO_3^- or H_2CO_3* alkalinity remained a small portion (like the case of the influent) but shows an increasing trend from 2% at the 10 day R_s to about 5% in the 60 day R_s of the AD system effluent.

7. However, significant differences between the predicted and measured results for Mg, ortho-P and FSA concentrations were observed at the different AD test sludge ages. These differences were due to struvite precipitation, which increased with sludge age. Struvite precipitation was confirmed with the calculated ionic product of the measured molar concentrations of Mg^{2+}, FSA and PO_4^{-3} (determined from the measured Ortho-P and the equilibrium equations) in solution were close to the thermodynamic solubility product (K_{spm}) of struvite. Quantification of the struvite precipitant is beyond the scope of this study. Struvite precipitation affected the pH of the experimental ADs, which affect the partial pressure of the gas and H_2CO_3* Alkalinity of the inorganic carbon system.

Comparing the predicted results obtained from the application of the steady state AD model with those measured on the experimental system it could be observed that the results for the compounds that are not affected by struvite precipitation, and consequently pH, compare reasonably well with the measured results. The AD model therefore determines the expected result for the components of struvite precipitation does not occur.

As a secondary objective, this study compares the UPO fractions determined for the NDBEPR AS system ($f_{up(AS)}$) with that determined from the AD system ($f_{up(AD)}$) to assess whether the UPO content of WAS in the NDBEPR AS system remains unbiodegradable when this WAS is treated in an AD system. The UPO of the NDBEPR WAS ($f_{up(AS)}$) fed to the AD system was calculated from the measured NDBEPR system performance to be 0.533, 0.533, 0.521, 0.533, 0.53, 0.529 and 0.551 at 10, 12, 18, 20, 25, 40 and 60 day AD sludge ages respectively. This resulted in a mean $f_{up(AS)}$ of 0.533 during the period of AD tests. From AD performance data (influent and effluent COD) Ikumi *et al.* (2009) used regression plots of the correlation coefficients (R^2) vs. f_{up} (in the expected UPO range) for the first order, Monod and saturation hydrolysis kinetics to obtain the best $f_{up(AD)}$ at the maximum R^2. The $f_{up(AD)}$ so determined was 0.54. Assuming the residual BPO and biomass BPO are zero, the $f_{up(AD)}$ was also measured on the 60 day sludge age effluent and found to be 0.55. All three NDBEPR WAS UPO fractions are reasonably similar, proving that the UPO content of the AS system remains unbiodegradable in the AD system and the UPO of NDBEPR WAS is the same for activated sludge systems and anaerobic digesters.

D. Principal Conclusion and Recommendation

The principal conclusions for this study are the following; (1) Mass balances for the COD, N, P, C and metals were performed over the AS and AD systems and found to be good. (2) The organics characterization procedure developed by Ekama (2009) has been extended in this study to include P as part of the elemental composition of the PO, UPO and BPO components. (3) PAO polyphosphate is coupled to the BPO part of NDBEPR WAS using a linkage factor but its hydrolysis and release during the AD process is much faster than the hydrolysis of the WAS BPO components. (4) The steady state AD model of Sötemann *et al.* (2005) has been extended and amended in this study to describe the AD of NDBEPR WAS. (5) The stoichiometry part of the AD model predicted very well the concentration of the AD products that are not affected by struvite precipitation and consequently pH. However, because the AD model does not include struvite precipitation the concentrations affected by precipitation and pH were not predicted effectively.

(6) Struvite precipitation took place during the normal operation of the AD system fed NDBEPR WAS.

Further research is recommended to extent the stoichiometric part of the steady state AD model developed in this study to quantify the mineral precipitation that took place in the AD of NDBEPR WAS during the operation of the experimental AD system because it strongly affects digester pH. This could be achieved by incorporating principles from the studies of Mustovo *et al.* (2000) and Morrison *et al.* (2000) to the steady state AD model developed in this project. Also, there is a need to analytically measure the TOC content of the PO, UPO and BPO components to confirm the f_C values obtained from the C balance in this study.

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CHAPTER ONE
INTRODUCTION

1.1 General Background

In the past, the design and operation of wastewater treatment plants (WWTP) were based on long and expensive experimental studies. The results from these experimental studies, for most cases, were only relevant to the design of a specific WWTP. As time progressed, research into individual unit operations of WWTP resulted in the development of mathematical models describing these individual unit processes. Examples of such mathematical models are Activated Sludge Model no.1 (ASM1) (Henze *et al*., 1987), Anaerobic Digestion Model no.1 (AMD1) (Batstone *et al.,* 2002) and The River Water Quality Model no.1 (RWQM1) (Reichert *et al.,* 2001). The application of these mathematical models as a component in design and operation evaluation has become increasingly favourable in recent times. The value of these mathematical models is manifested in significant reductions in time and cost related to design and operational evaluation of the relevant unit operations.

However, the lack of compatibility between the mathematical models of different unit operations raised concerns about their usefulness in application for plant-wide modelling. Problems arise because the state and output variables of the different mathematical models are different in type or units. This is the case when the output variables from ASM1 are used as input variables to ADM1 (Volcke *et al*., 2006). Recently research focus has centred on the development of plant wide WWTP models that facilitate the coupling or linking of simulation models for the activated sludge (AS) system and the anaerobic digestion (AD) system (Jeppsson *et al.,* 2006). These plant wide models produce outputs for one unit operation (the source unit) that are compatible to the next down stream one (the destination unit) in type or units (Ekama, 2009).

In the development of these plant wide models two approaches have been proposed. Firstly, the development of a mass balance interface compound transformation approach that maps the output compounds, from the source model, to the required type for use as state variable compounds, in the destination model (Continuity-based interfacing model {CBIM} interface transformation approach, Volcke *et al,* 2006). Secondly, the “super-model approach” defines the compounds required in the whole WWTP, in the same type and units, and then models the changes of these compounds in each operation within the WWTP (Jones and Takács, 2004 and Seco *et al.*, 2004). A combination of the CBIM and super-model approaches was proposed by Grau *et al.*(2007).

All the foregoing approaches require the input variables to be characterized in its elemental mass fraction composition or molar composition form as described by Volcke *et al.*(2006) and Ekama *et al.* (2006b). In doing so, the carbon (C) composition of the compounds is specified, allowing the closing of the C balance over the anaerobic digester, and fulfilling the requirements for predicting the gas production, i.e. the methane (CH_4) and carbon dioxide (CO_2) production in anaerobic digestion (AD) systems. However, due to the organic carbon experimental measurement not being a common measurement at most WWTPs, different carbon contents of various wastewater organic groups are assumed to determine the elemental composition for some state variable compounds.

Apart from the difficulties above, the plant wide simulation models are also large and complex. The effective application of such plant wide models requires significant modelling skills, experience and WWTP knowledge (Ekama, 2009). Furthermore, the application of such models requires a lot of input information such as kinetic and stoichiometric constants for many bioprocesses and design specifications, like reactor volumes and inter-connected flows. In contrast, steady state models require much less input information and are more suitable for design purposes, whereas, dynamic simulations are better suited in operational evaluation and control system design and process calibration applications. Therefore, as there is a necessity for the development of dynamic simulation models for specific applications, there is also a need for the development of steady state models for design applications.

In accordance with the need for plant wide modelling for WWTPs, Sötemann *et al.* (2005) developed a procedure that couples the primary settling tank (PST) to an anaerobic digester and the ND AS system to an aerobic digester. Furthermore, this procedure includes a steady state model that describes the AD of primary sludge (PS) and waste activated sludge (WAS) from the ND AS system to their final end products in the gaseous, dissolved and solid streams. However, that study excluded the AD of WAS from a nitrification denitrification (ND) biological excess phosphorus removal (BEPR) AS system.

The aim of this study, and that of the parallel study conducted collaboratively by Ikumi *et al.* (2009), addresses the coupling or linking of a NDBEPR AS system to an anaerobic digester. This includes the development of a steady state AD model that describes the anaerobic digestion of waste sludge from the NDBEPR AS system.

1.2 Hypothesis Development

The overall study focuses on incorporating several aspects related to an NDBEPR AS system coupled to an AD system as part of extending the mass balance based plant-wide models. Firstly, this research aims to develop a steady state AD model that describes the anaerobic digestion of NDBEPR WAS. This relates to the linking of the steady state NDBEPR AS system model developed by Wentzel *et al.* (1990) and an extended version of steady state AD model developed by Sötemann *et al.* (2005). This extension of the steady state AD model of Sötemann *et al.* (2005) focuses on the inclusion of the phosphorus components of NDBEPR WAS and is one of the core objectives of this study. The steady state NDBEPR AS model developed by Wentzel *et al.* (1990) is used to fractionate the WAS VSS produced within this AS system into its 5 constituent components i.e.actve OHO mass (X_{BH}), active PAO mass (X_{EH}), endogenous OHO mass (X_{BG}), endogenous PAO mass (X_{EG}), inert mass (X_i) at forms the Volatile Suspended Solid {VSS or X_V}) and X_{Io} (Inorganic Suspended Solid {ISS}). Added to this chemical oxygen demand (COD) based steady state model is complete COD, carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P) and counter-ion metals (Me – Mg, K and Ca) mass balanced stoichiometry required for the input to the AD system. These 5 constituent components of the particulate organics (PO) are then grouped to produce a biodegradable particulate organic (BPO) component and an unbiodegradable particulate organic (UPO) component. The COD, C, N and P mass ratios (f_{CV}, f_C, f_N and f_P respectively) of the particulate organic (PO), BPO and UPO components are used to determine the elemental composition of these components in terms of their C,H,O,N and P content. The resulting output variables of this AS model are therefore in the form required as input variables to the steady state AD model.

The development of a steady state AD model describing the anaerobic digestion of NDBEPR WAS is the main focus of this study and the parallel study conducted collaboratively by Ikumi *et al.* (2009). Like the AD model of Sötemann *et al.* (2005), this AD model comprises of 3 parts : (i) a COD balance based kinetic part which describes the hydrolysis of the particulate biodegradable organics (BPO), (ii) a C, H, O,N, P and COD mass and charge balanced stoichiometric part which transforms the biodegradable COD hydrolysed (reactant or substrate) to AD products and (iii) a two phase (aqueous and gas) weak acid/base chemistry part of the inorganic carbon and phosphate (which will be added) system from which the digester pH and potential mineral precipitation can be determined.

The steady state AD model development objective consist of two parts, (1) the development of the kinetic model for NDBEPR WAS (that includes the kinetic rates of hydrolysis and polyphosphate degradation) and (2) the stoichiometric model describing the anaerobic digestion of NDBEPR WAS. This study focuses on the development of the stoichiometric and mixed weak acid/base part whereas the study by Ikumi *et al.* (2009) focuses on the hydrolysis kinetic model part. So to enable comparison with the results determined from application of the stoichiometric model to the experimental observations, the results of steady state kinetic model developed by Ikumi *et al.* (2009) are required. The quantity of NDBEPR WAS COD utilized anaerobically at various AD test sludge ages is determined from application of the hydrolysis kinetic model and this COD utilized, with its CHONP constituents is then included as the reactant into the stoichiometry part of the model. The output of the kinetic hydrolysis part developed by Ikumi *et al.* is therefore important in the validation of the stoichiometric part of the AD model developed in this study. In this study the stoichiometry part of the model is developed.

The mixed weak acid/base chemistry part of the AD model is also developed in this study and is used to determine the possibility of struvite formation inside the AD system treating NDBEPR WAS. Due to the complexity of mineral precipitation this part of the steady state AD model cannot quantify the concentration of struvite precipitate as a product of anaerobic digestion. However, the steady state model results can be used in the 3 phase (aqueous, gaseous and solid) mixed weak acid/base model of Loewenthal *et al.* (1994) and Musvoto *et al.* (2000) to quantify the main Mg and Ca carbonate and phosphate minerals that precipitates.

1.3 Research Approach

To achieve the research objectives, a UCT membrane (UCT MBR) configuration NDBEPR AS system will be operated in this study to generate the WAS with the phosphorus accumulating organisms (PAOs) containing high concentrations of P (up to 0.38 mgP/mgPAOVSS, Wentzel et al., 1990), stored inside the PAOs in the form of polyphosphate. This AS system will be evaluated using the Wentzel *et al*. (1990) NDBEPR steady state model, modified to include the ISS model of

Ekama and Wentzel (2004). The WAS from this system will be fed to a continuously stirrer tank reactor (CSTR) completely mixed anaerobic digester. The steady state AD model of Sötemann *et al.* (2005) will be extended to include P and the AD of PAOs to describe this anaerobic digester, which is the core aim of this study. The complexities of a NDBEPR WAS mixed biomass culture, comprising of ordinary heterotrophic organisms (OHOs) and PAOs with a significant P content, will present some challenges that require significant modification of the reaction stoichiometry and weak acid/base chemistry parts of the AD model developed by Sötemann *et al.* (2005).

The steady state AD model developed by Sötemann *et al.* (2005), describes the anaerobic digestion of PS from a primary settling tank (PST). Because of differences in the composition of PS and WAS from an ND system and the WAS from a NDBEPR systems, there will be differences in the organic particulate elemental compositions of the components from these systems and, thus, also differences in the products generated during the anaerobic digestion of these components. The reaction stoichiometry used by Sötemann *et al.* (2005) to describe the AD of PS was first published by McCarty (1974) to demonstrate the anaerobic digestion of common domestic waste components that comprise of C, H, O and N. The anaerobic digestion of such waste components generate methane (CH_4), carbon dioxide (CO_2), ammonium (NH_4^+), bi-carbonate (HCO_3^-) and anaerobic biomass. Phosphorus was omitted from this reaction stoichiometry due to its limited impact on the outputs generated for the applications considered. In the context of this work the phosphate component of the NDBEPR WAS is significant due to the stored polyphosphate in the PAOs. So in this research the AD stoichiometry will be extended to include P, i.e. the organically bound P in the influent organics, the cell bound P of the OHOs and PAOs biomass and the inorganic polyphosphate P stored inside the PAOs with the changes reflected in the bulk liquid ortho-P concentration. The extended AD stoichiometry will therefore include the products of AD such as ortho-phosphates (HPO_4^{2-} and H_2PO_4) and the counter-ion metals (Me^+) related to the polyphosphate component of the NDBEPR WAS. Although the McCarty (1974) and Sötemann *et al.* (2005) reaction stoichiometry does not apply because the P is excluded, McCarty (1975) published a generalised procedure that can be utilized to derive the reaction stoichiometry including P.

Anaerobic digestion is sensitive to temperature and pH. However, because temperature is controlled externally at 35°C (mesophilic temperature range), it remains constant and does not affect the system as a variable. However, the anaerobic digester aqueous mixed weak acid/base chemistry pH is governed by the composition of the influent organics which controls the system pH (Sötemann *et al.*, 2005). The weak acid/base subsystems that simultaneously impact on the AD pH are the volatile fatty acids (VFAs), ammonia, carbonate, phosphate and water systems for the purpose of this work. In the anaerobic digester treating PS and WAS from a ND AS system under stable conditions, the ortho-phosphate subsystem can be ignored because the P concentration is very low. Also within the pH range established the ammonia and VFA subsystems are virtually completely ionized with the result that the AD system pH treating PS and/or WAS from a ND AS system is governed mainly by the inorganic carbon (carbonate) system. However, in this research the P concentration will be high and so will influence the AD pH. This complicates the weak acid/base chemistry part of the AD model to be developed because the phosphorus system has an equilibrium constant (pK value) near the normal operating range of the AD system (i.e. $pK_{p2} = 7.2$ at 35°C for the HPO_4^{2-} and the $H_2PO_4^-$ species). Therefore, both of these species need to be represented in the reaction stoichiometry as products of anaerobic digestion of WAS from NDBEPR systems.

To calibrate the AD model, experimental anaerobic digesters will be operated at various sludge ages and performance data collected. The sludge ages selected for this purpose are 10, 12, 18, 20, 25, 40 and 60 days. The shorter sludge ages are required for the determination of the hydrolysis rate of the NDBEPR WAS and the longer sludge ages for determining the unbiodegradable particulate fraction of the NDBEPR WAS in terms of VSS and COD concentrations. It will be assumed that all biodegradable components will be digested at a sludge age of 60 days and the remaining COD and VSS in the AD effluent, corrected for the AD biomass formed, is the unbiodegradable fraction. This unbiodegradable fraction is an important WAS characteristic in modelling the AD unit operation and will be compared with that determined from the NDBEPR MBR AS system performance. A second set of AD performance data, at 12 and 20 day AD test sludge ages will be collected to validate the hydrolysis and polyphosphate degradation kinetic rates and unbiodegradable fraction.

It has long been observed in the Water Research Group (WRG) that NDBEPR AS systems fed the same raw wastewater yield different influent unbiodegradable particulate COD fractions (f_{up}) than ND AS systems, i.e. around 0.12 to 0.14 for ND AS systems and around 0.17 to 0.22 for NDBEPR AS systems fed the same Mitchell's Plain WWTP (Cape Town, South Africa) raw wastewater. With AD systems treating the WAS from ND and NDBEPR AS systems at very long sludge ages of 60 days, it can be checked if this difference in f_{up} is real or a deviation in the ND AS and NDBEPR AS steady state models.

The experimental layout for this research project attemps to mimic full scale WWTPs at a laboratory scale and will include two Modified Ludzack–Ettinger (MLE) Nitrification Denitrification (ND) activated sludge (AS) systems, one University of Cape Town (UCT) configuration ND Biological Excess Phosphorus Removal (BEPR) activated sludge (AS) system and five Anaerobic Digestion (AD) systems. The research presented in this report will focus on the P removal in the ND BEPR AS system and the P release in the AD system fed its WAS. The parallel project by Ikumi *et al.* (2009) focuses on the operation of the two ND AS systems (one fed Raw WW and the other treating Settled WW) and the other four ADs (fed PS, Raw MLE system WAS, settled MLE system WAS and a blend of PS and Settled MLE system WAS). The hydrolysis kinetics obtained for the NDBEPR WAS from the Ikumi *et al.* (2009) study will be used in this project to extend the AD model to include P.

1.4 Research Objectives

The central aim of this study is the development of a steady state model that describes the anaerobic digestion of NDBEPR WAS for incorporation in a plant wide steady state WWTP model. This requires a procedure to be developed by which the NDBEPR WAS fed to the AD system is characterized into a form that is compatible with the composition of compounds required by the AD model. A second aim of this study is to determine whether or not the UPO content of the WAS established from the behaviour of the NDBEPR AS system {UPO (AS)} is the same as that determined from the performance of the AD systems fed this WAS {UPO(AD)}. The logical sequences to achieve the aims set for this study commences through determining the characteristics of the feed WAS in the required form used as input variable to the steady state model. Secondly the stoichiometric part of the steady state AD model is developed and this is done in parallel with determining the kinetic rate of polyphosphate degradation. Finally, the UPO (AS) and UPO (AD) are compared and discussed.

The characterization of NDBEPR WAS will be achieved by (i) applying the COD, N and P mass balanced steady state model for the ND BEPR activated sludge system of Wentzel *et al.* (1990) to fractionate the measured PO VSS into its 5 components i.e. OHO and PAO biomass, OHO and PAO endogenous residue and influent unbiodegradable organics. (ii) grouping these five components into their biodegradable (BPO) and unbiodegradable (UPO) components and (iii) adding a C, H, O, N, P, counter-ion metals (Mg, K &Ca) and COD mass balance stoichiometry for each component. In this way the different particulate organic (PO) components fed to the anaerobic digester will be defined in terms of their $C_XH_YO_ZN_AP_B$ compositions, thereby closing the CHONP and COD balance which is a requirement for the AD model. These PO components are the biodegradable particulate organics (BPO) of the OHOs and PAOs and the unbiodegradable particulate organics (UPO) of the OHO and PAO endogenous masses and the influent unbiodegradable organics of the NDBEPR WAS.

The stored polyphosphate in PAO component of the NDBEPR WAS is added as an inorganic elemental composition linked, using a linkage factor (q), to the PAO organic compositions ($C_XH_YO_ZN_AP_B$) i.e. $C_XH_YO_ZN_AP_B.q_{PAO}$ [$MePO_3$]. The reason for this is because the AD process may hydrolyse both the organic and stored inorganic content of the biodegradable particulate organic (BPO) components of this WAS at different rates. Determining the elemental composition of polyphosphate and linking this composition to the different PO components is another objective of the characterization procedure developed in this study.

The addition of the CHONPMe and COD mass balance stoichiometry that models the AD of WAS from a NDBEPR AS system is the main objective of this research. This objective includes the calibration and validation of the steady state model with data obtained from the experimental setup that couples an anaerobic digester to a UCT NDBEPR AS system.

To achieve the overall aims of this research, the objectives defined above are expanded and arranged in the order of presentation in this report.

A. ***Measured Data***

1. Construct the laboratory scale experiment and collect performance data throughout the period of experimental investigation.

2. Perform COD, Nitrogen, Phosphorus and Polyphosphate Counter-ion Metals (Mg, K & Ca) mass balances over the AS and AD systems to evaluate the quality of the measured data.

B. ***Characterization Procedure Development and Application***

3. Quantify the characteristics of the wastewater fed to the NDBEPR AS system and thereafter also that of the NDBEPR WAS (i.e. the five VSS and three ISS concentrations) by applying the COD based steady state AS model of Wentzel *et al.* (1990) to the experimental UCT

NDBEPR AS system. In this way the NDBEPR WAS is fractionated into its Active, Endogenous and Inert contents. These are then grouped into the BPO and UPO components of the NDBEPR WAS.

4. From elemental mass balance stoichiometry of the AS system extend the COD, VSS and N composition of the organic components determined from the steady state AS model to include their CHO and P elemental composition.

5. Determine the elemental composition of polyphosphate and develop a method to couple the organic components of PAOs and BPO to polyphosphate namely a linkage factor ($q_{ø}$)

6. Connect the elemental composition of the inorganic polyphosphate stored inside the PAOs, and linkages factor that connects it to the PAO component (q_{PAO}) and the BPO component (q_{BPO}), containing PAOs, in $C_XH_YO_ZN_AP_B.q_{ø}[MePO_3]$.

C. ***Steady State AD Model Development and Application***

7. Extend the elemental mass balance reaction stoichiometry of the steady state AD model to include biomass and polyphosphate P for the anaerobic digestion of NDBEPR WAS.

8. Determine the hydrolysis kinetic rates of polyphosphate that relates to the release of the P and Me contained by polyphosphate.

9. Apply the AD hydrolysis kinetics using the BPO COD concentration of the NDBEPR WAS input variable to determine the extent of hydrolysis of the BPO component (BPO utilized) at a specific sludge age and to determine the utilized BPO molar flux at that AD test sludge age. Furthermore, use the results from the hydrolysis kinetics to determine the UPO fraction (f_{up}) of the NDBEPR WAS treated in the AD system from regression plots.

10. Incorporate the utilized BPO fluxes and weak acid/base chemistry into the steady state stoichiometric AD model.

11. Apply the extended steady state AD model, including P, to predict the products of digestion of NDBEPR WAS. Compare the predicted and measured results of this study.

12. Determine the mineral precipitation potential of the AD liquor from the mixed weak acid/base chemistry extended to include the effect of the ortho-P system and the AD system pH.

D. <u>Comparison of the UPO (AS) and UPO(AD)</u>

13 Compare the unbiodegradable particulate organic (UPO) fraction of the NDBEPR WAS determined for the AS (3 above) and AD (9 above) systems respectively.

These objectives cover the various outcomes of this study in different stages. The sequence of above objectives set the order for the presentation of the research in this report.

1.5 Limitation and Boundaries

The steady state AS model including P will be calibrated on the laboratory scale UCT AS system fed wastewater from the Mitchell’s Plain WWTP. The WAS from this system will be fed to the anaerobic digesters. Although the AD model structure will be general, it will be calibrated on the characteristics of the UCT NDBEPR AS system. While it is expected that the AS (OHOs and PAOs) generated from the Mitchell’s Plain wastewater is typical of most NDBEPR AS systems, this cannot be guaranteed. However, it is sewage water that has been used in the WRG UCT research over the past four decades. Therefore, although the predictive accuracy of this steady state AD model is not known for wastewater and AS systems that vary significantly from that used in this study, the results should conform to those of previous UCT WRG studies.

Secondly, the AD model was developed for WAS particulate organics that contain insignificant concentrations of biodegradable (BSO) and unbiodegradable (USO) soluble organics in relation to the particulate organics (PO) fed to the AD system. Therefore it is not known how the hydrolysis kinetic rate of WAS with high BSO and USO concentrations will change.

The extended steady state AD model with the elemental mass balance stoichiometry only predicts the products of digestion in two phases, i.e. the aqueous and gaseous phases. While the potential for mineral precipitation is considered in the evaluation of the AD performance data, this third phase (precipitation) was not modelled. Introducing mineral precipitation was beyond the scope of this Masters Research project. The solid phase can be included in the steady state AD model developed using data from this study. Furthermore, models from previous studies by Loewenthal *et al*. (1994), Musvoto *et al.* (2000) and Ekama *et al.* (2006b) can be applied using the inorganic soluble products from this steady state AD model stoichiometry as input variables.

1.6 Report Layout

The layout of the work is in accordance with normal scientific writing. This work consist of six chapters namely Introduction (Chapter One), Literature Review (Chapter Two), Materials and Methods (Chapter Three), Characterization and AD Model development (Chapter Four), Results and Discussion (Chapter Five) and Conclusions (Chapter Six). This layout provides the overall structure of this work. However, each chapter consists of sectional structures that follows a logical sequence to provides the reader some step by step account of the development and application of the procedures and models.

Chapter One

The introduction chapter provides the rationale for the need of a steady state AD model describing the anaerobic digestion of NDBEPR WAS. Furthermore, the introduction chapter provide some general background into the topic and what the research objectives are to achieve the primary aims of this study. This chapter also gives some insight of the research approach, the limitations of the finding from this study and the overall layout of this work. It has been shown that the method of investigation consists partly of laboratory based experimental work and partly of the extension of mathematical models to evaluate the predicted results against those experimentally measured.

The general structure of Chapters Two, Four and Five are similar. This structure is given in Figure 1.1 below,

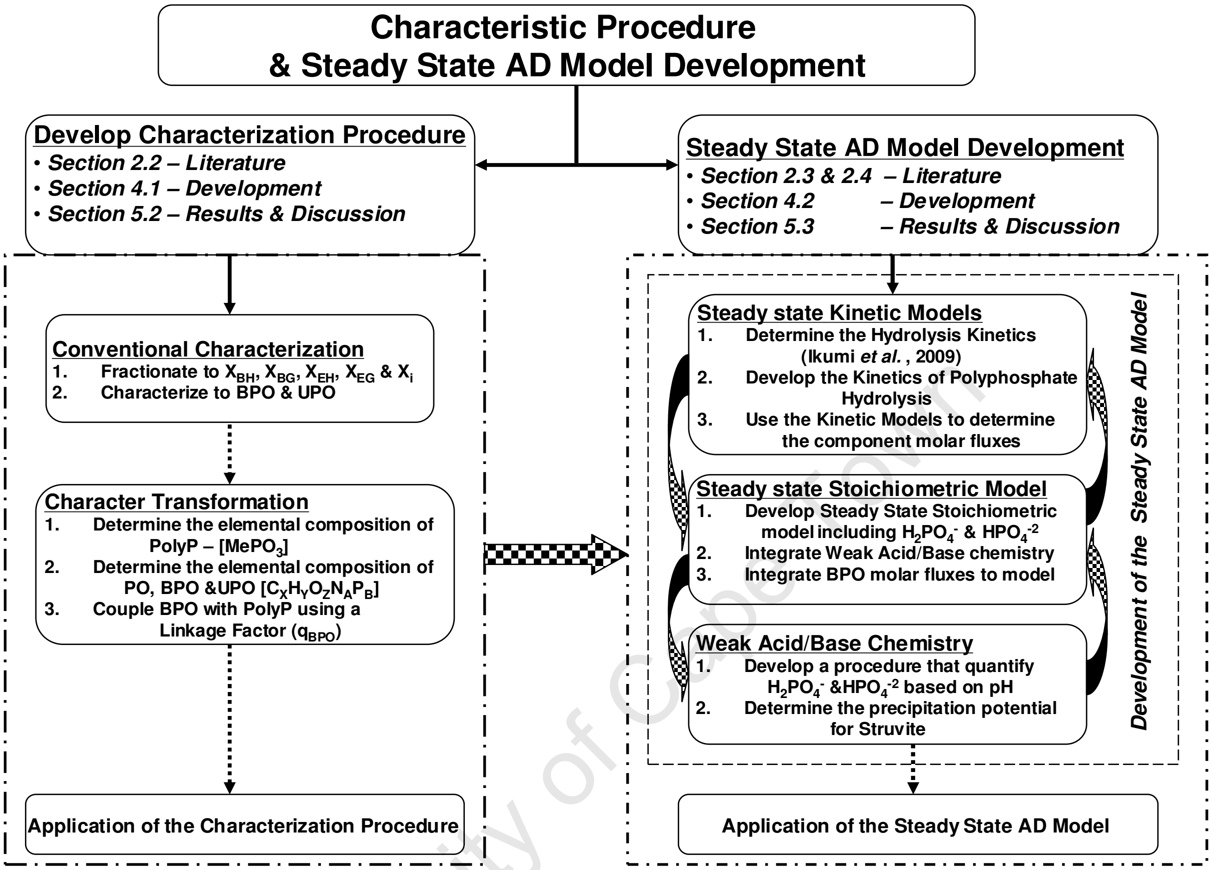

Figure 1.1: General Structure of Chapters 2, 4 and 5

Figure 1.1 describes the main sections and progression used in Chapters 2, 4 and 5 to achieve the core objectives set for this research. Although the full content of Figure 1.1 might not be completely understandable at this stage it does provide the reader with a map towards the final aims of the study. Furthermore, the reader will find this diagram useful while progressing though the relevant chapters.

Chapter Two

Reviews the literature used to support the development of the characterization procedure and steady state model describing the AD of NDBEPR WAS. The scientific publications referred to earlier in this chapter as well as various other publications are reviewed in Literature Review Chapter. Furthermore, this review provides more background detail to this research. This section reviews the ND and NDBEPR AS system configurations and their applications as well as methanogenic anaerobic digestion systems, the waste sludge of these AS and other WWTP systems, the kinetic rates and reaction stoichiometry related to the methanogenic AD system included and other important studies related to this work.

Chapter Three

The Materials and Methods chapter focuses on the experimental setup and analytical methods and procedures used during the experimental investigation phase of this study. The experimental setup relevant to this study consists of a UCT configuration membrane activated sludge system and a continuously stirred tank reaction (CSTR) anaerobic digester. The analytical procedures and testing plan are also described in this section.

Chapter Four

The Characterization Procedure and Steady State Model Development chapter proceeds through the various steps related to the development of the steady state model describing the characterization and anaerobic digestion of NDBEPR WAS. In this chapter the literature reviewed in Chapter Two are used with measured data to develop the model related to this study.

Chapter Five

This results and discussions Chapter presents, evaluates, compares and discusses the predicted results attained from the application of the procedures and steady state models developed in Chapter Four and the measured data obtained from the experimental AS and AD system. The possibility of struvite precipitation is evaluated, validated and discussed in this chapter. Furthermore, the secondary aim of this study, which relates to evaluating whether the UPO as measured in the AS system is the same as UPO as measured in the AS system, is dealt with.

Chapter Six

This chapter reports the conclusions reached from the research presented in earlier chapters. Chapter Six will also recommend further work required that might help to address some difficulties and uncertainty encountered in this work to establish it into the plant wide modelling developments. The final part of this report contains the references and the appendices of all the experimental data and other relevant methods related to this project.

CHAPTER TWO
LITERATURE REVIEW

The aim of this chapter is to review background literature that will support, in Chapter Four, the development of the characterization procedure and the steady state AD model describing the coupling between a nitrification-denitrification biological excess phosphorus removal (NDBEPR) activated sludge (AS) system and an anaerobic digester (AD), fed waste activated sludge (WAS) from the NDBEPR AS system. Furthermore, this background literature also serves as supporting literature to the other chapters in this study. During the period that the research for this study was conducted, the author of this work could not source literature of previous studies with the same specific objective to this project. However, this literature review chapter includes various previous studies that will be used to develop the characterization procedure and steady state AD model related to the characterization and AD of NDBEPR WAS.

The study by Sötemann *et al.* (2005) to develop a steady state model describing the AD of primary sludge (PS) is similar to this study. Sötemann *et al.* (2005) described the coupling of a Primary Settling Tank (PST) and an AD system, fed PS from the PST and later Ekama *et al.* (2006b) modelled the coupling of a nitrification-denitrification (ND) AS system to an AD system. The layout of the Sötemann *et al.* study includes (i) a procedure to characterize the PS to its elemental composition in terms of Carbon (C), Hydrogen (H), Oxygen (O) and Nitrogen (N) and (ii) a steady state AD model that describes the anaerobic digestion of PS or ND WAS to the products of digestion that consist of CH_4, CO_2, HCO_3^-, NH_4^+ and AD biomass ($C_5H_7O_2N_1$). The Sötemann *et al.* (2005) and related studies are described in more detail within this Chapter. This study follows the same approach as that of the Sötemann *et al.* (2005) study but incorporates extensions or/and amendments to fulfil the needs related the AD of NDBEPR WAS. One amendment applied in this study relates to the characterization of NDBEPR WAS containing significant concentration of polyphosphate, which requires a more complex procedure than that of PS or ND WAS. Studies describing the characterization of PS, ND WAS and NDBEPR WAS are reviewed in this chapter.

This study also describes the steady state and dynamic models and the advantages and disadvantages of each. An important issue in this study is the coupling of the AS and AD unit operations and the incompatibilities that arise in the variables of the two systems when doing this. The mass balance based plant-wide steady state models, like that developed by Sötemann *et al.* (2005), for steady state models and Volcke *et al.* (2006) for dynamic models incorporate interface transformation concept to ensure mass and elemental continuity in the modelling of the coupling of different unit operations.

The introduction section below lists the literature reviewed in this study under four headings, (a) the Characterization Procedure of sludge, (b) Anaerobic Digestion, (c) Physico-chemical processes and (d) Plant-wide Modelling.

2.1 Introduction

The development of the reaction stoichiometry associated with the steady state model describing the anaerobic digestion of NDBEPR WAS will adopt a similar approach to that reported by Sötemann *et a*l. (2005) for the anaerobic digestion of ND WAS. The Sötemann *et al.* (2005) steady state AD model consists of three parts,

(i) A COD mass balance hydrolysis kinetics part from which the unbiodegradable COD fraction of the PS organics and the COD of the biodegradable organics utilized is determined for a given AD sludge age.
(ii) A CHON and COD mass balanced stoichiometry part with which the COD and non-COD products of AD are calculated from the biodegradable COD utilized.
(iii) A weak acid/base chemistry part of the inorganic carbon system from which the digester pH is calculated from the relevant AD products.

The steady state AD model to be developed in this study will also comprise these three parts but an important difference arises from dissimilar requirements in the characterization of NDBEPR WAS. This difference is the consequence of the presence of a mixed active mass culture with the introduction of phosphate accumulation organisms (PAOs) and its stored polyphosphate as well as the ordinary heterotrophic organisms (OHOs) that mediate the biological processes in ND WAS described by Sötemann *et al.,* (2005). These differences in characteristics of the NDBEPR WAS result in additional products being formed during anaerobic digestion.

A. __Characterizations Procedure__

The objective of the characterization procedure is to determine the elemental composition of NDBEPR WAS in the format $C_XH_YO_ZN_AP_B$ (biologically bound part) and $MePO_3$ (Polyphosphate part) for use as the input variables to the reaction stoichiometry describing the anaerobic digestion step in the modelling process. This format incorporates the carbon, hydrogen, oxygen, nitrogen, phosphorus and metal content of the NDBEPR WAS as indicated in the introductory chapter of this work.

To improve understanding of this characterization procedure, background literature into ND and BEPR AS systems and the active organisms mediating the biological processes of these AS systems will be reviewed. In support of this, the papers by Marais *et al*. (1976), Wentzel *et al.* (1989), Ekama *et al*. (2004) shall be reviewed. These studies consider the VSS and TSS fractionation into PAOs and OHO biomass, PAO and OHO endogenous residue and inert organic mass from the influent as well as ISS fractionation into ISS from the influent and ISS from the OHOs and PAOs due to their inorganic content, in particular the PAOs with their polyphosphate content. Literature on the composition and structure of polyphosphate will be reviewed, since the storage of polyphosphate by PAOs is an important difference between the WAS from ND and NDBEPR AS systems. To that end, literature from Comeau *et al.* (1985), Arvin *et al.* (1985), Wentzel *et al.* (1985) and others will be reviewed. The VSS and TSS fractionation procedure will be extended by reviewing literature that explores the biodegradable and unbiodegradable components of WAS and primary sludge (PS) as shown by Ekama *et al.* (2006b) and Poinapen *et al.* (2008) for PS. This will conclude by reviewing literature that looks into the transformation of organics from their measured mass fraction ratios (e.g. gC/gVSS) to their elemental composition as required by the AD stoichiometry. In support of this, studies by Wentzel *et al.* (2006), Ekama (2009) and various other will be reviewed.

B. __Anaerobic Digestion__

The objective for the AD section is to review studies that will support the development of a steady state model that can describe the anaerobic digestion of ND BEPR WAS. To obtain adequate background information in support of the objective, this section will review the anaerobic digestion of complex organic waste, like ND WAS and PS, to the product of methane (CH_4), carbon dioxide (CO_2), bicarbonate (HCO_3^-), ammonium (NH_4^+) and anaerobic biomass ($C_5H_7O_2N$). Furthermore, this section will explore the active bacteria that mediate the biological processes of AD, the related reaction stoichiometry of these processes and the kinetic rates related to the substrate utilisation and growth of the AD biomass. This section will also review the generalised Anaerobic Digestion Model No.1 (ADM1). To achieve this, literature from studies by McCarty (1964, 1974 and 1975), Vavilin *et al.* (1996), van Haandel *et al.* (1998), Batstone *et al.* (2002), Sötemann *et al.* (2005) and Jardin *et al.* (1994) will be reviewed.

*C. **Physico-chemical processes***

The physico-chemical processes focus on the non-biological weak acid/base chemistry reactions which occur inside the anaerobic digester and govern the AD pH. These forward/reverse reactions are driven by equilibrium that exist between the reactants and products of the ionic species of single and multiple weak acid/base systems in single (aqueous), two (aqueous-gas) and three phases (aqueous-gas-solid). This weak acid/base chemistry of the system determines the protonated state of a compound, within the AD aqueous environment. Furthermore, this section will review also the weak acid/base chemical equilibria where a compound exists in more than one phase, like CO_2 that can be present in the gaseous and aqueous phase simultaneously. To support this section, background literature from Loewenthal *et al.* (1989, 1994), Moosbrugger *et al.* (1992), Batstone *et al.* (2002), Musvoto *et al*. (2000), van Rensburg *et al*. (2003) and Sötemann *et al.* (2005) will be reviewed.

*D. **Plant-wide modelling***

The section on plant-wide modelling focuses on the development and application of mathematical models of the whole WWTP with all its unit operations linked. These mathematical models can be developed based on steady state or dynamic flow and load conditions. This section will discuss the advantage of each of these types of models and their application. Furthermore, this section will also report on the two generalized standard models, ASM1 and ADM1, developed by specialised tasks groups for the ND activated sludge system and the anaerobic digester within the WWTP. The two approaches to connect these two models for plant-wide modelling are reviewed also. Background literature by Wentzel *et al.* (2006), Grau *et al.* (2007), Batstone *et al.* (2002) , Vanrolleghem *et al*. (2005), Volcke *et al.* (2006), Henze *et al.* (1987, 1995 and 2000) , Reinchert *et al.* (2001) and others are reviewed in support of the concepts presented in this section.

2.2 Characterization

The economical viability of activated sludge (AS) systems for the biological removal of carbon, nitrogen, phosphorus and some counter-ion metals for domestic and industrial effluent has been a driving factor in the popularity of these systems in the treatment of wastewater. An activated sludge system can comprise a single aerated reactor (zone) or various connected reactors functioning as aerated zones, anoxic zones and anaerobic zones. The configuration of these zones determines the removal capability and efficiency of the AS system. This work reviews the background literature for ND AS systems and the NDBEPR AS systems as this will provide insight into the characteristics of the WAS wasted from these systems. It is also reasonable to assume that for AS systems with long sludge ages all the biodegradable organics of the influent wastewater are utilized, producing a WAS mixed liquor suspended solids (MLSS) consisting of active biomass, its endogenous residue mass and the unbiodegradable particulate organics from the influent and if BEPR is included also PAO biomass and its endogenous residue.

2.2.1 Nitrification-Denitrification Activated Sludge systems

To study the ND AS systems this review will examine the modified Ludzack-Ettinger (MLE) AS system (Figure 2.1) which was developed by Barnard (1972) from a system first proposed by Ludzack and Ettinger (1962).

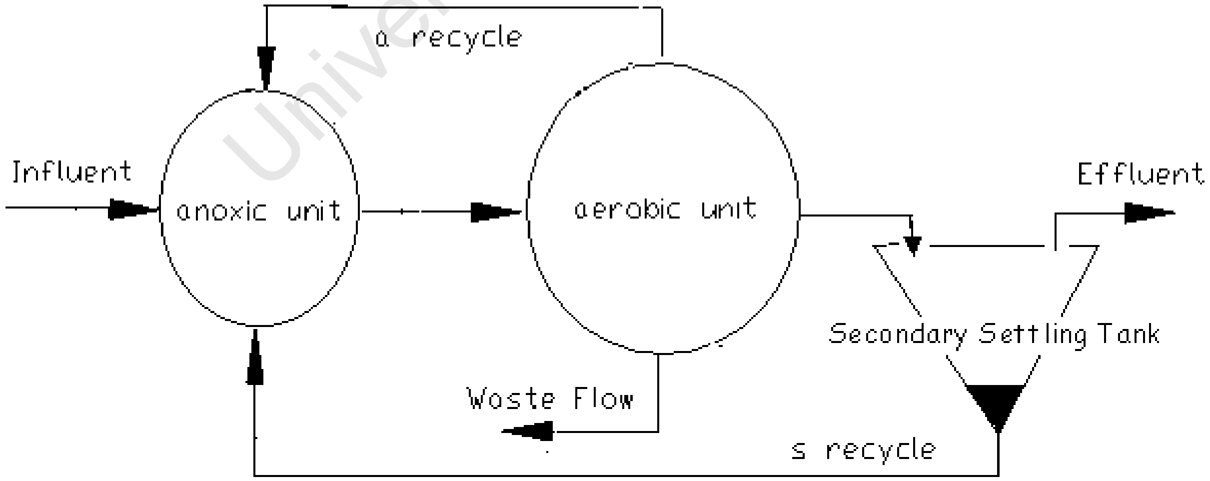

Figure 2.1: Process Flow diagram for the Modified Ludzack-Ettinger System

Ordinary heterotrophic organisms (OHOs) and autotrophic nitrifying organisms (ANOs) mediate the biological processes that are responsible for COD and nitrogen removal in the aerated and anoxic zones of this AS system. The main active mass of the ND AS system are the OHOs. The mass of OHOs in the ND systems makes up 97 to 99% of the live biomass in the system whereas the ANOs only make up 1 to 3% of the live biomass. The configuration of ND AS systems does not support the growth of the organisms responsible for phosphorus removal, the phosphorus accumulation organisms (PAOs), and so have very low P removal capacity. The active OHOs require some phosphorus for growth but P fraction of OHOs (f_{XBHPBM}) is low at about 0.03 mgP/mgVSS (Wentzel *et al.*, 1989) with the result that the P removal is low (2 to 4 mg P/l).

Marais and Ekama (1976) developed a steady state model for the aerobic AS system and later this was extended to include the ND AS system such as the MLE system (WRC, 1984). This steady state model describes AS system in terms of sludge age (R_s) or solid retention time (SRT). Van Haandel *et al.* (1980) extended this steady state model to include dynamic behaviour. Later, several of the concepts included in this model were absorbed into ASM1 (Henze *et al.,* 1987).

2.2.2 ND Biological Excess Phosphorus Removal Activated Sludge systems

Most domestic and some industrial wastewater contain significant concentrations of phosphate that needs to be removed because there is a risk of eutrophication if such water is discharged to rivers or other aquatic systems. Levin and Shapiro (1965) started research into phosphorus removal and showed that phosphates are released from the sludge mass to the bulk liquid in anaerobic conditions and taken up again into the sludge mass in aerobic conditions. Further research developed several theories related to P removal in activated sludge systems, e.g. the availability of short chain fatty acids (SCFA) to promote the growth of the organisms responsible for P removal and the negative effect of denitrification in the anaerobic zones. In due course researchers determined that AS systems including anaerobic, anoxic and aerobic zones are effective in the removal of COD, N and P from wastewater. These AS systems are known as nitrification-denitrification biological excess P removal (NDBEPR) AS systems. The UCT system (Figure 2.2) is an example of a ND BEPR AS system.

The heterotrophic organisms responsible for P removal are collectively called phosphorus accumulating organisms (PAOs). The PAO population is a significant proportion of the other organism populations active within a NDBEPR AS system such as the OHOs and therefore their mass cannot be ignored like the ANOs. Consequently, the biomass mediating the biological activities in the ND BEPR functions is a mixed culture of micro-organisms. This mixed culture comprises of OHOs (including ANOs) and PAOs. The mixed biomass culture changes the structure of the AS models (steady state and dynamic) compared with the single (OHO) biomass models for the ND system.

For the most part the function of the OHOs in the NDBEPR activated sludge system remains similar to that in the ND AS system except for the additional fermentation process they mediate which convert readily biodegradable COD to short chain fatty acids (SCFA) in the anaerobic zone (Wentzel *et al.*, 1989). The presence of SCFA in the anaerobic zone promotes the growth of PAOs. In the absence of oxygen, the polyphosphates (Polyphosphate), stored inside the PAOs, are cleaved to produce energy for sequestration (uptake) of SCFA. The SCFA are stored inside the PAOs as poly-hydroxyalkanoates (PHA). This results in phosphate release to the bulk liquid in the anaerobic zone. The OHOs present in the mixed culture biomass cannot take-up any substrate due to the absence of an electron acceptor, such as oxygen or nitrate. When nitrate or oxygen enters the anaerobic zone, the OHOs consume the RBCOD fermentation product themselves and so do not release SCFA to the bulk liquid for the PAOs. This results in competition between the OHOs and PAOs for the SCFA present, which reduces the growth of PAOs in the AS system.

When the PAOs enter the aerobic zone the internally stored PHA is utilized via the normal metabolic processes within the PAOs cells. The released phosphorus is taken up again and the new generation of PAOs grown also take up P in excess resulting in a greater uptake than release. The PAOs can store up to 0.38 mgP/mgPAOVSS (f_{XBGP}) (Wentzel *et al.*,1989). This stored P is in the form of polyphosphate (f_{XBGPP}) and the P required for biological cell construction (f_{XBGPBM}). For mixed cultures, the f_{XBGPP} can be lower, resulting in a low phosphorus storage capacity for PAOs in particular when a significant uptake of P takes place in the anoxic reactor (Ekama and Wentzel, 1999; Hu *et al.,* 2003). The polyphosphate content needs to be determined for each BEPR AS system and may vary from time to time (Ekama and Wentzel, 2004). The causes for the different P content of PAOs are not exactly understood yet.

The UCT NDBEPR AS system was developed in the early 1980's to avoid the recycle of nitrate to the anaerobic zone so the biological P removal behaviour could be investigated without the interfering influence of the nitrate recycle to the anaerobic zone. Before this the AS systems were based on Phoredox BEPR principle, for example the 5 stage Bardenpho systems. The Phoredox configuration allowed significant quantities of nitrate to be recycled to the anaerobic zone, limiting the growth of PAOs from the influent RBCOD (Siebritz *et al.*, 1983). This problem is eliminated in the UCT configuration NDBEPR AS system (Fig.2.2) and is the reason this system was operated in this investigation.

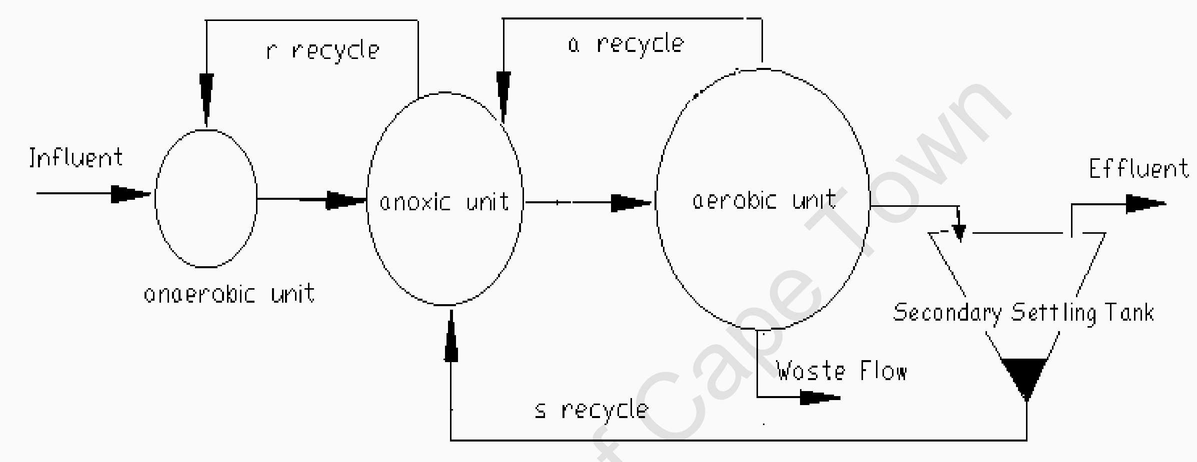

Figure 2.2: Process flow diagram for the UCT NDBEPR AS System

2.2.3 The Structure and Composition of Polyphosphate

Polyphosphate is a significant component of PAOs and, as such is important in the characterization of the elemental composition of the PAO biomass. The inorganic polyphosphate stored inside the PAOs is linear structured polymers of ortho-phosphate with chain lengths of a few monomers to several hundred. Energy-rich phosphoanhydride bonds link the ortho-phosphate components together (Kulaev *et al.*, 1999). Each orthophosphate monomer component within the polymer chain carries a negative charge.

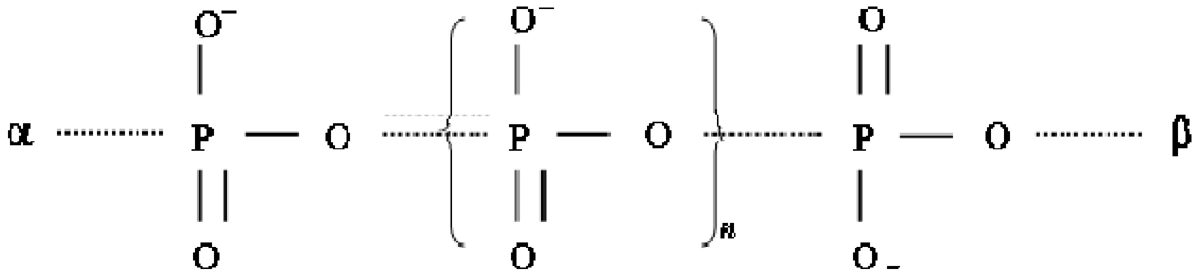

Figure 2.3: Linear structure of Polyphosphate. (Kornberg et al., 1999)

Studies by Miyamoto-Mills *et al.* (1983), Gerber *et al.* (1983), Arvin *et al.* (1985) and Comeau *et al.* (1985) showed the concurrent release and uptake of phosphate and metal cations. The function of these counter-ion metals is to neutralise the charges on the phosphate polymers stored inside the PAOs. The charge neutralisation effect reduces the activity of the Polyphosphate inside the PAOs.

The studies by Miyamoto-Mills *et al.* (1983), Arvin *et al.* (1985) and Comeau *et al.* (1985) found that the metal cations involved in this charge neutralising activity on the phosphate polymer are K^+, Mg^{2+} and Ca^{2+} . This is shown from the table published by Comeau *et al.* (1985):

Table 2.1: Cations co-transported with phosphorus (Molar Ratio) – (Comeau *et al.,* 1985)

Direction of transport	***P release***	***P release***	***P release / uptake***	***P release***	***P release***
K^+ / P	**0.27**	**0.23**	**0.34**	**0.20**	**0.23**
Mg^{2+} / P	**0.26**	**0.32**	**0.24**	**0.28**	**0.27**
Ca^{2+} / P	**0.00**	**0.05**	**0.06**	**0.94**	**0.12**
Charge Balance	**0.79**	**0.97**	**0.94**	**0.94**	**1.01**
Researcher	*Miyamoto-Mills*	*Arvin et al.(1985)*	*Comeau (1985)*		

Based on the observed measurements listed in Table 2.1, the elemental composition of polyphosphate relates to a PO_3^- : Mg^{2+}: K^+: Ca^{2+} molar ratio. The molar ratio P: Mg: K: Ca, as an average of the three studies shown in Table 2.1 is 1: 0.275: 0.295: 0.05 respectively. Furthermore, the charge neutralising capacity of K^+ relates one PO_3^- component forming KPO_3. In the case of Mg^{2+} and Ca^{2+} two PO_3^- components are neutralised forming $Mg(PO_3)_2$ and $Ca(PO_3)_2$ respectively (Arvin *et al.,*1985).

Earlier in this chapter the uptake and storage of SCFA by PAOs to produce PHA was described as a concurrent process with the degradation of Polyphosphate. This degradation process is named hydrolysis of Polyphosphate and produce ATP when it is presumed that no energy is produced (Smolder *et al.,* 1995). The equation used by Smolder *et al.* (1995) is shown in E2.1 (where $MePO_3$ is used in place of HPO_3)

$$[MePO_3]_n + xH_2O \leftrightarrow aATP + bH_2PO_4^{-} + cMe^{+} \tag*{(E 2.1)}$$

2.2.4 Steady state AS models used to Fractionate WAS

The Wentzel *et al.* (1990) steady state AS model describes the behaviour of mixed OHO and PAO culture in NDBEPR AS systems like the UCT system. This model describes the symbiotic relationship between OHOs and PAOs in the anaerobic zone where the OHOs convert the fermentable soluble biodegradable organics (f-RBCOD) to SCFA for use by PAOs. The model makes provision for nitrate recycled to the anaerobic zone resulting in competition between OHOs and PAOs. This fermentation process governs the partition of the influent f-RBCOD between the PAOs and OHOs. The PAOs get all the influent VFA and the f-RBCOD converted to VFA. The OHOs get all the slowly biodegradable organics and the f-RB organics not converted to VFA. Once the masses of OHOs and PAOs that accumulate in the reactor are known, the endogenous residue produced by each is calculated. The unbiodegradable particulate organics (UPO) from the influent wastewater that accumulate in the reactor is modelled identically as in the ND AS model. So for known wastewater characteristics (unbiodegradable soluble COD fraction (f_{usi}), unbiodegradable particulate COD fraction (f_{upi}) and readily biodegradable COD fraction with respect to the biodegradable COD ($f_{SB's}$)), the active OHOs (X_{BH}), endogenous OHOs (X_{EH}), active PAOs (X_{BG}), endogenous PAOs (X_{EG}) and the UPO (inert) mass from the influent that accumulates in the reactor (X_I) of the VSS can be calculated as shown in Eqs. 2.2a to 2.3, where % represents the % of RBCOD utilised by the PAOs (usually 80 – 100%).

A. Determining the active PAOs (X_{BG})and OHO (X_{BH}) mass

$$X_{BG}=\left(\frac{Q_i S_{ti}}{V_p}\right)\left(1-f_{upi}-f_{usi}\right)\left[\left(\frac{\%}{100}f_{SBs}\right)\frac{Y_G R_s}{1+b_{GT} R_s}\right]_s \qquad \textbf{(E 2.2a)}$$

$$X_{BH}=\left(\frac{Q_i S_{ti}}{V_p}\right)\left(1-f_{upi}-f_{usi}\right)\left[\left(1-\frac{\%}{100}f_{SBs}\right)\frac{Y_H R_s}{1+b_{HT} R_s}\right]_s \qquad \textbf{(E 2.2b)}$$

B. Determine the Endogenous PAOs (X_{EG})and OHO (X_{EH}) mass

$$X_{EG}=\left(\frac{Q_i S_{ti}}{V_p}\right)\left(1-f_{upi}-f_{usi}\right)\left[\left(\frac{\%}{100}f_{SBs}\right)\left(f_{EG} b_G R_s X_{BG}\right)\right]_s \qquad \textbf{(E 2.2c)}$$

$$X_{EH}=\left(\frac{Q_i S_{ti}}{V_p}\right)\left(1-f_{upi}-f_{usi}\right)\left[\left(1-\frac{\%}{100}f_{SBs}\right)\left(f_{EH} b_H Rs X_{BH}\right)\right]_s \qquad \textbf{(E 2.2d)}$$

C. Determine the influent UPO (inert) mass (X_I),

$$X_I=\left(\frac{Q_i S_{ti}}{V_p}\right)\frac{f_{upi}}{f_{cv}}R_s \qquad \textbf{(E 2.2e)}$$

The sum of the active mass, the endogenous residue mass and the accumulated inert mass produce the VSS (X_V) (Ekama and Wentzel, 2004). So adding Eqs. 2.2a and 2.2e yields,

$$X_V=\left(\frac{Q_i S_{ti}}{V_p}\right)\left[\left(1-f_{upi}-f_{usi}\right)\left[\left(\frac{\%}{100}f_{SBs}\right)\frac{Y_G R_s}{1+b_{GT} R_s}\left(1+f_{EG} b_{GT} R_s\right)+\left(1-\frac{\%}{100}f_{SBs}\right)\frac{Y_H R_s}{1+b_{HT} R_s}\left(1+f_{EH} b_{HT} R_s\right)\right]+\frac{f_{upi}}{f_{cv}}R_s\right]$$

(E 2.3)

where % defines the portion of influent RBCOD obtained by the PAOs (usually between 80 and 100%). From Eqs. 2.2a to 2.2e, the active mass of the PAOs and OHOs with respect to VSS

(f_{avPAO} and f_{avOHO}) are given by f_{avPAO} = X_{BG}/X_V. With the different components of the VSS known, the P removal (ΔP, mgP/l influent) is calculated by assigning a P content to each component and noting that the mass of VSS wasted per day is the mass of VSS in the reactor divided by the sludge age i.e.

$$\Delta P = \frac{V_P}{Q_i Rs}\left[f_{XBGP} X_{BG} + f_p\left(X_{BH} + X_{EH} + X_{EG} + X_I\right)\right] \qquad \textbf{\textit{(E 2.4a)}}$$

All the equations stated in this section conform to the arrangement and symbols used in WRC (1984).The P content of the non PAO VSS components (f_P) are accepted to be 0.03 mg P/ mg VSS as stated by Wentzel *et al.* (1990). For predominantily aerobic P uptake (Ekama and Wentzel, 1999), the P content of the PAOs (f_{XBGP}) was measured by Wentzel *et al.* (1989) to be 0.38 mgP/mgPAOVSS, of which 0.03 is biomass P and 0.35 is polyphosphate.

The Polyphosphate content of the PAOs contributes significantly to the inorganic suspended solids (ISS) content of the NDBEPR WAS (Ekama and Wentzel, 2004). Wentzel *et al.* (1989) measured the VSS/TSS ratio in an enhanced PAOs culture systems at 7.5, 10 and 20 day sludge ages and obtained 0.45, 0.46, 0.46, and 0.48 mgVSS/mgTSS. This differs significantly from the 0.83 to 0.87 mgVSS/mgTSS ratios observed for ND AS systems (Power *et al.*, 1992; Ubisi *et al.*, 1997 and Beeharry *et al.*, 2001). This high ISS content is due to the high polyphosphate and associated conter-ion metal content of the PAOs. From its composition mentioned above it has an ISS value of 3.19 mgISS/mgP. Ekama and Wentzel (2004) measured 3.286 mgISS/mgP in a wide range of NDBEPR systems. Hence, the ISS content (f_{iPAO}) of the PAO with a P content of f_{XBGP} is given by

$$f_{iPAO} = f_{iOHO} + 3.286\left(f_{XBGP} - 0.03\right) \qquad \textbf{\textit{(E 2.4b)}}$$

where f_{iOHO} is the ISS content of the OHOs = 0.15 mgISS/mgOHOVSS which is also assigned to the PAO biomass.The total ISS concentration is the sum of that of the OHO and PAO ISS and the ISS that accumulate in the reactor from the influent. i.e.

$$X_{IO} = f_{iOHO} X_{BH} + f_{iPAO} X_{BG} + \left[\frac{Q_i X_{IOi} Rs}{V} \right] \qquad \textbf{\textit{(E 2.4c)}}$$

where X_{IOi} is the influent ISS concentration (mgISS/l)

Practically, the wastewater characterization (determining the f_{us} and f_{up}) and VSS fractionation is done simultaneously, with the NDBEPR AS model of Wentzel *et al.* (1990) and the ISS model of Ekama and Wentzel (2004) reviewed above. The f_{us} is simply function of the effluent filtered COD and total influent COD concentration (f_{us} = S_{use}/S_{ti}). The RBCOD concentration is measured and expressed as a fraction with respect to the biodegradable COD i.e. $f_{SB's}$= S_{bsi}/ [S_{ti} (1- f_{up}- f_{us})]. The f_{up} is found by trail and error. Provided the COD balance on the experimental system is acceptable, the correct value for f_{up} is the value at which the calculated VSS mass in the NDBEPR system matches that measured. Once f_{up} is known then the concentration of the 5 components making up the VSS is also known. With f_{up} known X_{BG} is known and the correct value for the P content of the PAOs (f_{XBGP}) is that value for which the calculated P removal equals that measured for an accepted P content of the non-PAO VSS constituents of say 0.03 mgP/mgVSS. With the polyphosphate content of the PAOs known (f_{XBGPP} = f_{XBGP}), the ISS concentration can be calculated from the ISS content of the OHOs and PAOs plus the ISS accumulated in the reactor from the influent. This calculated ISS should then match quite closely the measured ISS.

2.2.5 Biodegradable and Unbiodegradable Components

Knowledge of the characteristics of WAS and PS is required to use of the steady state anaerobic (AD) or aerobic digestion (AerD) models. The WAS and PS can be characterized (subdivided) into organic COD and inorganic (ISS) components that are either soluble (dissolved) or particulate (solid). Furthermore, the organic part is sub-divided into biodegradable soluble organics (BSO), biodegradable particulate organics (BPO), unbiodegradable soluble organics (USO) and unbiodegradable particulate organics (UPO). Insofar as the AS system is concerned the BPO of WAS is the biodegradable part of the OHOs and PAOs and any residual biodegradable organics from the influent in cases where the AS system sludge age (R_s) is too short for utilisation of all influent biodegradable organics. Additionally, the WAS UPO comprises the endogenous residue mass of the OHOs and PAOs produced on the AS system (X_{EH}, X_{EG}), the part of the OHO and PAO biomass (X_{BH}, X_{BG}) that is unbiodegradable and the unbiodegradable particulate organics (UPO) from the influent that accumulate in the reactor. For PS, the BSO comprise of VFA and RBCOD but for WAS this is usually zero. This characterization scheme is shown in the Figure 2.4 below,

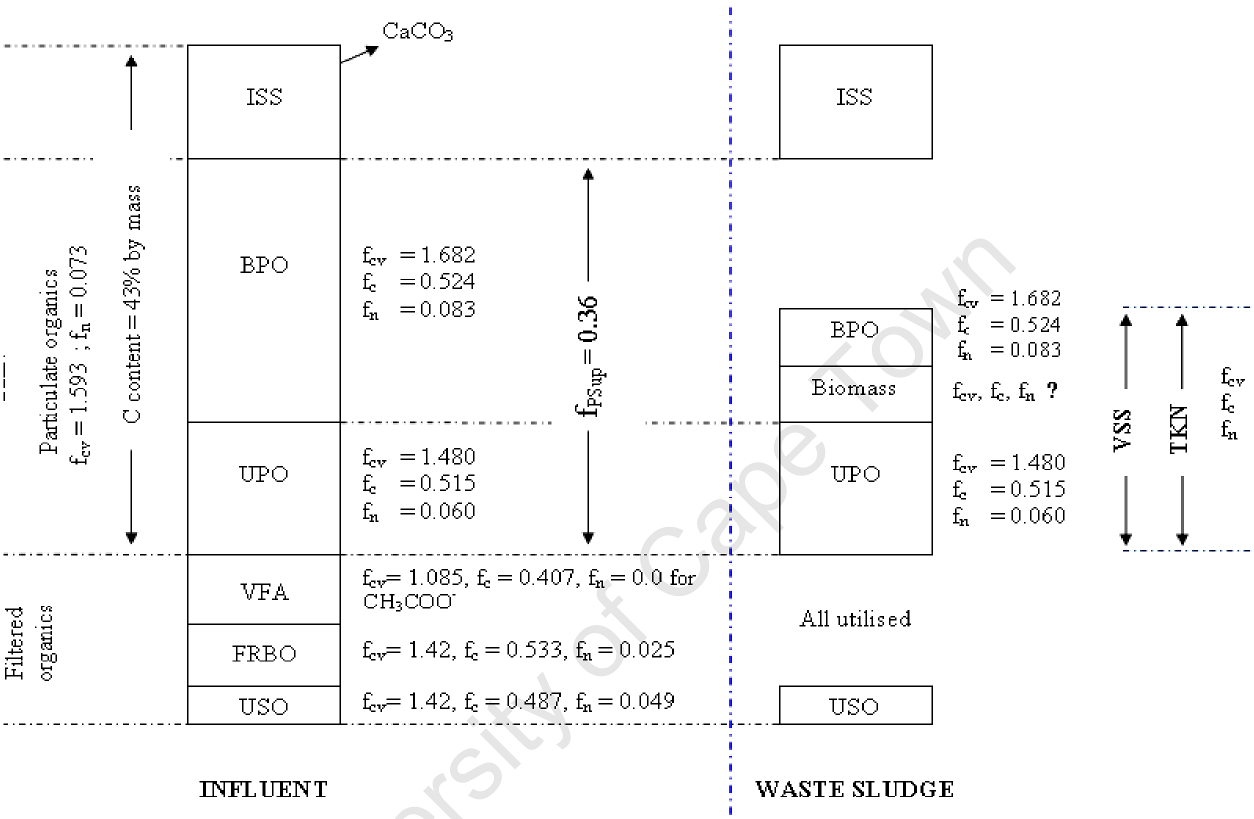

Figure 2. 4: Characterization of PS influent and AD effluent (waste) sludge (Poinapen et al., 2008)

Poinapen *et al.* (2008) used PS as influent for a biological sulphate reduction (BSR) in an upflow anaerobic sludge bed (UASB) reactor. The PS was characterized as shown in Figure 2.4 to determine the BPO, UPO, SBO, USO and ISS components for the PS.

For WAS, provided the unbiodegradable organics from the AS system remain unbiodegradable in the AD (which is validated also in this investigation, Ikumi at al., 2009), the characterization is simpler and can be determined from the VSS composition. So, the UPO ($S_{up(AS)}$) of ND WAS is the sum of its inert mass (X_I), the endogenous residue mass (X_{EH}) and the unbiodegradable partof the active mass, which in terms of the death regeneration model is 8% of the X_{BH} (as determined by Mebrahtu et al., 2008).

This is described by E2.4d at shown below,

$$S_{up(AS)} = \left[X_{inert} + X_{EH} + 0.08\left(X_{BH}\right)\right]f_{cv} \qquad \textbf{\textit{(E2.4d)}}$$

This approach was adopted by Ekama *et al.* (2006b) for the AD of ND WAS and Sötemann *et al*. (2005) for aerobic digestion of ND WAS. That this approach predicted the correct unbiodegradable fraction of the WAS for aerobic digestion is not surprising because aerobic (or anoxic-aerobic digestion) is merely a continuation of the same bioprocesses in the AS system. But what is surprising is that the approach also predicted the correct unbiodegradable fraction for the AD. This means that the UPO concentration as defined by the AS system remained unbiodegradable in the AD system. This simplifies plant wide modelling because the definition of the BPO and UPO seem to carry through the whole WWTP. The same was found for the unbiodegradable particulate fraction of PS ($f_{PS'up}$). Very closely similar $f_{PS'up}$ fraction of PS was measured in AD experiments as estimated for the PS from a COD balance over the PST and UPO COD fraction (f_{upi}) of raw and settled wastewater to the AS system (Sötemann *et al.,* 2005; Wentzel *et al.,* 2006). This approach will therefore also be adopted in this study and checked with the experimental results measured on the AS and AD systems.

2.2.6 Elemental Compositions of Organics

The characterization procedure to determine the different components of WAS and PS is extended to include the elemental composition of the components in terms of their Carbon, Nitrogen, Hydrogen and Oxygen content. This is done to transform the output parameter of the activated sludge system to the form required for the input variables of the steady state AD model. This characterization approach is similar to that of dynamic model ADM1 (Batstone *et al*., 2002). However, instead of the influent organics being characterized to carbohydrate, lipids and proteins as is the case for AMD1, the influent biodegradable organic types (VFA, f-RBCOD and BPO) are defined in their elemental composition of C, H, O and N in the format $C_XH_YO_ZN_A$. As far as possible this elemental composition is determined from measurements.

To date, the elemental composition in terms of C, H, O and N have only been determined for PS and WAS from fully aerobic and ND AS systems. The phosphorus (P) and metal content of this NDWAS is insignificant and so were excluded from the elemental composition with little or no impact on the stoichiometric reactions involving PS or NDWAS or a mixture of both.

The procedure used to determine the elemental composition of PS or ND WAS is explained by Ekama *et al.* (2006b). In light of the importance of this procedure to this study, a summary of this is presented. A more detailed description of the method for determining the X, Y, Z and A values in the elemental composition $C_XH_YO_ZN_A$ for BPO of ND WAS or PS given by Ekama (2009).

To determine the four unknowns X, Y, Z and A, at least four measurements are needed, i.e. the fractional mass of N, O, H and C of the VSS of the WAS (i.e. f_N, f_O, f_H and f_C g element/g VSS respectively). Due to equipment constrains, elemental analysis for fractional mass of O, H and C are not normally preformed. However, analytical measurements for three i.e. COD, VSS and TKN can be routinely measured and so the f_N and f_{cv} ratios of the VSS can be determined. which are usually expressed as mass fractions f_{cv} and f_N, the COD/VSS and N/VSS ratio of the VSS. One additional measurement is therefore required. The best is the C content of the solids (f_C, gC/gVSS) which can be measured via Total Organic Carbon (TOC) analysis. The O and H ratios (f_O and f_H) do not need to be measured because the O content is replaced by COD and the H content by mass balance, i.e. $f_C + f_H + f_O + f_N = 1$. So if f_{cv}, f_C and f_N are known the X, Y, Z and A values in $C_XH_YO_ZN_A$ can be calculated. Sötemann *et al.* (2005) determined f_{cv} and f_N of PS from measurements of COD, VSS, TKN and FSA on the influent and effluent samples of the ADs. However, they needed the f_C also which was not measured in the data set they used for model validation so they calculated it from the measured CO_2 (gas and dissolved) and CH_4 production.

The problem of this approach is that the BPO and UPO cannot be separated, unless the AD is operated at a very long sludge age so that the BPO are all utilized and the effluent solids are all unbiodegradable (plus a little AD biomass). At short sludge ages the AD influent and effluent solids comprise both BPO and UPO and so COD, VSS and OrgN measurements on the influent and effluent solids includes both components, making the composition of the BPO and UPO difficult to isolate.

The problem of isolating the mass fraction ratios of the BPO and UPO not withstanding, accepting that the f_{cv}, f_C and f_N for the WAS are known and a value of Y selected (say at seven), then the values of X, Z and A can be calculated[1]*. This is accomplished by using equations E2.5a to E2.5c (Ekama *et al.*, 2006b; Ekama, 2009),

$$Z = \frac{Y\left(1 - {f_{CV}}/{8} - {8f_C}/{12} - {17f_N}/{14}\right)}{2\left(1 + f_{CV} - {44f_C}/{12} + {10f_N}/{14}\right)} \quad \textit{(a)} \qquad X = \frac{f_C(Y + 16Z)}{12(1 - f_C - f_N)} \quad \textit{(b)}$$

$$A = \frac{f_N(Y + 16Z)}{14(1 - f_C - f_N)} \quad \textit{(c)} \qquad \textit{(E 2.5)}$$

These equations are derived by simultaneously solving the equations for f_{CV}, f_C and f_N mass ratios of an organic in terms of the X, Y, Z and A molar compositions as shown in Eqs. 2.6a to 2.6e. These equations for organic COD, VSS, total organic carbon (TOC) and Total Kjeldahl Nitrogen (TKN) incorporate X, Y, Z and A for each of the stated parameter. This is shown in the Equations E2.6a to E2.6e that follows,

$$COD = 4X + Y - 2Z - 3A = D_S \quad (a) \qquad VSS = 12X + Y + 16Z + 14A = MM_{COMPOUND} \quad (b)$$

$$f_C = \frac{TOC}{VSS} = \frac{12X}{12X + Y + 16Z + 14A} \quad (c) \qquad f_N = \frac{TKN}{VSS} = \frac{14A}{12X + Y + 16Z + 14A} \quad (d)$$

$$f_{CV} = \frac{COD}{VSS} = \frac{4X + Y - 2Z - 3A}{12X + Y + 16Z + 14A} \quad (e) \qquad \textit{(E 2.6)}$$

This same procedure can be used to determine the elemental composition the UPO and BPO for WAS and the BPO and UPO for PS, provided the mass ratios f_{CV}, f_C and f_N for these organics are known. This approach will be adopted also in this study, except the equations will be expanded to include P of ND WAS, PS and NDBEPR in terms of C, H, O, N and P, which will be derived in Chapter 4.

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[1] * Any of the X, Y, Z and A can be accepted as a basis for the elemental composition of the organics. To conform to some data in literature, Ekama (2009) selected X=1. It is easy to change the basis,e.g. with X=1, the composition becomes $C_1H_{Y/X}O_{Z/X}N_{A/X}$.

2.2.7 Short Review of Organic Elemental Compositions for PS and ND WAS

This review presents and compares various elemental compositions for PS and ND WAS determined from studies within the Water Research Group (WRG) of the Department of Civil Engineering at University of Cape Town, as well as that found from studies in the literature. This is done to determine the possible range for elemental composition and as such place the results of this investigation within the context of other findings. At this stage, no values have been set for what the elemental composition for UPO and BPO of PS and NDWAS approximately should be. Results from studies by Ekama *et al.* (2006a&b), Wentzel *et al.* (2006), Sötemann *et al.* (2005), Ristow *et al.* (2004), Poinapen *et al.* (2008) and Volcke *et al.* (2006) give some values and these will be reviewed below. The procedure used to determine the elemental compositions for the components of UPO and BPO is that described above except for the study by Volcke *et al.* (2006) which accepted some literature values.

2.2.7.1 Ekama *et al.* (2006b)

To test the characterization procedure described in Section 2.2.6 , Ekama *et al.* (2006b) determined the elemental composition for experimental data from Van Haandel *et al.*, (1998) for the WAS from an aerobic lagoon AS system at 2 day retention time. Ekama *et al.* (2006b) used the measured data from Van Haandel *et al.*(1998) to determine the elemental composition of the BPO and PO (BPO+UPO) components of WAS. The elemental composition of the BPO was determined at $C_{5.67}H_7O_2N_{0.865}$. The PO (BPO+UPO) composition of the same WAS was also determined and found to be $C_{4.96}H_7O_2N_{0.773}$. Except for the N content, this is not significantly different from the elemental composition generally accepted for active mass, like OHOs, $C_5H_70_2N_1$ (WRC, 1984).

On determining the composition of WAS from their own AS system, a ND system at 15 day sludge age, Ekama *et al.* (2006b) found the elemental composition of PO, BPO and UPO to be $C_{3.513}H_7O_{1.921}N_{0.431}$, $C_{3.69}H_7O_{1.999}N_{0.503}$ and $C_{3.724}H_7O_{1.885}N_{0.393}$ respectively. This is significantly different from that found for the composition of the aerated lagoon of WAS of Van Haandel *et al.* (1998). However, this difference is probably due to using the C in the CO_2 (gaseous and dissolved) and CH_4 production to calculate the C content of the BPO. Ekama *et al.* determined a C/VSS ratio (f_C) of 0.544 for the PO and 0.57 for the BPO of the WAS from the van Haandel *et* *al.* (1998) aerobic lagoon WAS and a C/VSS ratio of 0.491 for the PO, 0.491 for the BPO and 0.512 for the UPO for their own 15 day sludge age ND AS system WAS. These compositions are based on the experimental system C balance so are subject to error.

2.2.7.2 Sötemann *et al.* (2005) and Ristow *et al.* (2004)

Sötemann *et al.* (2005) determined the elemental composition of PS BPO with the aid of their steady state anaerobic digestion model because the Izzett and Ekama (1992) AD data set they used for model validation did not include TOC measurements on the influent and effluent solids. So the f_{cv}, f_N and f_C ratios of the BPO were calculated from the measured COD and VSS removal, the FSA produced and the C in the CO_2 (both aqueous and gaseous) and CH_4 generated. This approach is approximate because it assumes zero AD biomass production and assumes that the effluent solids are only UPO which for PS is reasonable but for WAS is not. From the measurements they obtained for f_{cv}, f_N and f_C values of PS BPO 1.48 mgCOD/mgVSS, 0.033 mgN/mgVSS and 0.502 mgC/mgVSS respectively, yielding a PS BPO composition of $C_{3.5}H_7O_2N_{0.196}$ for the Izzett and Ekama (1992) AD data.

To confirm whether the composition determined for the Izzett data was reasonable for PS, Sötemann *et al.* (2005) acquired various PS samples from the Mitchell's Plain and Athlone WWTPs in Cape Town (South Africa). These samples were then analysed to determine the COD, VSS, TSS and OrgN and then sent to an independent laboratory in dry solid form to determine the elemental C, H and N content of the dried sludge. Accepting that the results obtained give the C, H and N contents with respect to the TSS (dried solids), the f_C, f_H and f_N ratios were calculated with respect to the VSS and f_O from mass balance, i.e.($f_O = 1 - f_N + f_C + f_H$) following the characterization framework set out in Figure 2.4 for influent PS (but with different values). With mass fractions so determined, the X, Y, Z and A elemental composition was calculated. Then from the elemental composition the COD/VSS ratio was calculated. If the calculated f_{cv} was different to that measured, the f_O was adjusted until the measured f_{cv} ratio was obtained. In this way elemental composition of the PS PO (BPO + UPO) from the Mitchell's Plain and Athlone WWTPs was determined to be $C_{3.91}H_7O_{2.04}N_{0.16}$ and $C_{3.38}H_7O_{01.9}N_{0.21}$ respectively. The composition of $C_{3.5}H_7O_2N_{0.198}$ determined for the BPO of PS is between the two PS compositions, which was deemed an acceptable validation of the steady state AD model by Sötemann *et al.* (2005). This AD model will be extended to include P in this investigation.

Following the same procedure Wentzel *et al.* (2006) evaluated the AD data of Ristow *et al.* (2004) from their 60 day sludge age AD fed with PS from the Athlone WWTP. Accepting that at such a long retention time, all the BPO are utilized, they determined the elemental composition for the UPO of PS being determined to be $C_{4.62}H_7O_{4.4}N_{0.24}$.

2.2.7.3 Ekama (2009)

Ekama (2009) compiled all the PS and WAS composition data measured in various investigations in a Table (Table 2.2), with comments on how these values were determined. The elemental composition in this Table 1 of Ekama (2009) are given with respect to X (for the C) = 1, not for Y (for the H) = 7. However, Y was set = 7 in this study before Ekama (2009) changed to X = 1. It is easy to recalculate the basis for the elemental composition from Y = 7 to X = 1 using the formula below,

$$C_1H_{Y/X}O_{Z/X}N_{A/X} \qquad \textbf{(E2.7a)}$$

The compositions listed in Table 2.2 will be useful to compare the elemental composition obtained in this investigation for BPO and UPO component of NDBEPR WAS. The only difference is that the X, Y, Z and A values will change slightly when P is included because the mass balance then changes to ,

$$f_C + f_H + f_O + f_N + f_P = 1 \qquad \textbf{(E2.7b)}$$

Table 2.2 is a summarized version of Table 1 from Ekama (2009) and is included to provide a comparison with the composition resulted in this investigation.

Table 2.2: Composition of various OP from data measured on methanogenic and sulphidogenic AD

Reference	Data Source	Sludge Type	Organic Type	Unbio Frac	gCOD/ gVSS	gC/ gVSS	gH/ gVSS	gO/ gVSS	gN/ gVSS	mgN /gCOD	x	y	z	a	Notes
McCarty (1975)	Theoretical	Activated sludge	Biomass	-	1.416	0.53	0.06	0.28	0.12	87.6	5.00	7.00	2.00	1.00	Commonly accepted composition for WAS. Used when linking ASM1 and ADM1 models (Volcke *et al.*, 2006, Jeppsson *et al.*, 2006).
			End Residue	-											
			UPO	-											
Dold *et al.* (1980)	Used in ASMs 1&2	Activated sludge	Biomass		1.48	0.52	0.07	0.31	0.1	67.6	4.08	7.00	1.85	0.68	Used in ASM 1 and 2 dynamic models.
			End Residue												
McCarty (1975)	Theoretical	Specific organics	Starch	0.46	1.185	0.44	0.06	0.49	0	0	4.19	7.00	3.49	0.00	A mixture of 46% Starch ($C_6H_{10}O_5$) + 37% lipids [$H(CH_2)_nCOOH$] and 17% proteins ($C_{16}H_{24}O_5N_4$) produces $CH_{1.741}O_{0.502}N_{0.050}$, which is close to PS BPO of Poinapen *et al.* (2008)
			Lipids	0.37	2.875	0.75	0.13	0.13	0	0	3.50	7.00	0.44	0.00	
			Proteins	0.17	1.5	0.55	0.07	0.23	0.16	106	4.66	7.00	1.46	1.17	
				Mix	1.633	0.53	0.08	0.36	0.03	19	4.02	7.00	2.02	0.20	
Sötemann *et al.* (2005)	Izzett et al (1992)	Primary and humus	UPO+BPO	0.36											Determined C content of BPO from C balance over ADs. Calculated UPO by difference between PS (UPO+BPO) data below and BPO.
			BPO		1.568	0.5	0.08	0.38	0.03	21	3.50	7.00	2.00	0.20	
	Meth ADs		UPO		1.69	0.54	0.08	0.35	0.03	16	3.89	7.00	1.90	0.17	
Sötemann *et al.* (2005)	Own data	Primary sludge	UPO+BPO	?	1.609	0.52	0.08	0.37	0.03	19.3	3.65	7.00	1.97	0.19	From COD, VSS, TSS and OrgN (TKN-FSA) and C, H and N elemental analysis of PS from 2 WWTPs.
	Meth ADs														
Wentzel *et al.* (2006)	Moen *et al.*	Primary sludge	UPO+BPO	0.35	1.617	0.5									TKN and FSA concs not reported. C content of BPO from difference between influent and effluent concs and gas measurements.
	-2001		BPO		1.321										
	Meth ADs		UPO		2.167										

Reference	Data Source	Sludge Type	Organic Type	Unbio Frac	gCOD/ gVSS	gC/ gVSS	gH/ gVSS	gO/ gVSS	gN/ gVSS	mgN/ gVSS	x	y	z	a	Notes
Ekama *et al.* (2006)	van Haandel *et al.* (1998)	Waste	WAS	0.25	1.5	0.54	0.06	0.29	0.1	65.8	4.96	7.00	2.00	0.77	No elemental analysis. Assumed z=2.
		Activated Sludge	Biomass,	to	1.55	0.57	0.06	0.27	0.1	66	5.67	7.00	2.00	0.87	
			ER+UPO	0.79						68.5					
Ekama *et al.* (2006)	Own data	Waste	WAS	0.637	1.482	0.49	0.08	0.36	0.07	47.2	3.51	7.00	1.92	0.43	60d retention time - all BPO utilized. C, H and N elemental analysis on influent and effluent solids.
		Activated Sludge	Biomass		1.444	0.49	0.08	0.35	0.08	54	3.69	7.00	1.99	0.50	
			ER+UPO		1.552	0.51	0.08	0.35	0.06	40.6	3.71	7.00	1.88	0.39	
Wentzel *et al.* (2006)	Ristow *et al.* (2004)	Primary sludge	UPO+BPO	0.334	1.4	0.49	0.07	0.41	0.03	21	4.16	7.00	2.61	0.21	UPO from C, H and N elemental analysis, BPO from gas and alkalinity measurements.
	Meth ADs		BPO		1.533	0.46	0.1	0.42	0.03	19.6	2.71	7.00	1.87	0.15	
			UPO		1.194	0.46	0.06	0.46	0.03	22.6	4.42	7.00	3.32	0.22	
Takács and Vanrolleghem (2006)	Own estimates	Waste-water organics	USO & UPO		1.551	0.55	0.06	0.39	0	0	5.56	7.00	2.93	0.00	Estimates from specific organic types and literature values.
			BSO & BPO		1.907	0.59	0.08	0.33	0	0	4.29	7.00	1.77	0.00	
			Biomass		1.416	0.53	0.06	0.28	0.12	87.6	5.00	7.00	2.00	1.00	

Note 1: Elemental ratio for O (f_O, α^O) and H (f_H, α^H) are not required because COD replaces one and mass balance ($f_C+f_H+f_O+f_N+f_P=1$) the other.

2.2.7.4 Volcke *et al.* (2006)

The continuity-based interfacing method (CBIM) approach was developed to construct model interfaces that transform components of unit operation model to those compatible of another unit operation model. So CBIM can be used to link various WWTP unit operations while maintaining mass and charge balances between the unit operations (Vanrolleghem *et al.*, 2005). The general approach towards CBIM described by Volcke *et al.* (2006) is an extension of CBIM approach that included a procedure to formulate elemental mass fractions and charge densities. This procedure is similar to the method of Ekama (2009) described above for determining the values of X, Y, Z and A in the elemental composition $C_XH_YO_ZN_A$. The CBIM approach was developed to transform output components from one unit operation to another form compatible to a subsequent unit operation while maintaining mass balances on all the elements and charge, e.g. when linking ASM1 and AMD1 which have different forms for the output and input components.

The first step of the CBIM general approach deals with the formulation of elemental mass fractions (α = g element / g component which is the same as the ƒ mass fractions used by Ekama, 2009) for all state variables associated with the subsystems considered. The purpose of this is to transform the outcome parameters from one model to a compatible form of input state variables for another model. Similar to Ekama (2009), this method assumes that C, H, O and N are the most commonly present elements throughout wastewater treatment processes, with the incorporation of P to anticipate future applications that include reactions involving P (as is the case in this investigation). Therefore, the composition of any component can be summarised as,

$$\alpha_k^C + \alpha_k^H + \alpha_k^O + \alpha_k^N + \alpha_k^P = 1 \qquad \textbf{\textit{(E2.8a)}}$$

Where α refers to the elemental mass fraction per total mass of component (k) and the superscript identifies the individual element being considered. The incorporation of the charge density and COD content for one gram of component k is reflected in the format below,

$$\left[C_{\frac{\alpha_k^C}{12}} H_{\frac{\alpha_k^H}{1}} O_{\frac{\alpha_k^O}{16}} N_{\frac{\alpha_k^N}{14}} P_{\frac{\alpha_k^P}{31}} \right]^{\alpha_k^{ch}} \qquad \textbf{\textit{(E2.8b}}$$

Where each element remains as stated above with the addition of *ch* that refers to the charge per gram of component.

Volcke *et al.* (2006) utilized mass fractions directly obtained from Activated Sludge Model Number1 (ASM1) (Henze *et al.*, 1987) or otherwise indirectly determined. Mass fractions relevant to this work, from Table 1 (Volcke *et al.*, 2006) are summarised in the Table 2.3 below. For ease of comparaison, the X, Y, Z, A and B (for P) associated with the α mass fraction are given in Table 2.3 also.

Table 2.3: Composition of ASM1 components (Volcke *et al.*, 2006)

Description	α^C	α^N	α^H	α^O	α^P	α^{Ch}	X	Y	Z	A	B
USO	0.65	0	0.07	0.28	0	0					
RBO	0.62	0	0.08	0.28	0.0	0	4.48	7	2.65	0	0
UPO	0.56	0.09	0.06	0.28	0.01	0	5.44	7	2.04	0.75	0.038
SBO	0.62	0	0.08	0.28	0.02	0					
OHO	0.516	0.114	0.06	0.28	0.03	0	5	7	2	1	0.114
ANO	0.516	0.114	0.06	0.28	0.03	0	5	7	2	1	0.114
$^{*}{}_{EH}$	0.5575	0.0925	0.06	0.28	0.01	0					

The elemental compositions of the ASM1 components can be determined from the mass fractions in Table 2.3 as input variables to Eq. E2.8b. However, α^{COD} (f_{cv}) is more commonly used than α^O (f_O) so α^O can be calculated from Equation E2.8c. Also if the mass balance is imposed, α^H (f_H) is not required because $1 - \alpha^N - \alpha^P - \alpha^C - \alpha^O = \alpha^H$ can be added in its place.

$$\alpha^{COD} = 32\left[\frac{\alpha^C}{12}\right] + 8\alpha^H - 16\left[\frac{\alpha^O}{16}\right] - 24\left[\frac{\alpha^N}{14}\right] + 40\left[\frac{\alpha^P}{31}\right] - 8\alpha^{ch} \qquad \textbf{\textit{(E2.8c)}}$$

As mentioned above, the α^C and α^N used by Volcke *et al.*, refer to the same mass fractions f_C and f_N used by Ekama (2009). Both approaches are completely general but used in different ways, e.g. a difference in the two methods is that Volcke *et al.* compiled a table of mass fractions and as such limits the application of the method to the available data in the table whereas Ekama (2009) use measurement characterization methods to determine the mass fractions for every case. However, this is not a permanent difference because the data tables of Volcke *et al.* can be updated with revised mass fraction data for other cases when these become available. Another difference is that the Volcke *et al.* method can incorporate new elemental components with ease where as the Ekama method requires lengthy derivations to include new elemental components to the mass fraction to elemental composition conversion equations. However, once derived, even the non-specialist user can be certain of accurate results from the application of the Ekama procedure if the procedure is applied correctly.

Using the mass fraction listed in Table 2.3 for the UPO, BPO and OHO components, and applying the Ekama (2009) Equations described in Section 2.2.6 with the adjustment to include phosphorus (Section 4.2.2) the elemental composition determined from the Volcke *et al.* (2006) mass fractions for UPO is $C_{5.44}H_7O_{2.04}N_{0.75}P_{0.038}$ and OHO is $C_{5.02}H_7O_{2.04}N_{0.95}P_{0.113}$ as shown in Table 2.3. The OHO and ANO composition can be seen to be very close to the often quoted $C_5H_7O_2N$ and was probably used as a basis for the OHO and ANO composition.

2.2.7.5 Summary Table of Waste Activated Sludge and Biomass Elemental Compositions

Table 2.4 presents a summary of the elemental compositions of the particulate organic (PO), UPO, BPO and OHO Biomass for the WAS reviewed above. Some of these results are also given in Table 2.2 from Ekama (2009).

Table 2.4: A Summary of the Elemental Composition of PO, UPO, BPO and Biomass of ND WAS

Author of Study and Date	**Component of ND WAS**	*$C_XH_YO_ZN_AP_B$ and $C_XH_YO_ZN_A$ composition of the WAS Components*		
		OP	**UPO**	**BPO**
McCarty (1975)	**Biomass**	***No Results***	***No Results***	$C_5H_7O_2N_1$
Dold *et al.* (1980)	**Biomass**	***No Results***	***No Results***	$C_{4.8}H_7O_2N_{0.77}$
Ekama *et al.* (2006b)	**ND WAS for van Haandel et al. (1998)**	$C_{4.96}H_7O_2N_{0.77}$	***No Results***	$C_{5.67}H_7O_2N_{0.866}$
Ekama *et al.* (2006b)	**ND WAS for Own Experiments**	$C_{3.51}H_7O_{1.92}N_{0.431}$	$C_{3.72}H_7O_{1.885}N_{0.393}$	$C_{3.69}H_7O_{1.99}N_{0.503}$
Volcke *et al.* (2006)	**ND WAS UPO & BPO**	***No Results***	$C_{5.44}H_7O_{2.04}N_{0.75}P_{0.038}$	$C_{4.52}H_7O_{1.53}N_0P_{0.056}$
Volcke *et al.* (2006)	**Biomass**	***No Results***	***No Results***	$C_{5.02}H_7O_{2.04}N_{0.95}P_{0.113}$

Table 2.4 will allow easy comparison with the composition to be determined this study in subsequent chapters. As results on the elemental composition of NDBEPR WAS could not be

found in the literature, Table 2.4 represents the closest correlation to the results to be determined this study.

Therefore, it is expected that the organic part or the NDBEPR WAS should be comparable to some extent to that of OHOs in terms of the C, H, O and N composition of the BPO component. This applies only to WAS from AS systems at long sludge ages where the BPO content from the influent waste water (WW) have all been utilized or negligible quantities remain. A reasonably close comparison is expected between the compositions of the BPO of the WAS (comprising only OHOs) and NDBEPR WAS (comprising OHOs and PAOs) because the PAOs are likely to have the same organic biomass composition (excluding the polyphosphate) is the OHOs.

2.2.8 Conclusion to characterization

At this stage, the characterization process has been reviewed sufficiently to understand the process by which the NDWAS and PS feed to anaerobic digestion can be characterized to the required format that includes the elements C, H, O and N. This background is adequate for later use to extend the characterization procedure to determine the elemental composition of NDBEPR WAS. This is one of the main objectives of this study and it will be fully explored in Chapters Four and Five of this work. The next section of this review will focus on the literature on the anaerobic digestion process and its the reaction stoichiometry, and the kinetics of hydrolysis of slowly biodegradable organics (BPO) that governs the conversion that establishes the quantity of reactants changed to the products of the digestion process.

2.3 Anaerobic Digestion

Anaerobic digestion is widely used to stabilise WAS and PS at wastewater treatment facilities. The health risks and environmental impact associated with these WAS and PS wastes are significantly reduced with the application of a stabilisation process.

The health risks associated with PS and WAS relate to the high pathogen content of these sludges, which is significantly reduced through anaerobic digestion. The environmental impact associated to AD of these waste sludges is the reduction in sludge mass by the production of gaseous products like methane and carbon dioxide. Firstly, the sludge mass reduction reduces the solid waste burden to waste landfill sites. Secondly, this technology provides a net positive energy output, via the production of methane (CH_4), which can be used as an energy source, thus, reducing the energy requirement from fossil fuels. However, the sludge mass reduction and gas production capability resulting from anaerobic digestion are directly related to the biodegradable (anaerobically) particulate organics (BPO) content of the sludge. In this regard, the BPO content of PS is around 65% to 70% of the PO (Sötemann *et al.,* 2005) whereas BPO content of WAS is far less, specifically for sludge from long sludge age AS systems and hydrolysis more slowly (Ekama *et al.,* 2006b).

2.3.1 Anaerobic Digestion Microbiology, Process Kinetics and Stoichiometry

The anaerobic digestion of complex organics, such as WAS and PS, follows biochemical and physico-chemical transformation processes. A consortium of four organism groups mediates the biochemical transformation processes (Batstone *et al.,* 2002; Sötemann *et al*., 2005). These organisms are as follows,

(a) Acidogens, responsible for the conversion of complex organics to SCFA, CO_2 and H_2,
(b) Acetogens, responsible for converting propionic and higher SCFA to acetic acid,
(c) Acetoclastic methanogens mediate the process of converting Acetic acid to CO_2 and CH_4,
(d) Hydrogenotrophic methanogens convert H_2 to CH_4 using CO_2 as an electron acceptor.

In the digestion of complex organics, these anaerobic organisms function in two stages. Initially, the Acidogens hydrolyse complex organic substrate to simple organic compounds like SCFA and H_2. However, this biochemical reaction could be further divided into,

i. The hydrolysis of WAS and PS complex organics to smaller carbon chain length compounds such as carbohydrates, proteins and lipids.
ii. The internal acidification of these simpler organics by the acidogens to produce SCFA and H_2.

These SCFA and H_2 are then further oxidation to CH_4, CO_2 and water by the Acetogenic and Methanogenic organisms as is described in steps (b) to (d) (Sötemann *et al.,* 2005 ;McCarty *et al.,* 1964). The kinetics of the hydrolysis/acidogenesis process is the first part of an AD model and defines the concentration of BPO digested. This is shown in Figure 2.4 below,

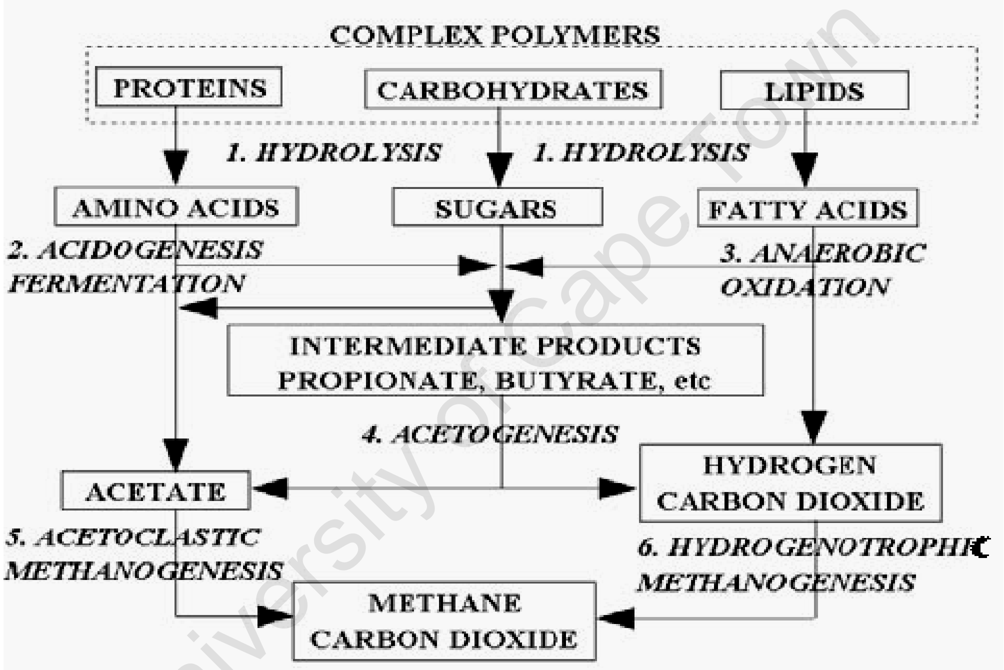


Figure 2.5: Anaerobic Digestion process scheme {Gujer and Zehnder (1983)}

The hydrolysis process in anaerobic digestion of WAS and PS is the slowest process step and, as such, is the rate limiting step of the biochemical reaction describing the AD process. Therefore, the kinetic rates that describe the hydrolysis/acidogenesis of this complex organic govern the overall rate of PS and WAS digestion.

Hydrolysis is an extracellular biological and non-biological process. The non-biological part refers to the extracellular degradation of complex organic to its soluble monomers through a process catalysed by enzymes, which are likely secreted by the acidogens (Batstone *et al.*, 2002). The secrete enzymes while attached to the surface of the complex organic particle, thus, directly benefit from the soluble AD products (Vavilin *et al,* 1996; Batstone *et al.*, 2002).

In ADM1 (Batstone *et al.*, 2002), first order kinetics (hydrolysis rate $\{r_h\} = K_hS_{bp}$) are applied to describe the rate limiting hydrolysis process of complex organics because this conformed to observations (Where r_h is the volumetric hydrolysis rate, gCOD/(l.d), S_{bp} the hydrolysable biodegradable COD concentration and K_H the 1st order rate constant). Using a simple hydrolysis model in ADM1 allows modellers to use their own hydrolysis kinetic expression e.g. specific 1st order $r_h = K_HS_{bp}Z_{AD}$ where Z_{AD} is the acidogen concentration in gCOD/l; Monod $r_h = K_mS_{bp} / (K_S + S_{bp})Z_{AD}$ and saturation $r_h = K_M\ (S_{bp}/Z_{AD})\ /\ [K_S + (S_{bp}/Z_{AD})]Z_{AD}$. Since, the utilization rate of the hydrolysis product is much faster than the preceding hydrolysis rate, the hydrolysis product utilization rate is governed by the hydrolysis rate that produces the substrate for the utilization step. Therefore, the overall kinetic rate for substrate utilisation is governed by the kinetic rate of hydrolysis.

McCarty (1974) described the rate of complex organic hydrolysis/utilisation by the AD microorganisms in a steady state model with a Monod equation as follows,

$$\frac{dF}{dt} = \frac{kS_d X}{K_s + S_d} \qquad \textbf{\textit{(E2.9a)}}$$

where dF/dt = rate of waste hydrolysis/utilization (gCOD/l.d)
k = Maximum utilisation rate constant gCOD/ mg active mass/ d
K_S = Half velocity coefficient (gCOD/l)
X = AD biomass concentration (gCOD/l)

The kinetic rate at which substrate is anaerobically disintegrated, hydrolyzed, acidified and utilized to its products can be retarded by inhibitors. Although several inhibition factors can influence the kinetic rates for the methanogenic anaerobic digestion of PS and WAS from predominantly domestic wastewater, the effect of pH is crucial and discussed below. Change in pH disrupts cell homeostasis caused by the passive transport of free acid and base across the cell membrane and subsequent dissociation (Henderson, 1971; Batstone *et al.,* 2002). pH inhibition is driven by the dependency of the concentrations of free acids and bases that chemically dissociate (ionize) within aqueous medium, depending on the pH of the aqueous medium. The result is that free acids, like associated organic acids and hydrogen sulphide, causes inhibition at lower pH values and free bases, like NH_3, causes inhibition at higher pH values (Batstone *et al.,* 2002). The optimal operation pH range for anaerobic digestion is between 6.6 and 7.6 (McCarty *et al.,* 1964). Another factor affecting the kinetic rates is the operating temperature of the AD system. The change temperature affects the growth and death rates of the micro-organisms and, thus, the rate of substrate hydrolysis/utilization. The reaction rates proceed much faster at higher temperatures (McCarty *et al.,* 1964). The optimum temperature ranges are psychrophilic, at temperatures between 16 and 18 ^{o}C, mesophillic, at temperatures between 35 to 42 ^{o}C, and thermophilic, at temperatures between 59 to 68 ^{o}C (Batstone *et al*., 2002). However, the cost related to the operation AD systems at thermophilic range are not economically viable in most cases and therefore it is found that most anaerobic digesters are operated within the mesophilic temperature range.

As mentioned earlier, the reaction stoichiometry describing the methanogenic anaerobic digestion process of complex organic waste to produce CH_4, CO_2, HCO_3^- and NH_3, developed by McCarty (1974), Eq. E2.9 is important in the context of this study. Later, McCarty (1975) published a generalized procedure to derive this stoichiometric equation. This is reviewed below because this procedure will be needed to include P into the stoichiometry.

2.3.2 Stoichiometry (McCarty, 1974 and 1975)

McCarty (1974) developed a generalised reaction stoichiometry to describe the methanogenic anaerobic digestion process for a complex organic substrate producing CH_4, CO_2 bicarbonate (HCO_3), ammonium (NH_4^+) and biomass as the products of this digestion process. This stoichiometry is the 2nd part of an AD model and converts the BPO utilized to AD products. McCarty assumed the elemental composition of AD biomass produced to be all the groups lumped together $C_5H_70_2N$. This is shown by the Equation *E2.9b* below,

$$C_xH_yO_zN_a+\left(2x+a-z-\frac{9sd}{20}-\frac{ed}{4}\right)H_2O\rightarrow$$
$$\rightarrow\frac{ed}{8}CH_4+\left(x-a-\frac{sd}{5}-\frac{ed}{8}\right)CO_2+\frac{sd}{20}C_5H_7O_2N+\left(a-\frac{sd}{20}\right)NH_4^+ +\left(a-\frac{sd}{20}\right)HCO_3^- \qquad \textbf{(E2.9b)}$$

where**:** $d = 4x + y - 2z - 3a$ = (e^- donating capacity of the organics) ***(E2.10)***

Moreover, the values of **s** and **e** in Eq. E2.9 refer to the portion of substrate e^- transformed to AD biomass and the portion of the substrate e^- used to produce CH_4, respectively. So for a COD (e^-) balance, this can be represented as,

$$s + e = 1 \qquad \textbf{\textit{(E2.11)}}$$

The e^- captured in biomass, s relates to the fraction of the utilized BPO COD (S_{bp}) flux (gCOD/d) converted to anaerobic digestion sludge mass harvested from the AD (gCOD/d) (Sötemann *et al.,* 2005). The parameter named s by McCarty (1974) was changed to E by Sötemann *et al.* (2005) and can be determined from the COD mass balance based hydrolysis kinetic part of the steady state AD model as shown by Equation E2.12a stated below,

$$s = E = \frac{Flux \quad biomass \quad COD \quad produced}{Flux \quad organic \quad COD \quad utilized} = \frac{V(Z_{AD} + Z_{ED})}{R_s Q_i (S_{bpi} - S_{bpe})} \qquad \textbf{\textit{(E2.12a)}}$$

Which for the flow through the AD system and zero endogenous residue generation ($f_{AD} = 0$ so $Z_{ED} = 0$) simplifies to Equation E2.12b

$$s = E = \frac{Z_{AD}}{S_{bpi} - S_{bp}} = \frac{Y_{AD}}{[1 + b_{AD} R(1 - Y_{AD})]} \qquad \textbf{\textit{(E2.12b)}}$$

Where Y_{AD} refers to the pseudo acidogen yield coefficient (mgCOD biomass/ mgCOD substrate hydrolysed) because it includes the methanogens and b_{AD} refers to the acidogen endogenous respiration rate (/d). These parameters were estimated from literature values as described in Sötemann *et al.* (2005) i.e. Y_{AD} = 0.113 mgCOD/mgCOD and b_{AD} = 0.041/d.

The generalized procedure for deriving bioprocess stoichiometric equations like Eq. E2.9 above is based on biologically mediated reactions comprising two coupled reactions. (1) The reaction that describes the synthesis process or anabolic pathway and (2) the reaction that describes the energy production reaction or catabolic pathway (McCarty, 1975). Basically the e$^-$ donated by the break down of the organics are all captured either in new cell mass (anabolism) or transferred to the e$^-$ acceptor (catabolism). These pathways are shown a follows (van Zyl *et al.*, 2008),

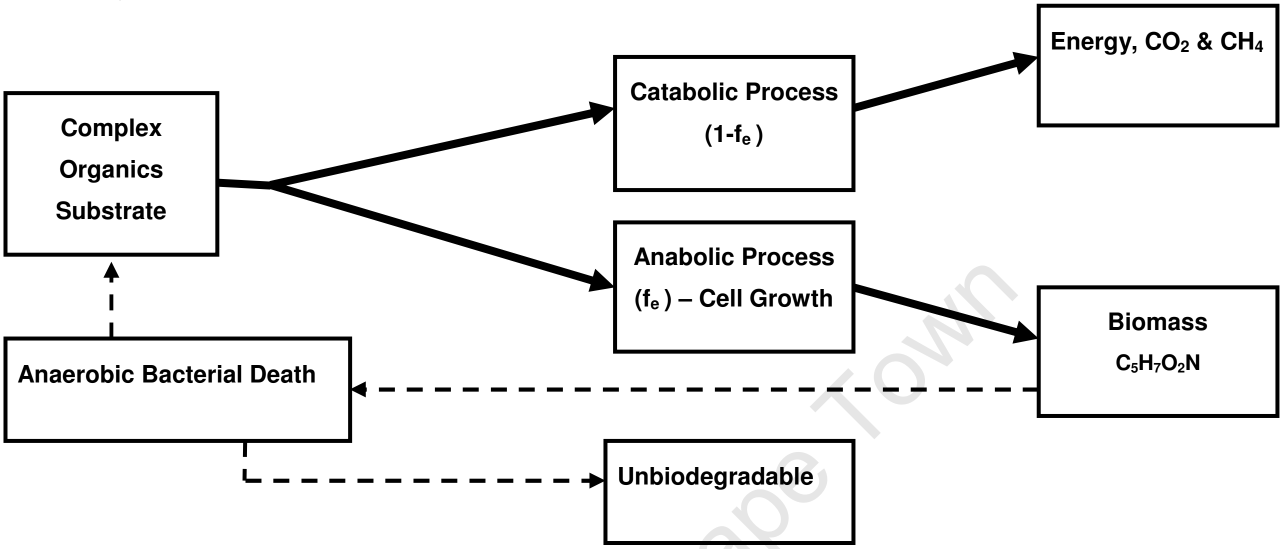


Figure 2. 6: Catabolic and Anabolic Pathway of Anaerobic Digestion (van Zyl *et al.,* 2008)

These biologically mediated reactions can be described by reduction – oxidation (redox) half reactions because of the e$^-$ transfer that occurs during these reactions. McCarty (1975) published a table of common half reactions for AS and AD processes. In application of these redox reactions for developing the AD stoichiometric equation (E2.9), three half reactions are required. One reaction to describe the e$^-$ donor reaction (R_d) of the organics, another half reaction to describe the e$^-$ acceptor reaction catabolism (catabolism - R_a) and a third reaction to describe the synthesis reaction (anabolism - R_c). The half reactions describing R_a and R_c can be directly obtained from the table, however the half reaction describing the R_e in a generalised format are derived inline with the practice applied for those listed in the published table. These half reactions are as follows,

A. The e- donor (Substrate as derived in the characterization section) half reaction

$$C_X H_Y O_Z N_A + (2X + A - Z)H_2O \leftrightarrow (X - A)CO_2 + (A)HCO_3^- + (A)NH_4^+ + D_s(H^+ + e^-)$$

‘ **(E2.14)**

where: D_S = 4X + Y – 2Z – 3A = (e^- donating capacity of the organics in e^-/mol)

B. The e⁻ acceptor (Catabolic Pathway) half reaction for the AD product CH_4,

$$f_e\left[CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O\right] \qquad \textbf{(E2.15)}$$

C. The Synthesis (Anabolic Pathway) half reaction,

$$f_s\left[4CO_2 + HCO_3^- + NH_4^+ + 20H^+ + 20e^- \rightarrow C_5H_7O_2N + 9H_2O\right] \qquad \textbf{(E2.16)}$$

The overall reaction (Eq. E2.9) is determined by manipulating the three reactions as shown below,

$$R = R_d - f_e R_a - f_s R_c \qquad \textbf{(E2.17)}$$

Where f_e and f_s refer to the fractions of the e^- donated by the substrate that will be utilized through the Catabolic pathway and Anabolic pathway, respectively. Equation E2.17 is essentially an e^- balance where all the electrons donated by the organics end up either in the biomass (anabolism as a fraction f_s) or passed to the e^- acceptor (catabolism as a fraction f_e). Because all the e^- must be accounted for, the sum of these fractions must be equal to one as given below,

$$f_e + f_s = 1 \qquad \text{or} \qquad f_s = 1 - f_e \qquad \textbf{(E2.18a)}$$

The f_s is the same as the E used by Sötemann et al (2005) and so,

$$f_S = E \qquad \text{and} \qquad f_e = (1 - E) \qquad \textbf{(E2.18b)}$$

This procedure is used in Chapter Four to derive the reaction stoichiometry including P related to the anaerobic digestion of NDBEPR WAS. This procedure is completely general and can be applied to derive the bioprocess stoichiometry for any bioprocess reaction. Ekama (2009) used it to derive the stoichiometric equations for aerobic activated sludge, nitrification, denitrification and anoxic aerobic digestion of WAS, to build a plant wide steady state WWTP model including anaerobic digestion of PS and ND WAS. Poinapen and Ekama (2009) used it to derive the bioprocess stoichiometry for biological sulphate reduction (BSR) with PS as electron donor and Lu *et al.* (2009) for the bioprocess stoichiometry of autotrophic denitrification with sulphide as electron donor.

2.3.3 Sötemann *et al.* (2005)

Sötemann *et al*. (2005) developed a two-phase (aqueous-gas) steady state model to describe the anaerobic digestion of PS and ND WAS that includes the CHON and COD mass balanced stoichiometry reviewed above. This steady state model comprises three parts,

A. A COD based hydrolysis kinetic part from which the biodegradable COD concentration hydrolysed/ utilisation is determined,

B. A reaction stoichiometry part like Eq. E2.9 which converts the biodegradable COD utilized (converted to mol unit) to AD products NH_4^+, biomass, HCO_3^- and gaseous CO_2 and CH_4 which set the partial pressure of CO_2 (pCO_2), and

C. An inorganic weak acid/base chemistry part with which the AD pH is calculated from the pCO_2 [$= CO_2/(CO_2 + CH_4)$]and HCO_3^- AD products.

To describe the kinetic rate of hydrolysis, Sötemann *et al.* considered four different rate equations for describing the hydrolysis kinetics of PS and ND WAS. These kinetic equations are as follows,

a. first order with respect to the residual biodegradable particulate organics COD concentration (S_{bp}) i.e. $r_h = S_{bp}K_H$,

b. Monod kinetics, i.e. $r_h = K_mS_{bp} / (K_S + S_{bp})Z_{AD}$

c. first order with respect to the residual biodegradable particulate organics COD concentration and the Acidogens concentration (Z_{AD}), $r_h = K_hS_{bp}Z_{AD}$,

d. Saturation kinetics, i.e. $r_h = K_M (S_{bp}/Z_{AD}) / [K_S + (S_{bp}/Z_{AD})]Z_{AD}$.

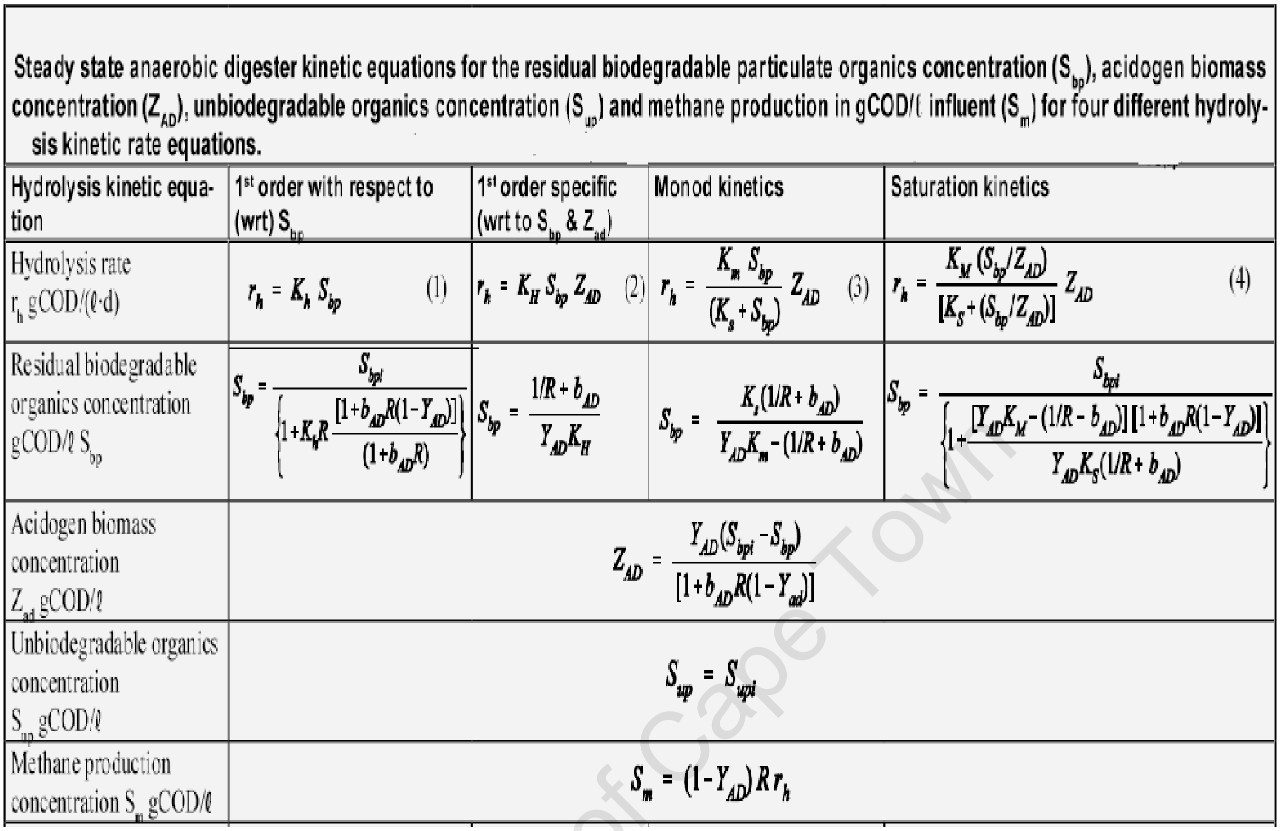
Where: r_h = volumetric hydrolysis/acidogenesis rate [gCOD/(l.d)]

These equations for the hydrolysis rate of the BPO (S_{bp}) were used as a basis for deriving the COD based hydrolysis kinetic model for AD of PSS organics which relates the acidogen biomass concentration (Z_{AD}), residual (not hydrolysed) biodegradable particulate organics (S_{bp}) to the sludge age of the AD. These equations are all summarized in Table 2.5 (Table 1 in Sötemann *et al.,* 2005).

In developing the AD stoichiometry, Sötemann *et al*. applied the generalised reaction stoichiometry for the anaerobic digestion of a complex organic substrate, Eq. E2.9 as published by McCarty (1974). Because PS contains a significant concentration of SCFA in the influent, they included the reaction stoichiometry of influent SCFA in the stoichiometry.

Sötemann *et al.* used literature data to validate the AD model, i.e. the primary/humus sludge mixture data of Izzett and Ekama (1992) and the “pure” PS data of O’Rourke (1968). From the hydrolysis kinetic rates determined for these two AD data sets, they concluded that “pure” PS hydrolysed much faster than the humus/PS mixture. However, both sludges had approximately the same unbiodegradable COD fraction ($f_{PS,up}$) i.e. between 0.34 and 0.36. Also they could not choose which hydrolysis rate equation was the best because the unbiodegradable fraction of the sludges were not known and each yielded a slightly different $f_{PS,up}$ between 0.34 and 0.36.

Table 2.5: Steady state AD equations as published in Sötemann *et al.* (2005)



Steady state anaerobic digester kinetic equations for the residual biodegradable particulate organics concentration (S_{bp}), acidogen biomass concentration (Z_{AD}), unbiodegradable organics concentration (S_{up}) and methane production in gCOD/ℓ influent (S_m) for four different hydrolysis kinetic rate equations.

Hydrolysis kinetic equation	1st order with respect to (wrt) S_{bp}	1st order specific (wrt to S_{bp} & Z_{ad})	Monod kinetics	Saturation kinetics
Hydrolysis rate r_h gCOD/(ℓ·d)	$r_h = K_h S_{bp}$ (1)	$r_h = K_H S_{bp} Z_{AD}$ (2)	$r_h = \frac{K_m S_{bp}}{(K_s + S_{bp})} Z_{AD}$ (3)	$r_h = \frac{K_M (S_{bp}/Z_{AD})}{[K_S + (S_{bp}/Z_{AD})]} Z_{AD}$ (4)
Residual biodegradable organics concentration gCOD/ℓ S_{bp}	$S_{bp} = \frac{S_{bpi}}{\left\{1 + K_h R \frac{[1 + b_{AD} R(1 - Y_{AD})]}{(1 + b_{AD} R)}\right\}}$	$S_{bp} = \frac{1/R + b_{AD}}{Y_{AD} K_H}$	$S_{bp} = \frac{K_s(1/R + b_{AD})}{Y_{AD} K_m - (1/R + b_{AD})}$	$S_{bp} = \frac{S_{bpi}}{\left\{1 + \frac{[Y_{AD} K_M - (1/R - b_{AD})][1 + b_{AD} R(1 - Y_{AD})]}{Y_{AD} K_S (1/R + b_{AD})}\right\}}$
Acidogen biomass concentration Z_{ad} gCOD/ℓ	$Z_{AD} = \frac{Y_{AD}(S_{bpi} - S_{bp})}{[1 + b_{AD} R(1 - Y_{ad})]}$			
Unbiodegradable organics concentration S_{up} gCOD/ℓ	$S_{up} = S_{upi}$			
Methane production concentration S_m gCOD/ℓ	$S_m = (1 - Y_{AD}) R r_h$			

2.3.4 Jardin *et al.* (1994)

Jardin and Pöpel (1994) conducted studies on a pilot plant that included BEPR AS systems and anaerobic digesters to treat the thickened WAS from the AS system. These ADs were operated at a 20 day sludge age and a temperature of 35°C. The waste sludge was thickened to between 8 to 10% TSS concentration.

The total phosphorus concentration of the AD, fed with BEPR sludge only, stabilised at a value of 4000 mgP/l. The soluble total phosphorus increased to about 1500 mgP/l in this period. The change in soluble P concentration was accompanied by the release of K and Mg cations related to the ratio observed during the uptake of P in the AS systems. However, Jardin *et al.* (1994) found the difference between the soluble and influent total P concentration of the AD remarkable. Jardin *et al.* hypothesised this difference in P concentration was either due to struvite ($MgNH_4PO_4$) precipitation inside the AD or incomplete digestion of the feed BEPR WAS. To test this hypothesis, a potassium (K) balance was preformed on the AD. This is based on the assumption that the release of phosphorus is companied by the release of K, in a ratio, of 0.328 g/g (ΔK/ΔP), related to the uptake within the AS system. Furthermore, K does not form any mineral precipitation in the AD environment, because NH_4^+ is in excess (if NH_4^+ is limiting as in nitrifying aerobic digestion of BEPR WAS, K can replace NH_4^+ in struvite).

In conclusion, Jardin *et al*. found that most of the polyphosphate was released within 7 days of digestion. Based on the potassium balance, all the WAS P had been released but only a fraction of the P released remained in solution. The aqueous element ionic and solubility products of Mg precipitation confirmed that the condition prevailing in the AD was conducive to the formation of struvite. Based on computational method and X-ray diffractometry it was determined that mineral precipitation occurred with in the AD in the case of Jardin *et al*. (1994).

2.3.5 Conclusion to Anaerobic Digestion

Thus far, the literature review has discussed all relevant aspects needed to extend the anaerobic digestion model, as published by Sötemann *et al*. (2005) to include P and thereby describe the anaerobic digestion of NDBEPR WAS. However, the physico-chemical processes involving the products of AD has not been described in detail. The next section will deal with the weak acid-base chemistry and gas-liquid transfer related to the AD of ND WAS and PS. This knowledge will be applied in Chapter Four to develop a steady state model to predict the products from the AD of NDBEPR WAS in two phases (aqueous-gas).

2.4 Physico-chemical processes of Anaerobic Digestion

2.4.1 Introduction to physico-chemical processes of anaerobic digestion

In addition to the biological processes that occur within the anaerobic digestion environment, there are non-biologically mediated processes, excluding enzyme activities, known as physico-chemical processes. These processes influence the phase of the intermediate and final products of digestion. There are three types of physico-chemical processes that occur within the AD environment (Batstone *et al*., 2002), as shown below:

(i) Liquid-liquid processes or aqueous weak acid/base chemistry,
(ii) Liquid-gas processes such as the escape of CH_4 and CO_2 gas, and

(iii) Liquid-solid processes or precipitation/solubilisation processes.

The liquid-liquid and liquid-gas processes are commonly included in most anaerobic digestion models because these are the most common processes operating in the AD environment. Usually mineral precipitation is insignificant, such as in methanogenic AD of PS and ND WAS. The concentrations of phosphorus and metal cations, like Mg and Ca, in solution are too low. However, this was found not to be the case for some thickened BEPR WAS, when struvite precipitation occurs, as discussed by Jardin *et al.* (1994) reviewed above. Nonetheless, specific conditions have to be satisfied within the AD environment to start and sustain precipitation processes.

2.4.2 Aqueous Weak acid-base chemistry (liquid-liquid processes)

Anaerobic digesters include mixed weak acid/base systems involving a number of chemical species at different molar concentrations. The differences in species concentrations produced by anaerobic digestion are a function of the concentration and composition of the substrate directly affecting the aqueous concentration of the digestion product. In fact, the pH established in the AD is entirely dependent on the composition of the influent organics (and inorganics).

The pH of anaerobic digesters treating PS and NDWAS is a function of the aqueous weak acid-base chemistry of the inorganic carbon system. Although other weak acid/base systems are present such as the ammonia (N_T), phosphate (P_T) and SCFA sub-systems, these do not significantly affect pH because either their concentration is low (as for the P system) or their pK values are far outside the normal pH range of ADs (as for the VFA [$pK_a = 4.7$] and ammonia [$pK_n = 9.1$] systems) (Loewenthal *et al.* 1994). Nevertheless, these sub-systems can be described by a set of aqueous phase equilibrium and mass balance equations:

A. Aqueous phase equilibrium equations:

(i) **Carbonate sub-system (C_T)** :

$$K_{C1} = \frac{(H^+)[HCO_3^-]}{[H_2CO_3^*]} \qquad \textbf{\textit{(E2.19a)}}$$

$$K_{C2} = \frac{(H^+)[CO_3^{-2}]}{[HCO_3^-]} \qquad \textbf{\textit{(E2.19b)}}$$

(ii) **Ammonia sub-system**:

$$K_N = \frac{(H^+)[NH_3]}{[NH_4^+]} \qquad \textbf{\textit{(E2.19c)}}$$

(iii) **Phosphate sub-system**:

$$K_{P1} = \frac{(H^+)[H_2PO_4^-]}{[H_3PO_4]} \qquad \textbf{\textit{(E2.19d)}}$$

$$K_{P2} = \frac{(H^+)[HPO_4^{-2}]}{[H_2PO_4^-]} \qquad \textbf{\textit{(E2.19e)}}$$

$$K_{P3} = \frac{(H^+)[PO_4^{-3}]}{[HPO_4^{-2}]} \qquad \textbf{\textit{(E2.19f)}}$$

(iv) Acetate sub-system (assumed to represent the SCFA) :

$$K_{A1} = \frac{(H^+)[Ac^-]}{[HAc]} \qquad \textbf{\textit{(E2.19g)}}$$

where (H^+) is the hydrogen ion activity and [ ] the species molar concentrations.

B. Mass Balance Equations:

$$C_t = [H_2CO_3^*] + [HCO_3^-] + [CO_3^{-2}] \quad \textbf{(E2.20a)}$$

$$P_t = [H_3PO_4] + [H_2PO_4^-] + [HPO_4^{-2}] + [PO_4^{-3}] \quad \textbf{(E2. 20b)}$$

$$N_t = [NH_4^+] + [NH_3] \quad \textbf{(E2. 20c)}$$

$$A_t = [HAc] + [Ac^-] \quad \textbf{(E2. 20d)}$$

Sötemann *et al.* (2005) accepted that the pH established within AD systems treating PS and ND WAS is primarily affected by the inorganic carbon system for reasons mentioned above so that the concentration of inorganic carbon species are much higher than any of the other weak acid species present. The bicarbonate concentration, which is the main inorganic carbon system species in the pH range 7 to 7.5, is generated from the N and VFA content of the PS and ND WAS (Sötemann *et al*, 2005), i.e. from the reaction between,

(a) NH_3 and dissolved CO_2 (H_2CO_3*), which are both products of AD to produce ammonium (NH_4^+) and bicarbonate (HCO_3^-), which are the products of physico-chemical processes,

(b) the dissociated acetic acid (Ac^-) and the dissolved CO_2 to form HAc and HCO_3^- because the acetoclastic methanogens utilize the associated form of acetic acid.

Loewenthal *et al.* (1989) describes Alkalinity equations for an aqueous system that only contains the carbon and water species as the H_2CO_3* Alkalinity (presented in Eq. E2.21a), the phosphate system species as the Alk. H_3PO_4 (i.e. excluding the water system) (presented in Eq. E2.21b), the ammonium system species as Alk. NH_4^+ (presented in Eq. E2.21c) and the VFA system species Alk (presented in Eq. E2.21d). Systems such as the NDBEPR AS system and the AD system HAc treating NDBEPR WAS contain a mixture of all the above mentioned weak acid/base species as described in Eq. E 2.21e.

$$H_2CO_3 * Alk = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+] \quad \textbf{(E2.21a)}$$

$$Alk.H_3PO_4 = [H_2PO_4^-] + 2[HPO_4^{2-}] + 3[PO_4^{3-}] \quad \textbf{(E2.21b)}$$

$$Alk.NH_4^+ = [NH_3]$$ ***(E2.21c)***

$$Alk.HAc = [Ac^-]$$ ***(E2.21d)***

Hence the total Alkalinity is given by

$$Total \quad Alk = H_2CO_3 * Alk + Alk.H_3PO_4 + Alk.NH_4^+ + Alk.HAc$$
$$............ = [HCO_3^-] + 2[CO_3^{2-}] + [H_2PO_4^-] + 2[HPO_4^{2-}] + 3[PO_4^{3-}] + [NH_3] + [Ac^-] + [OH^-] - [H^+]$$

(E2.21e)

As mentioned above for PS and ND WAS AD, the effect of the P_t, N_t, and A_t systems negligible. This is also true for anaerobic digestion of BEPR WAS, except that the phosphate species concentration is much greater than in the case of PS and ND WAS and therefore, will have a notable impact on the system pH. This aspect will be explored in the investigation.

2.4.3 Gas-Liquid processes

Some products of anaerobic digestion exist at equilibrium in both a gaseous and aqueous phase. During the anaerobic digestion process, the gas-liquid transfer equilibrium is dependent of the partial pressure of the gas phase (Moosbrugger *et al.*, 1992). Henry's law can be applied to describe the equilibrium relationship between the gaseous and aqueous phases in relatively dilute aqueous phase concentration systems (Batstone *et al.,* 2002), such as ADs. So in AD, the aqueous/dissolved CO_2 concentration (H_2CO_3*) is dependent on the two-phase equilibrium that exists between the aqueous and gaseous phases (Moosbrugger *et al.* 1992). The gas phase CO_2 partial pressure ($p$$CO_2$) is established in the AD headspace by the stoichiometry of the AD bioprocesses.

During methanogenic AD, like the treatment of PS and ND WAS, the composition of the biogas comprising gaseous CO_2 and CH_4, and therefore the CO_2 partial pressure (p_{CO2}), is set by the composition of the organics digested i.e. Eq E2.9 (Sötemann *et al.*, 2005). The solubility of CH_4 at normal AD operational conditions is so low that CH_4 can be accepted to be insoluble. In contrast CO_2 is significantly soluble and forms both the gaseous and dissolved species. The dissolved CO_2

species concentration ($[H_2CO_3^*]$) in the aqueous phase is in equilibrium with the pCO_2 in the headspace and can be determined using the Henry's law expression (Loewenthal *et al.,* 1994):

$$\left[H_2CO_3^*\right] = K_H \times p_{CO_2} \qquad \textbf{\textit{(E2.22)}}$$

Where: K_H = Henry's law constant

$[H_2CO_3^*]$ = the dissolved CO_2 concentration in mol/l

In circumstances where the $H_2CO_3^*$ concentration is known, these expressions are used to determine the p_{CO2}. However, in situations where the biogas composition (pCO_2) is known, the dissolved CO_2 gas concentration can be determined which in turn is in equilibrium with the bicarbonate concentration (HCO_3^-) via Eq. E2.19a. Because, the predominant components of the biogas from methanogenic anaerobic digestion is CO_2 and CH_4, the pCO_2 can be determined from the CO_2 and CH_4 gas mol fraction in the biogas by using the equation E2.22:

$$p_{CO2} = \frac{[CO_2]_g}{\left([CO_2]_g + [CH_4]_g\right)} \qquad \textbf{\textit{(E2.23)}}$$

Knowing the pCO_2 and the HCO_3^- concentration generated from the stoichiometry, the pH of the digester can be calculated because 2 parameters of the inorganic carbon/water system are known. For AD of NDBEPR WAS with high P concentrations, the P_t system needs to be included because it will affect the AD pH. With a mixed weak acid/base system comprising the inorganic carbon (IC), P and water systems, 3 parameters need to be known to determine the pH. The aqueous OP (P_t) can concentration is this 3rd parameter. This will be discussed in Chapter Four.

2.4.4 Precipitation / Solubility (Liquid – Solid processes)

Anaerobic digester supernatant contains Mg, Ca, free and saline ammonia, phosphates and carbonate as species that under favourable conditions are likely to form various mineral precipitates. Anaerobic digestion supernatant has the potential to form precipitation like struvite ($MgNH_4PO_4.6H_2O$), newberyite ($MgHPO_4.3H_2O$), amorphous calcium phosphate ($Ca_3(PO_4)_2$), magnesium carbonate ($MgCO_3$) and calcium carbonate ($CaCO_3$) (Musvoto *et al.,* 2000). Anaerobic digesters treating thickened BEPR WAS, thus operating at high concentrations of ammonium, magnesium and phosphate, struvite scaling is a common problem (Jardin *et al.*, 1994; Miya *et al.*, 1984).

Struvite precipitation occurs when the ionic product of the molar activity of Mg^{2+}, NH_4^+ and PO_4^{-3} in solution exceeds the thermodynamic solubility product (K_{spm}) of struvite in the aqueous phase (Bhuiyan *et al.*, 2008). The solubility product of struvite at infinite dilution in the negative log form (pK_{spm}) is 12.6 and can be applied in the equation (Loewenthal *et al.*, 1994),

$$\left[Mg^{2+}\right]\cdot\left[NH_4^+\right]\cdot\left[PO_4^{3-}\right]=\frac{K_{spm}}{f_d f_m f_t}=K'_{spm} \qquad \textbf{\textit{(E2.24)}}$$

Where f_m, f_d and f_t refer to the activity coefficients of mono- , di- and tri-valent ionic species, respectively. The method of determining the activity coefficients for the ionic species is described in Appendix One of Loewenthal *et al.* (1989). This is based on a modification of the Debye-Huckel theory, by Davies, describing the activity of ions in low salinity water (Butler *et al.*, 1964). A summary of this method is described in Appendix B3 of this work. For a total dissolved solid (TDS) concentration of around 2500 mg/l, the pK'_{spm} value is 11.85.

Jardin *et al.* (1994) compared the difference between the K and P mass balances to establish the extent of mineral precipitation in the AD treating thickened BEPR WAS. From their experiments and computations they concluded that approximately 20% of P released formed struvite. Even at total phosphorus concentrations of about 4000 mgP/l, the concentration of orthophosphate in solution did not increase above 1500 mgP/l. Mineral precipitation affects digester pH making pH calculation a complex three phase mixed weak acid/base problem.

2.4.5 Conclusion to Physico-chemical processes

Theoretically, a comprehensive anaerobic digestion model should include a three phase physico-chemical process component, which includes equilibria of species that exist in more than one phase within the AD environment. Furthermore, a three phase model will ensure mass and charge balance continuity within the unit operation. In instances like that studied by Jardin *et al.* (1994), the application of such a model is required to describe the anaerobic digestion system. However, the introduction of a solid phase to existing two phase (gas-liquid) AD models is a complex undertaking and will result in a complicated model, possibly too complicated for a steady state AD model.

Furthermore, the Jardin *et al.* (1994) case is not very common because the conditions needed to start and sustain mineral precipitation are normally not typical of anaerobic digester environments. Most mineral precipitation occurs in subsequent processes, like centrifuges, and outlet pipelines and bends where the partial pressure of CO_2 decreases causing an increase in pH (van Rensburg *et al.*, 2003). The need to include a three-phase physico-chemical process within the model describing the AD process for this case will be discussed in Chapter 4 of this study.

2.5 Plant-Wide Modelling

2.5.1 Introduction to plant-wide modeling

As indicated earlier, steady state models and dynamic simulation models for WWTP processes are useful tools for the selection and optimization of unit operations and evaluating different operational strategies for improved effluent quality and reduced design and operation cost (Grau *et al.*, 2007). Steady state models describing one or more unit operation within a WWTP are simplifications of complex dynamic models that can be used to estimate principal design and operational parameters. Once the unit operations are sized by means of the explicit algebraic steady state equations, the complex dynamic simulation models can be applied to individual unit operations to refine their design and evaluate their operational performances under dynamic conditions (Ekama, 2009).

The use of mathematical models to quantitatively describe various individual unit operations within WWTPs became increasingly popular in the 1980's. However, until the mid-1990's, these model based studies focused primarily on issues related to a single unit operation within the overall WWTP. The result was various task groups focussing on specific unit operations. Under the umbrella of the International Water Association (IWA), specialised task groups developed generalised models describing specific unit operations (Vanrolleghem *et al.*, 2005),

A. Activated Sludge Model number one (ASM 1) (Henze *et al.*, 1987), ASM2(d) (Henze *et al.*, 1995) and ASM3 (Henze *et al.*, 2000),
B. River Water Quality Model number one (RWQM 1) (Reichert *et al.*, 2001),
C. Anaerobic Digestion model number one (ADM 1) (Batstone *et al.*, 2002).

A growing demand for optimisation of WWTPs has led to an increasing awareness that synergies can be found in studying these treatment plants as holistic systems instead of individual unit operations (Vanrolleghem *et al.*, 2005). However, challenges arise from the incompatibilities and different descriptions of the state variables and output parameters for the generalised models developed by the different IWA task groups (Grau *et al.*, 2007).

To address these problems, two main plant-wide modelling approaches have been proposed, (1) the "super-model" approach by Jones and Takács (2004) and (2) the continuity based interface method (CBIM) developed by Copp *et al.* (2003), Vanrolleghem *et al.* (2005) and Volcke *et al.* (2006).

2.5.2 Supermodel Approach and Interface Transformation (CBIM) Approach

The “super-model approach” defines all the compounds required in the entire WWTP in the same form and units and then models the changes in these compounds in each unit operation (Jones and Takács, 2004 and Seco *et al.*, 2004). This approach ensures continuity of all state variables and components in all unit operations within the overall WWTP, thus, requiring no transformation functions at interfaces between unit operations. However, the disadvantage is model size and complexity and the difficulty to increase new bioprocesses due to a lack of flexibility to add or remove components in these models (Volcke *et al.*, 2006; Grau *et al.*, 2007)

The CBIM approach keeps the individual unit operation models unchanged and concentrates on the construction of interface transformer models to connect existing generalised models, such as connecting ASM1 to ADM1 (Volcke *et al.,* 2006). This approach maps the output compounds from the source model to the required form for input to the destination model, while maintaining mass balances on the various elements, C, H, O, N, P and COD (Vanrolleghem *et al.*, 2005; Volcke *et al.*, 2006). This approach does not require alterations to the existing, proven standard models, like ASM1 and ADM1, but the disadvantage of this approach is that there are limitations related to transforming some model components at the interface between different models (Jeppeson *et al.,* 2006).

2.5.3 Steady State and Dynamic Modelling

Steady State models describing biological processes, in general, are based on the kinetic rate of the slowest bioprocess which governs the overall rate in the system (Wentzel *et al.,* 2006). Steady state models therefore comprise explicit algebraic equations link unit operation performance to size defining parameters like sludge age or loading rates. Some of the key advantages of steady state models are that (Ekama *et al.,* 2006),

- steady state models are simpler and easier to construct than dynamic simulation models and require much less input information,
- much less input information is required,

- the initial setup cost is significantly lower and computations can be performed in a simple spread sheet platform,
- the principal system design parameters, like sludge age, reactor volume, recycle ratios, oxygen requirement or gas production can be determined with explicit algebraic equations,
- the principle design parameters from the steady state models, can be used as the start up or initial input variables to dynamic simulations models,
- sensitivity of unit operation to operational parameters can be performed,
- results can be used to cross-check dynamic simulation model results and for economical evaluation of specific unit operations and overall WWTP.

Dynamic simulation models, on the other hand, require the bioprocess modelling of each component with interconnected differential equations (Wentzel *et al.,* 2006). Petersen matrices are utilized to produce these models and can then be programmed as input components to simulation software, like WEST^{TM}, which perform the computation to simultaneously solve the differential equations. These dynamic simulation models are powerful tools for predicting system performance during dynamic flow and load conditions, the development of process control elements and process trouble shooting functions. The choice of using steady state or dynamic simulation models is based on the level of detail required, and the resources and technical competence available (Ekama, 2009).

2.5.4 Conclusion to Plant-wide Modelling

Sötemann *et al*. (2005) developed a steady state model for anaerobic digestion of PS and WAS from a ND AS system with an AD system. The finding of Ekama *et al.* (2006) that unbiodegradable organics, as defined by the aerobic AS system, remain unbiodegradable in the AD, simplifies the coupling of steady state AS and AD models. To achieve this coupling, the results obtained from the steady state AS model are transformed to elemental compositions. These elemental compositions are the input variables to the steady state AD model. Thus, in concept the steady state plant-wide model of Ekama (2009) is similar to the CBIM approach of Vanrolleghem *et al.* (2005) and Volcke *et al.* (2006). There is no doubt that plant-wide models will be increasingly used for WWTP design and operation to maximize treatment capacity and minimize effluent organic and nutrient concentrations. In fact combining steady state models with dynamic simulation models will significantly facilitate and simplify dynamic model simulation software use because with the steady state models the unit operation sizes, interconnecting flows and initial reactor concentrations can be calculated for design of new WWTPs or WW characteristics estimated for operation of existing WWTPs (Ekama, 2009).

2.6 Closure

This chapter presented and reviewed literature from various sources that supports the development of a steady state model describing the AD of NDBEPR WAS in Chapter 4. The steady state AD model developed by Sötemann *et al.* (2005) was reviewed to provide insight into its formation and structure. The procedure used in the development of the Sötemann *et al.* (2005) AD model will be used extend this model to include P and describe the AD of NDBEPR WAS, which is the aim of this study.

Background literature on the characterization of PS, ND WAS and NDBEPR WAS was presented in Section 2.2. To support the characterization procedure of the ND and NDBEPR waste activated sludge, the AS system that produces these kinds of WAS were reviewed in Section 2.2.1 (ND AS systems) and Section 2.2.2 (NDBEPR AS systems). To feed the NDBEPR AS system WAS to the AD system, characteristics are required to be determined. NDBEPR WAS contains stored inorganic polyphosphate which is the most significant difference between this WAS and that from the ND AS system and PS and is the cause for most of the extensions and modification needed to the Sötemann *et al.* (2005) AD model. Section 2.2.3 presents literature that described the structure and composition of polyphosphate. This section also described the chemical make-up of polyphosphate in its elemental composition $MePO_3$ and described equations to determine a factor (or linkage factor - q_θ) to link elemental composition of the inorganic polyphosphate to the relevant organic particulate components. Background literature that describes the fractionation of the VSS in AS systems into its various components like OHO and PAO biomass was presented in Section 2.2.4. This review included the description of the steady state AS models by Wentzel *et al.* (1990) and Ekama and Wentzel (2004) for fractionating NDBEPR WAS into biodegradable, unbiodegradable and inorganic components.

Section 2.2.6 reviewed literature that describes the transformation of the outputs of the steady state AS models to the format required for the steady state AD models. The biological and physico-chemical processes of anaerobic digestion were also reviewed in this Section. The transformation procedure of the different VSS components to their elemental compositions in the form $C_XH_YO_ZN_AP_B$ for the organic particulate components and $MePO_3$ for the polyphosphate part were examined. This section also describes the coupling of the organic and polyphosphate elemental compositions, with the linkage factor to form a single component

$C_XH_YO_ZN_AP_B.q_\theta[MePO_3]$. The final Section 2.2.7 reviewed literature from previous studies discussing the elemental composition of PS and ND WAS, and its biodegradable and unbiodegradable components and summarised these in Table 2.4.

The literature review continued by exploring the development of the AD models describing the digestion of PS and ND WAS in Section 2.3. Section 2.3.1 reviewed studies that provided a brief overview of the microbiology, kinetic rates and stoichiometry of AD. Furthermore, Sections 2.3.2 and 2.3.3 presented and reviewed papers by Sötemann *et al. (*2005) and McCarty (1974 &1975) that described the development the steady state model for AD of PS because these procedures will be used to extend the model to include AD of NDBEPR WAS. Section 2.3.4 reviewed a study by Jardin *et al.* (1994) that looked at the AD of NDBEPR WAS, the aim of which was not to develop a model describing the AD process but rather to observe whether or not precipitation occurs in the digester fed BEPR WAS. It did.

Section 2.4 presented background literature on the physic-chemical processes associated with the anaerobic digestion of PS, ND WAS and NDBEPR WAS. Section 2.4.2 reviewed literature that describes the aqueous phase weak acid/bases chemistry that occurs in the AD of this waste sludge. Sections 2.4.3 and 2.4.4 reviewed literature that describes the gas-liquid processes and the liquid-solid processes of anaerobic digestion respectively. Finally, Section 2.5 reviewed literature that describe the context of this study on a plant-wide scale and other models that describes coupling of unit operations in WWTPs. This section also presents a case for the use of steady state models as a complement to dynamic models.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Introduction

The core objective of this chapter is to explain the experimental setup and analytical procedures utilized during experimental work. This chapter and the equivalent by Ikumi *et al.* (2009) are largely similar because the experimental work for both projects was done collaboratively. However, the same data is used for different research questions. Ikumi *et al.* (2009) will focus on the development of a steady state hydrolysis kinetic model and biodegradability in the anaerobic digestion (AD) of primary sludge (PS), waste activated sludge (WAS) from a nitrification–denitrification (ND) system and WAS from ND biological excess P removal (NDBEPR) activated sludge system while this focuses on the Phosphorus (P) release rate and the development of a steady state stoichiometry model describing the AD of NDBEPR WAS.

The experimental layout comprised, at laboratory scale, three types of full scale wastewater treatment plant (WWTP) schemes, i.e. (1) a Modified Ludzack – Ettinger (MLE) N removal activated sludge (AS) system treating settled WW with separate AD of primary sludge (PS), WAS and PS-WAS blends, (2) a MLE N removal AS system treating raw WW with AD of WAS and (3) a University of Cape Town (UCT) N and P removal system treating settled WW with AD of WAS. All three AS systems were fed the same wastewater collected from the Mitchell's Plain wastewater treatment plant (WWTP), in Cape Town. To ensure a consistent composition of the raw and settled wastewater, measured masses of macerated PS collected from the Athlone WWTP (Cape Town) was added to the collected Mitchell's Plain (raw) WW. Hence in this experimental programme, raw WW is Mitchell's Plain raw WW with Athlone PS added, and settled WW is Mitchell's Plain (MP) raw WW only. In order to increase the BEPR in the UCT system 200 mg/l of acetate was dosed to the settled wastewater feed.

3.2 Experimental Setup

A diagrammatic representation of the experimental layout is shown in Figure 3.1.

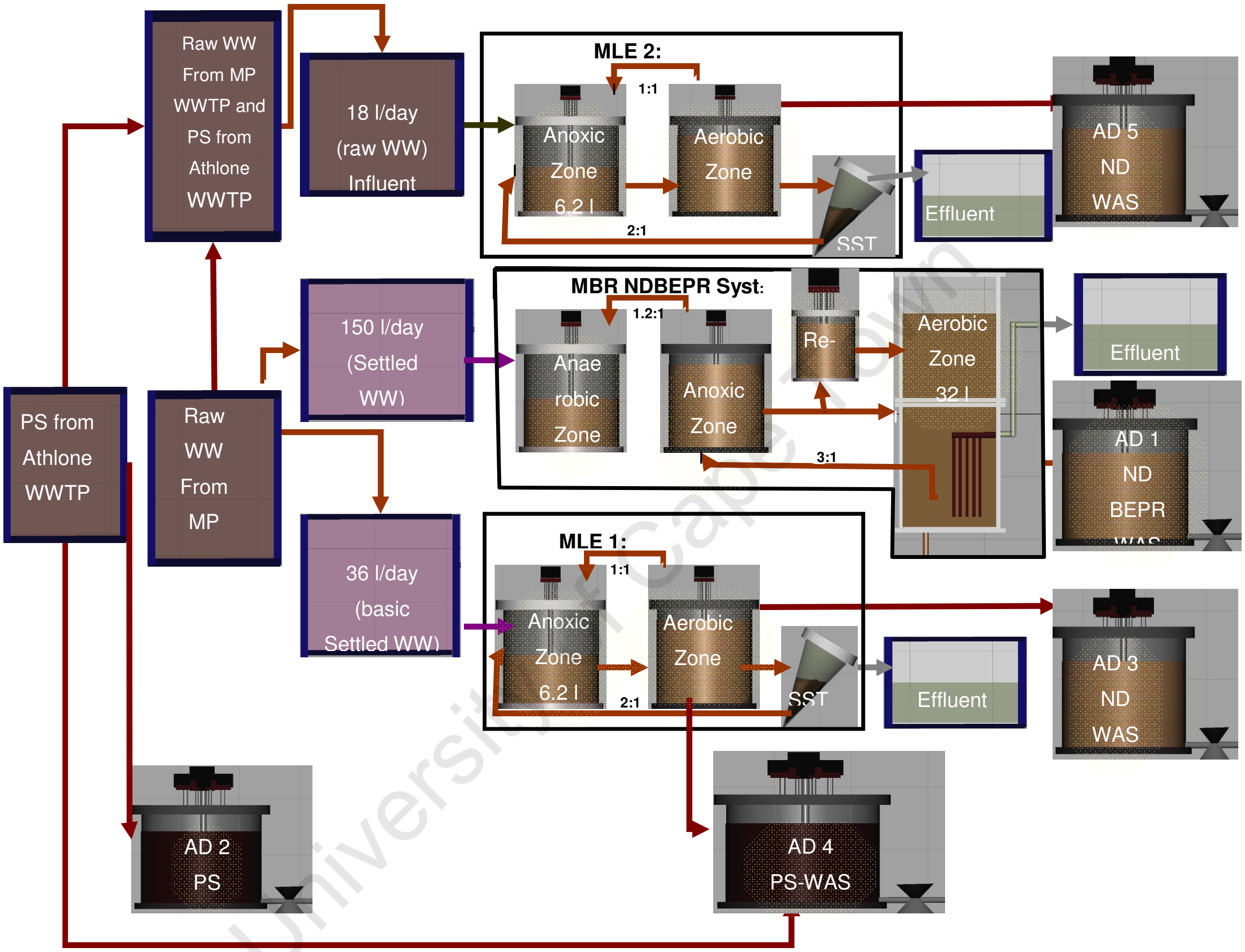


Figure 3.1: Experimental Set-up (Ikumi *et al.*, 2009)

Raw WW was fed to one of the MLE systems (MLE 1) and settled WW to the UCT NDBEPR and the other MLE system (MLE 2). The PS added to the collected WW to make the raw WW and the WAS from the three AS systems were fed to 5 completely mixed flow through ADs, i.e. AD1 fed WAS from the NDBEPR AS system, AD2 fed PS only, AD3 fed WAS from the settled WW MLE system, AD4 fed WAS from the settled WW MLE blended with PS and AD5 fed WAS from the raw WW MLE system.

3.2.1 Wastewater Collection and AS System Feed Preparation

The collected WW was pumped from the main collection sump at the Mitchell's Plain wastewater treatment plant (MP WWTP) in Cape Town (South Africa). This WWTP treats mainly domestic sewage with a small (less than 10 %) industrial component. The Raw WW was collected in 2 m^3 batches with a small tanker truck and transported to the Water Research Group (WRG) laboratory at the University of Cape Town (UCT). While mixed with high pressure compressed air, the collected WW was transferred by gravity through an in-line macerator into five 400-liter stainless steel storage tanks. These storage tanks are located in the laboratory cold room maintained at 4ºC. A batch of sewage normally lasted about 15 to 20 days, after which it was discarded and a new sewage batch collected. The storage of sewage for longer than three weeks usually caused the sewage to become septic (hydrogen sulphide accumulation) and undergo significant WW characteristic changes. Upon arrival, Chemical Oxygen Demand (COD) analysis was performed on the collected WW. Typically, undiluted sewage from the MP WWTP ranged between 1200 and 1500 mg COD/l, but may tend to vary as a result of rainfall, causing dilution, especially during the winter rainy season. Daily, after thoroughly mixing the WW, the required volume was withdrawn from the stainless steel tanks and diluted with tap water to a target COD of 600 mg/l. This was done to ensure that the COD load to the AS systems remained consistent throughout the experimental period. The 600 mg COD/l feed represented the settled WW and was fed to the UCT NDBEPR system and one of the MLE systems (MLE 1).

A measured mass (volume × concentration) of PS was dosed into one of the stainless steel tanks to make the raw WW. Primary Sludge (PS) was obtained from the underflow of the PST at the Athlone WWTP. This was generated from the settling of domestic raw sewage at the treatment plant. It was collected in about 50 litre batches and stored in the 4˚C cold room. Primary sludge (PS) usually undergoes considerable anaerobic fermentation, even at temperatures of 4˚C. This causes an increase in SCFA concentration of the stored PS. To keep the changes in PS characteristics small, its storage was limited to a maximum of 3 months. Before adding to the collected WW the PS was thoroughly macerated to reduce its particle size to prevent blockages in the experimental systems. The PS from the Athlone WWTP had a COD concentration of around 80000mgCOD/l, but this varied with different batches. The PS was diluted with tap water to 60000mgCOD/l in order to have a consistent PS COD concentration to make the mass balance calculations over the virtual PST easier.

3.2.2 Activated Sludge Systems

All three AS systems were fed the same basic “settled” wastewater but two of the systems’ feed COD was adjusted to conform to the objectives for this research. All three AS systems were operated at constant temperature of 20˚C (± 1˚C) and at a sludge age (R_s) of 10 days, by harvesting the required volume of sludge from the aerobic reactor (taking due account of the mixed liquor abstracted for samples from the different reactors).

3.2.2.1 Feed Preparation for ND activated sludge systems (MLE1 and MLE2)

The MLE 1 and MLE 2 were fed raw and settled wastewater respectively. The settled wastewater for MLE 2 was set at a COD of 600 mg/l. At times where the Total Kjeldahl Nitrogen to COD (TKN/COD) ratio was lower than the 0.1 Ammonium Chloride was dosed to the influent to make up the influent TKN/COD ratio to 0.1. MLE 2 was fed 36 l/d at a constant 24h rate. The daily 36l influent to this system was stored in a 50 litre feed tank housed inside a chest refrigerator to maintain the temperature of the influent below 8^oC. The influent was gently stirred to keep the wastewater particulates in suspension.

The raw wastewater feed for MLE 1 was produced by adding a measured mass of PS to the settled wastewater. PS was added to increase the basic 600mgCOD/l settled WW to a target COD of 1000 mgCOD/l raw WW. Due to the higher influent COD, the MLE 1 was fed at half the daily volume of MLE 2, i.e.18 l/d. The daily influent was stored in a 30 litre feed tank housed in the chest refrigerator and gently stirred to prevent settling of the PS settleable solids.

To ensure that each AS system was fed its required mass of COD per day, at the end of a 24 h period, any WW and solids left in the feed tank (usually less than 0.5 l) was collected and added batch wise into the first reactor of the AS system.

3.2.2.2 Feed Preparation for the NDBEPR activated sludge system (UCT- MBR)

The UCT NDBEPR system was fed the same basic 600 mgCOD/l “settled” WW with 200 mgCOD/l acetate added to increase the BEPR by the system. This was achieved by the adding 40g of sodium acetate to the daily required feed volume of 150 l/d. Also, to avoid P limitation di-potassium hydrogen orthophosphate (K_2HPO_4) was added to the feed, to provide potassium and to increase the phosphorous concentration to 40mgP/l and when required NH_4Cl was added to increase the TKN/COD ratio to 0.1 (before acetate addition).

The daily influent volume was stored in a 200 l tank housed in a chest refrigirator at 8ºC. Because the influent flow is very high (150 l/d), the feed pipe to the reactor was coiled in a 20 l water bucket to raise its temperature, to avoid reducing the temperature in the anaerobic reactor to below 19ºC. Also, as for the MLE systems, any feed and particulates left in the feed tank after a 24 h period was added batch wise into the anaerobic reactor. To prevent wall growth in the feed drums and feed pipes of the three AS systems, they were cleared with hot water and chlorine every 2nd day

3.2.2.3 Description of ND Activated Sludge Systems (MLE1 and MLE2)

Both MLE systems comprised two reactors and a secondary settling tank (Fig. 3.2). The first reactor was a 6.2-liter anoxic tank followed by a 16.2-liter aerobic tank both made from clear cylindrical Perspex. The influent wastewater enters the anoxic reactor and thereafter flows through to the aerobic reactor. In both the anoxic and aerobic reactors, motorized stirrers create agitation to keep the mixed liquor suspended solids (MLSS) completely mixed. The outflow from the aerobic reactor enters the Secondary Settling Tank (SST), which separates the biological sludge from the treated water. The SST was made from a 600 mm long 100 mm diameter clear Perspex cylindrical tube fitted with a wiper blade to keep its inner walls clear of sludge. The wiper blade made 3 revolutions in 15 seconds every 10 minutes. The SST was set up at an angle of about 60 degrees to enable the sludge entering the SST at its base to be rapidly removed by the recycle flow diagonally opposite to the entry point. The effluent (clear, treated water) overflows the top of the cylinder. The two reactors and SST were connected with 12 mm soft clear plastic tubing. The outflow was withdrawn from the base of the reactor via an inverse U-tube, mounted on the side of the reactor, with which the liquid volume of the reactor could be set. The MLE systems had a 2:1 mixed liquor recycle flow that returned mixed liquor from the aerobic to anoxic tanks and a 1:1 underflow sludge recycle flow that returned sludge from the secondary settling tank to the anoxic reactor.

Each MLE system was operated with one multichannel peristaltic pump set to deliver the daily influent feed volume over 23.5 to 24 h. The recycle flows were delivered by the same pump, one channel for the sludge return (s =1:1) and two for the mixed liquor recycle (a = 2:1). These flows were checked regularly with a measuring cylinder and stopwatch to check that they correctly paced the influent flow.

Compressed air was supplied via a fine bubble diffuser at the bottom of the aerobic reactor to provide aeration. As the air bubbles rise to the surface, oxygen from the air bubbles dissolves into the mixed liquor. A Hi-tech Micro system DO controller/OUR meter was utilized to control the dissolved oxygen (DO) concentration between the 2.0 mgO/l and 5.0 mgO/l low and high set points respectively. When the DO reaches the high set point, aeration stops and the oxygen utilization rate (OUR) is recorded by measuring the slope of the decreasing DO versus time line. When the DO reaches the low DO set point, aeration commences again. The OUR readings accumulated in the OUR meter over 24 h are downloaded daily to a data collection computer.

The two MLE systems were operated at a 10 d sludge age by wasting 2.2 l of mixed liquor from the aerobic reactor daily, which includes any mixed liquor taken for samples.

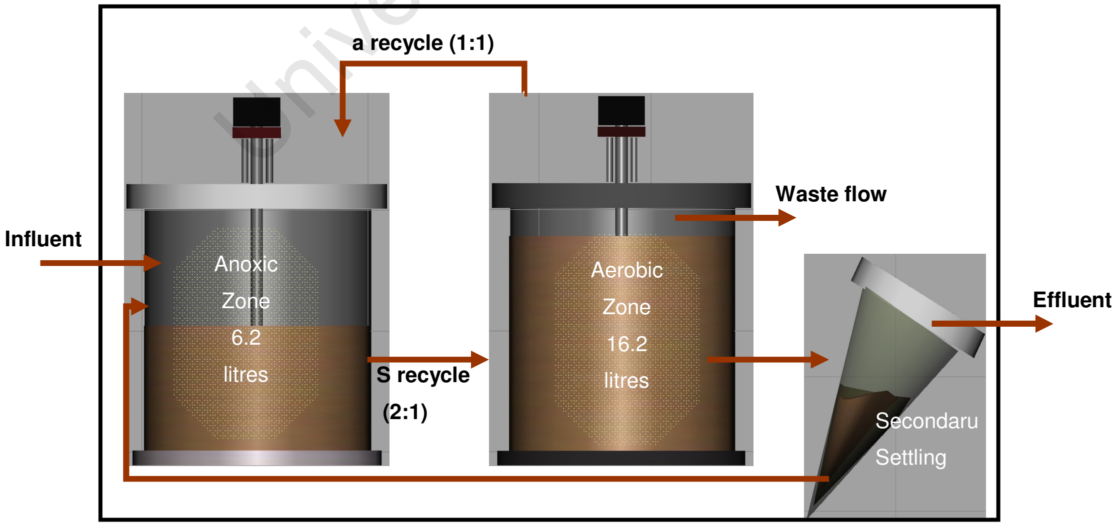


Figure 3.2: MLE process used in research project

3.2.2.4 Description of NDBEPR activated sludge system (UCT- MBR)

The nitrification-denitrification biological excess phosphorus removal (ND BEPR) AS system was set up in a UCT configuration with sequential anaerobic, anoxic and aerobic reactors (Fig. 3.3). The anaerobic reactor was 19 l, the anoxic 21 l and aerobic zone 35 l. The aerobic zone comprised two reactors – a 32 l membrane reactor and a 3 litre side stream aeration tank for OUR measurements. The membrane tank was fitted with Kubota ^{TM} A4 size membranes through which the final effluent was produced. The membrane panels were fitted vertically in the bottom section of the main aerobic tank. Continuous coarse bubble aeration was supplied at the base of the reactor. The air bubbles were forced to rise between the membrane panels to provide scour and minimize fouling. The 3 l side stream aeration reactor was fitted with a DO controller/ OUR meter to measure the OUR. The flow rate from the anoxic reactor to side stream reactor was set to give the same actual retention time as in the MBR reactor. The solids concentrations in the side stream aerobic reactor was same as that in the anoxic reactor, hence the effective volume of the aerobic reactor at its higher solids concentration was lower than 35 l. This was taken into account when calculating the total sludge mass in the system and the anaerobic, anoxic and aerobic sludge mass fractions.

The UCT system was operated with one peristaltic pump set to deliver the influent feed volume of 150 l in 23.5 to 24 h The mixed liquor recycles were set at 3:1 (3 channels) for the as-recycle from the aerobic to the anoxic and 1:1 (1 channel) for the r-recycle from the anoxic to the anaerobic reactors. These recycle flows were regularly checked with a measuring cylinder and stop watch and recorded as a ratio with respect to the influent flow. For the fixed volume reactors the anaerobic, anoxic and aerobic mass fractions are set by the recycle ratios. The relationships between the mass and volume fractions in terms of the recycle ratios are given by Ramphao *et al.* (2004). The long term averages of the measured reactor MLSS concentrations could therefore be used to check the measured recycle ratios. The anaerobic, anoxic and side stream aeration tanks were fitted with stirrers for mixing while the main aerobic MBR reactor was mixed by continuous coarse bubble aeration.

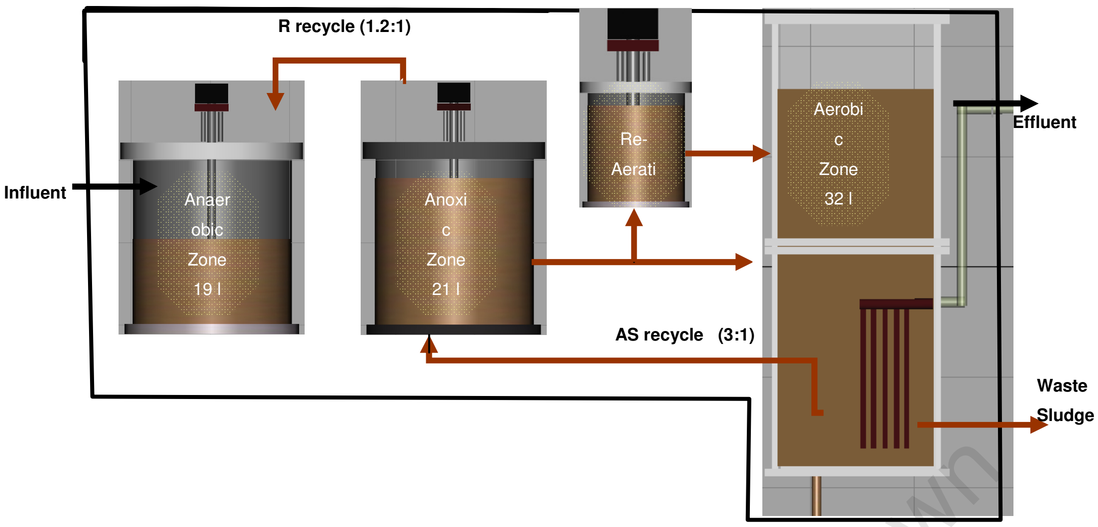


Figure 3.3: NDBEPR system used in research project.

The UCT NDBEPR sludge age was maintained by wasting daily a total equivalent volume of 5.74 l sludge from the aerobic membrane reactor, which included the mixed liquor taken from the anaerobic and anoxic reactors for testing, taking due account of the differences in reactor MLSS concentrations.

3.2.2.5 Sampling (see Table 3.1 for details)

Filtered and unfiltered samples are taken from the two MLE systems. Samples were collected from the influent, anoxic reactor, aerobic reactor and effluent. In case of the UCT-MBR system, 50ml samples were drawn from the anaerobic, anoxic and aerobic reactors and two drops of polyelectrolyte flocculent (1g/l) added to make subsequent filtration easier, due to the high non settleable solids in the MBR system mixed liquor. These samples were immediately placed in 50ml centrifuge tubes and centrifuged at 3500rpm for 10 minutes. The centrifuge supernatants are filtered through 0.45 micrometer membrane filters and stored in the cold room for later analysis. This filtrate was analysed for COD, TKN, FSA, NO_3, NO_2, TP and OP as will be discussed, in more detail, in the subsequent section on analytical procedures. The MBR NDBEPR system effluent was not filtered because the membrane pore size is less than 0.45 micrometer membrane filter paper. In fact the effluent COD from the UCT MBR system was consistently lower than the 0.45 μm membrane filtered COD in the aerobic reactor. The solids in the centrifuge tube were used for the TSS, VSS and ISS tests. Hydrogen ion concentrtion (pH) was measured in the anoxic and aerobic reactors of the ND BEPR system. Samples of the NDBEPR system influent, effluent and mixed liquor (both unfiltered and 0.45 membrane filtered) were used in testing the counter-ion (magnesium, potassium and calcium) concentration. Also 500ml and 100ml was drawn from aerobic reactors of the MLE and NDBEPR systems respectively and used to measure the DSVI (dilute sludge volume index).

3.2.3 Anaerobic Digestion Systems

The PS and WAS from the three AS systems was fed daily, batch wise, to the five completely mixed ADs. Three of the ADs received WAS from each AS system (MLE 1 for AD 3, MLE 2 for AD 5 and UCT MBR for AD 1), one AD received the PS used to make the raw WW (AD 2) and one received a 1:1 blend (by COD mass) of PS and MLE 2 (fed settled WW) WAS. In this way the experimental setup simulates the connection of a PST to an AD and AS systems to ADs. All five ADs were not fed continuously over a day but batch wise once daily for the ADs fed WAS and two or three times per day for the ADs receiving PS and PS-WAS blend. Initially, when the ADs fed PS were fed once per day, the volatile fatty acid (VFAs) concentrations increased rapidly resulting in a drop in pH over time and eventual AD failure. The spreading of the daily feed mass over two to three batches per day prevented system failure. Each 20 l digester contained 16 l liquid volume and was fed the same COD concentration daily. The daily feed volume was determined by the sludge age (R_s or retention time, Rhn) established on the AD in conformity with $Q = V/R_s$.

Each digester was operated at 7 different sludge ages i.e. 10, 12, 18, 20, 25, 40 and 60 days. The COD results of the 10, 18, 25, 40 and 60 day sludge ages are used to calibrate the steady state AD model while the 12 and 20 day sludge ages are used to validate the AD model. The short sludge ages are useful to determine the hydrolysis rate of the different sludges and the very long 60 day sludge age is useful to determine the unbiodegradable fraction of the sludges, as recommended by Sötemann *et al.* (2005). For the short and long sludge ages, once the time period of 3 and 2 steady states respectively had elapsed, testing of the ADs commenced for a period of 2 to 3 weeks, aligned with one or two sewage batches fed to the AS systems.

3.2.3.1 AD Feed Preparation

Anaerobic digesters 1, 3 and 5 were fed WAS from the UCT-MBR system, MLE 2 and MLE 1, respectively. The WAS from the UCT-MBR system (~ 10g TSS/l) was fed directly to AD 1 without any thickening. Consequently, there was a change in the COD mass load for every change in the sludge age i.e. 1.6, 1.333, 0.889, 0.8, 0.640, 0.4 and 0.267 l/d for 10, 12, 18, 20, 25, 40 and 60 days sludge age, because a large volume of WAS was available from the UCT MBR system to feed a high flow at the short sludge ages. In contrast, because the two MLE systems did not produce a large mass of WAS daily, the WAS from MLE 1 and MLE 2 was thickened to a higher concentration with change in the sludge age to maintain a constant daily mass load throughout the duration of this study. Before the WAS was fed to the three ADs, it was heated to above 35˚C to avoid causing a temperature shock to the temperature-sensitive methanogenic biomass.

Anaerobic Digesters 2 and 4 were fed PS only and a 1:1 ratio (by mass) of PS-WAS mixture respectively. The daily TSS load of PS fed to AD 2 and used in the mixture of AD 4 was equal to the PS TSS mass dosed in the ‘settled’ WW to make the raw WW fed to MLE 1 (i.e. 18 l/d × 400mgCOD/l = 7.2gCOD/d). The daily WAS from the MLE 2 treating the settled WW was split into two halves, one half was fed to AD 3 as mentioned above, the other half was blended with 7.2 gCOD/d PS and fed to AD 4. It was possible to split the WAS from MLE 2 while maintaining the approximate relative proportions of PS and WAS at full scale WWTPs because MLE 2 treated double the settled WW flow (36 l/d) compared with MLE 1 treating raw WW (18 l/d).

AS mentioned above the feed to AD 2 and AD 4 receiving PS was spread over the day in 2 to 3 batches. A fixed mass of COD/d was fed to ADs 2 and 4. The volume of feed per day was fixed by the sludge age of the ADs. The PS and PS-WAS blend were diluted or thickened as required to contain the fixed COD mass load into the required feed volume. In the initial start up stage or after changes of sludge age, half of this sludge was fed in the mornings and the other half in the evenings to avoid shock loading, which would result in digester failure. This shock loading occurred because, unlike the WAS which were fed directly from the AS systems, the VFA concentration of the PS was quite high. These high concentrations of VFAs batch fed to the ADs cause the digester pH to drop suddenly, negatively affecting the methanogenic biomass that is highly sensitive to pH variations. This high VFA concentration in the PS was the result of anaerobic fermentation during its storage period in the cold room. In instances where the AD showed signs of failure when changing the sludge age, the loading rate on the digester was reduced to half the sludge mass per day and hydrogen carbonate added to the influent feed.

3.2.3.2 Description the of AD System used for Experimental Research

The anaerobic digesters (ADs) were continuously stirred tank reactors (CSTR) (Fig 3.4). The reactor tank was manufactured from Perspex and cylindrical stainless steel rods for structural support and to ensure a gas tight seal. A stirrer driven by a single phase motor was mounted on the top lid of the unit. The stirring shaft passed through the lid via a sealed bearing to ensure the reactor was gas tight under low positive gas pressures (< 50 mm water). A stop clock was fitted at the base of the reactor for sampling and removal of waste sludge.

A gas outlet port was provided in the top lid. The gas-outlet pipe was connected to a wall-mounted gas counter. The anaerobic digesters were operated at a temperature of approximately 35 ˚C, optimal for mesophilic organisms. This temperature was controlled by means of heating coils wrapped around the outside of the digester walls and connected to temperature controller with a temperature probe in the reactor mixed liquor. The ADs were all completely sealed, except for the provision of the gas outlet pipe and the access port which was closed with a rubber bung. The access port was opened only once daily to measure the pH. The sludge inlet/ outlet pipe at the base of the AD, controlled by a valve, was only opened during feeding process when waste sludge was drawn and new feed sludge added.

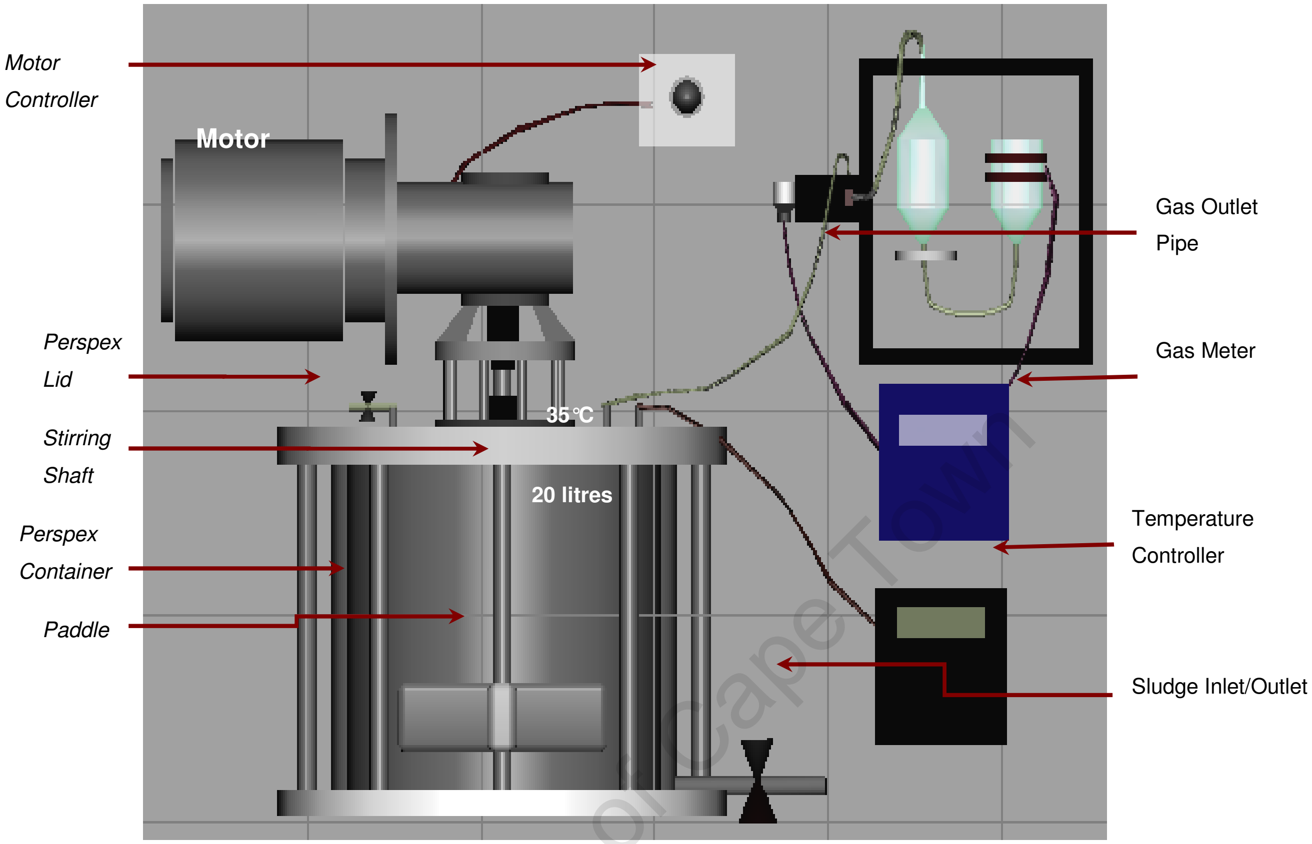


Figure 3.4: Anaerobic Digester used in research project

The total volume of the reactor tanks was 20 litres. However, the operating volume of AD 1 was set at 16 litres while those of ADs 2 to 5 were set at 15 litres. Each digester was operated at 5 short sludge ages (i.e. 10, 12, 18, 20 and 25 days) and two long sludge ages of 40 and 60 days. Because it was difficult to grow and maintain a stable methanogenic population at short sludge ages, the digester operation commenced with the longer sludge ages. Then for the shorter sludge ages, the methanogenic biomass was already established allowing the AD systems to remain operating stably.

The access port was opened once daily for the ADs receiving WAS but 2 or 3 times daily for the ADs receiving PS. First the in-situ pH was measured and then the required volume of waste sludge withdrawn via the outlet at the AD base. Then the AD liquid volume was restored back to the operating volume by adding the required volume of feed sludge, thereby maintaining the prescribed sludge age.

When a time period of three sludge ages had elapsed, experimental tests and measurements were performed on the anaerobic digesters.

3.2.3.3 Sampling of AD Systems

Samples for analysis were collected from the AD influent and effluent taken from the digester. However, for the ADs fed WAS only, sampling was not required because the WAS fed to these ADs had been tested and characterized already as part of the measurements conducted on the AS systems, therefore, influent samples were only collected for the ADs fed PS (AD 2) and PS-WAS mixture feed (AD 4).

In order to check the stability of the ADs on a routine basis, a five point titration was conducted on a filtered effluent sample at least every second day. The in-situ pH and 5 point titration method (Moosbrugger *et al.*, 1992) gives the $H_2CO_3^*$ alkalinity and VFA concentration. For optimal operation, the in-situ pH should be above 6.5 but preferably within the range of 7 and 8 (McCarty, 1974) and the H_2CO_3 alkalinity to VFA ratio should be maintained at more than 3:1 (Ripley *et al.*, 1986). During the intensive measuring periods, once the ADs reached steady state at a particular sludge age, the influent (for ADs 2 and 4) and effluent (for all ADs), unfiltered and membrane filtered VFA, COD, TKN and FSA, TP and Ortho P tests were preformed to determine the extent of digestion and the COD, N and P mass balances over these digesters. For the AD 1, fed NDBEPR WAS the unfiltered and membrane filtered metal ions i.e. magnesium (Mg), potassium (K) and calcium (Ca) were also tested.

The daily gas flow was measured by means of the gas counter and gas samples were collected in 5 litre impermeable Tedlar gasbags connected to the AD gas outlet pipes. The gas was analysed to determine the CO_2 and CH_4 content and was a requirement to establish the COD and carbon balance over the digesters.

3.3 Experimental Testing Methods

The analytical measurements performed on the samples collected from influent wastewaters, PST, AS systems and ADs include the following:

1. Chemical oxygen demand (COD) tests
2. Total Kjeldahl Nitrogen (TKN) test and free and saline ammonia (FSA) test
3. Nitrate (NO_3) and Nitrite (NO_2) analysis
4. Total Phosphate (TP) and Orthophosphate concentration test
5. Volatile fatty Acids (VFA) , H_2CO_3 alkalinity and pH measurements
6. Mixed liquor total and volatile settleable solids (MLSS)
7. Oxygen utilization rate (OUR) in the AS system
8. Gas composition analysis and flow rate measurement on the AD systems
9. Counter-ion metals (Mg^{2+}, K^+ and Ca^{2+}) analysis
10. Organic Carbon and Organic Nitrogen by elemental analysis

All the above analysis was performed in the laboratory of the Water Research Group (WRG) in the Department of Civil Engineering, UCT, except for the gas composition, organic carbon and organic nitrogen analysis.

These measurements were sufficient to allow for the characterization of wastewater and sludge components and perform COD, nitrogen and phosphorus mass balances over all the units and to extend these balances to the full experimental layout. Furthermore, this data set was used in calibration and verification of the steady state models developed from this work. The tests performed on the AD system effluents included all the abovementioned tests for AS systems with the exception of OUR and addition of gas production and gas composition. These tests are briefly described below.

3.3.1 Chemical Oxygen Demand (COD)

The COD was measured using the dichromate and sulphuric acid open reflux method, followed by a titration with ferrous ammonium sulphate (FAS) (American Public Health Association [APHA], 1989). The COD test involves the reflux of a 10 ml sample in strongly acidic solution (15 ml sulphuric acid) with a known excess (~ 5 ml at 0.25 N) of potassium dichromate ($K_2Cr_2O_7$). In principle, the organic matter (electron donor) is oxidised by the boiling dichromate (electron acceptor). After boiling, the quantity of potassium dichromate reduced is determined by FAS (electron donor) titration which gives the electron donating capacity of the oxidised organic matter in terms of oxygen equivalent (Sawyer *et al.*, 1994).

3.3.2 Total Kjeldahl Nitrogen (TKN) and Free and Saline Ammonia (FSA)

The TKN and FSA concentration was measured using i.e. semi-micro Kjeldahl digestion and distillation method, 420B (APHA, 1989). The TKN is the combination of Organic nitrogen (Org-N) and FSA. In the TKN test the sample is digested with a sulphuric acid solution containing potassium sulphate with mercuric sulphate as a catalyst. The digestion converts all organic nitrogen compounds such as proteins and peptides to ammonia. The sample is then steam distilled using micro-distillation apparatus with sodium hydroxide and sodium thiosulphate. On being stripped from the sample as a gas, the ammonia generated from the organically bound N and any ammonia originally present in the sample is condensed and dissolved in a boric acid solution turning it from purple to green. The boric acid is then titrated with standard 0.001 N sulphuric acid solution until it again turns purple and the volume of acid titrated is proportional to the TKN concentration. For the FSA concentration only, the sample is not digested but steam distilled only. The difference between the TKN and FSA is the organically bound N (Org N).

3.3.3 Nitrate (NO_3) and Nitrate (NO_2) test

The Technicon Auto-Analyser Automated Method was applied for the measurement of nitrate and nitrite concentration in solution. This test procedure is described in the operational procedures for the Technicon Auto-Analyser Methodology (Industrial methods 33, 68 and 35.67W). The method is based on nitrate reduction to nitrite and then measuring the nitrite concentration. The chemical reagents for nitrate reduction are Hydrazine sulphate, Sodium Hydroxide and Copper Sulphate. The colour reagent with nitrite makes a pink colour, the intensity of which is proportional to the nitrite concentration and which is measured with a colorimeter. However, samples had to be diluted to below 2mgN/l, because the colour intensity versus nitrite concentration is not linear above this concentration. The nitrate concentration is the difference between the nitrite concentration with nitrate reduction (nitrate + nitrite) and the nitrite only (with no reduction). For more detail on this method refer to the source indicated above.

3.3.4 Total Phosphates (TP) and Ortho-Phosphates (OP)

The TP and OP were measured using persulphate digestion method (Standard Methods, 1985, Method 424CIII) and the molybdate-vanadate colorimetric method (Standard Methods, 1985, Vanadomolybdophosphoric acid colometric method). In principle, orthophosphates react with molybdates, in the presence of vanadates, to form yellow phosphovandomolybdate solution. The intensity of the yellow colour is proportional to the concentration of orthophosphate present and is measured by absorbance using a spectrophotometer. A Unicam 8625 UV/VIS spectrophotometer set at a wavelength of 470µm was used for this colour intensity measurement and is valid up to a concentration of 300mgP/l. Measurement of total phosphates requires conversion of organic and polyphosphates to orthophosphate through boiling the sample with sulphuric acid and potassium persulphate.

3.3.5 Volatile Fatty Acids (VFAs), H_2CO_3 Alkalinity and pH

The pH, volatile fatty acid (VFA in mgAc/l) and $H_2CO_3^*$ alkalinity (measured as $mgCaCO_3/l$) were measured using the 5-point titration method (Moosbrugger *et al.*, 1992). In this test a sample of digester supernatant is titrated to 5 predetermined pH points with dilute standard hydrochloric acid. The acid added to the 4 predetermined pH points and the in-situ pH are keyed into a computer program (Titra 5) which calculates the $H_2CO_3^*$ alkalinity (as $mgCaCO_3/l$) and VFA (as mgHAc/l) concentrations. A Metrohm Dosimat (715) and Metrohm pH meter (744) combo was used in the 5 pt titration method.

3.3.6 Mixed Liquor Settleable Solids (MLSS)

The MLSS concentration (measured in mg/l) was measured using the Total Settable Solids (TSS) and Inorganic Settleable Solids (ISS) tests (Standard Methods, 1985). The TSS is obtained by first centrifuging a known volume (usually 2 × 50) of mixed liquor, decanting all the (usually) clear supernatant, transferring the collected solids to a clean and dry crucible of known mass and drying the solids at 105ºC for 24 hours. The ISS, performed subsequently, is obtained by incinerating the sample in a furnace at 600ºC for above 20 minutes. The difference between the TSS and ISS gives us the Volatile (organic) Settleable Solids (VSS).

3.3.7 Oxygen utilization rate (OUR)

This automated inline measurement was described above in the section on the operation of activated sludge systems. The yellow springs DO probe was calibrated every two to three days in an aerated (saturated) tap water solution (9.2 mgO/l at 760 mmHg and 20ºC) and sodium thiosulphate solution (zero mgO/l).

3.3.8 Gas Production and Composition

The biogas volume produced was measured using gas counters connected to the AD system gas outlet pipes, Fig 3.4.The gas meter/counter is based on a batch venting system where the number of fixed batch volumes daily are counted (Figure 3.5). Once the biogas production is known for a given AD steady state period, 5 litre impermeable Tedlar gasbags were connected to the gas outlet pipes for the collection of gas samples. Thereafter, these samples were sent to a laboratory at the University of Stellenbosch (Department of Food Sciences) for analysis, using a gas chromatograph to give the percentage composition of methane, carbon dioxide and nitrogen of the total gas sample.

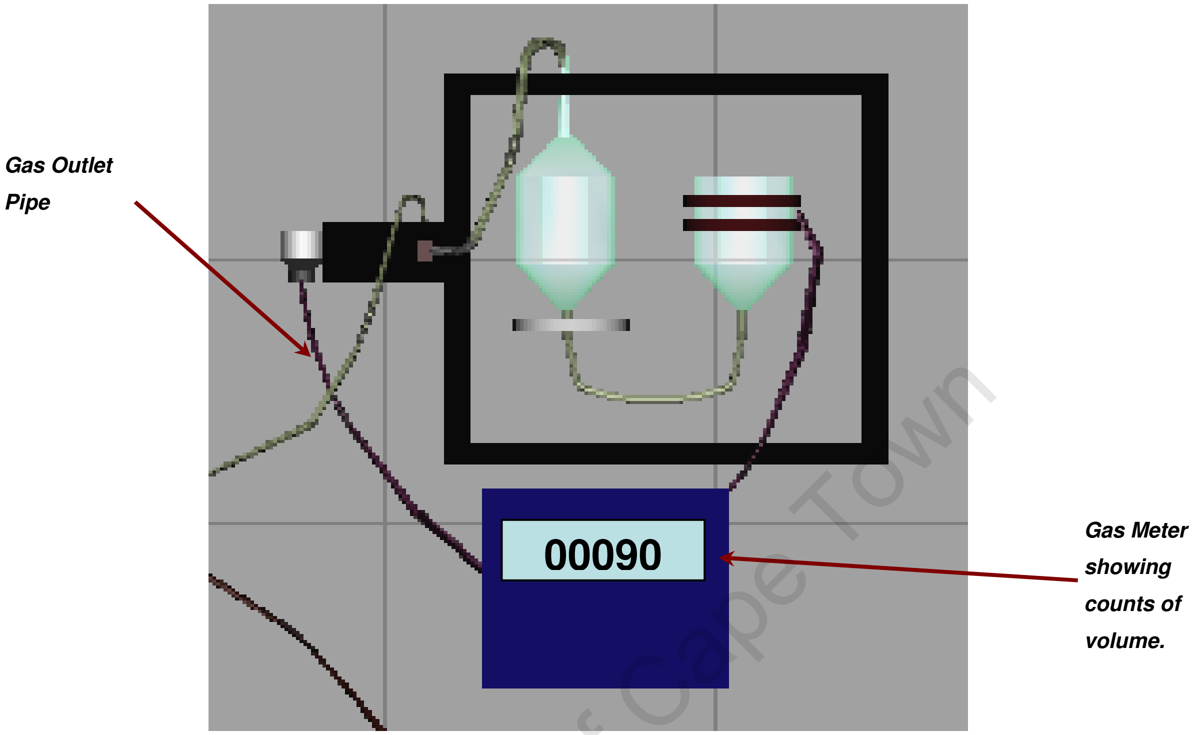


Figure 3.5: *Gas flow meter*

3.3.9 Total Organic Carbon (TOC) and Total Organic Nitrogen (TON) analysis

Elemental analysis for the total organic carbon and total organic nitrogen of sludge samples was done by an external laboratory. The CSIR marine analytical service laboratory was used for this purpose. These analysis was preformed on 104^{o}C dried WAS sample from the NDBEPR AS system and waste sludge from AD1 (fed NDBEPR WAS) at a sludge age of 60 days.

3.3.10 Total and dissolved Counter-ion metal (Me) analysis

The analytical measurement of the counter-ions metals contained within the polymer structure of polyphosphate, magnesium (Mg^{2+}), potassium (K^{+}) and calcium (Ca^{2+}), consist of two parts, (1) the preparation of the samples in the WRG laboratory and (2) the sample analysis in the external laboratory equipped to perform the analysis.

The preparation of the NDBEPR WAS sample in the WRG laboratory entails the digestion of the sludge using a strong acid (H_2SO_4). This digestion procedure is the same as that used in the case of the TKN analysis but the digestion mixture is slightly altered by replacing the K_2SO_4 component (used in the TKN digestion mix) to Na_2SO_4 as potassium is one of the counter-ion metals being analized for in this study. The sample is then analyzed at external facility using the Atomic Absorption Spectrophotometer (AAS) method to determine the Mg, Ca and K elements in the sample. These results are used to determine the counter-ion metal Mg: K: Ca ratio of the sludge. This ratio is then linked to the polyphosphate P content of the sludge.

3.3.11 Analytical Guide

Table 3.1 below presents a summary of all measurements preformed on samples taken from the experimental setup:

Table 3.1: Summary of Samples and Tests used in Research Experimental Period (Ikumi *et al.,*2009)

		TEST	COD	TKN	FSA	NO_3	NO_2	Ortho-P	TP	TSS	VSS	OUR	DSVI	pH
Activated Sludge Systems	NDBEPR AS System	Influent	Unf &	Unf &	Filt			Filt	Filt	-	-	-	-	dir
			Filt	Filt										
		Anaerobic				Filt	Filt	Filt	Filt	Unf	Unf			
		Anoxic				Filt	Filt	Filt	Filt	Unf	Unf			
		Aerobic	Unf	Unf		Filt	Filt	Filt	Filt	Unf	Unf	dir	dir	dir
		Effluent	Unf	Unf	Unf	Unf	Unf	Unf	Unf	-	-	-	-	dir
	MLE ND AS System	Influent	Unf &	Unf &	Filt			Filt	Filt					dir
			Filt	Filt										
		Anoxic				Filt	Filt	Filt	Filt	Unf	Unf			
		Aerobic	Unf	Unf		Filt	Filt	Filt	Filt	Unf	Unf	dir	dir	dir
		Effluent	Unf &	Unf &	Unf	Unf	Unf	Unf	Unf					
			Filt	Filt										
Anaerobic Digesters		TEST	COD	TKN	FSA	VFA	Gas	Ortho-P	TP	TSS	VSS	H_2CO_3*	$\%CO_2$	pH
												Alk.	$\%CH_4$	
		Influent	Unf &	Unf &	Filt	Filt	-	Filt	Unf	Unf	Filt			dir
			Filt	Filt										
		Effluent	Unf &	Unf &	Unf	Unf	dir	Filt	Unf	Unf	Filt	dir	dir	dir
			Filt	Filt										

	Abbreviation	Meaning
Abbreviations	NO_3	Nitrates; Hydrazine reduction (Technicon Auto-Analyzer)
	NO_2	Nitrites; Hydrazine reduction (Technicon Auto-Analyzer)
	DSVI	Dilute Sludge Volume Index; (Ekama and Marais, 1984b)
	OUR	Oxygen Utilization rate; automated
	Filt	Filtered through Schleicher & Schull ME 25/21 0.45 micrometer membrane filters
	Unfilt	Unfiltered Samples
	dir	Direct measurement taken.

3.4 Closure

Due to the differences in the overall objectives of this study to that of Ikumi *et al.* (2009), not all analyses are relevant to this report. The focus of Ikumi *et al.* (2009) is primarily on the kinetics of hydrolysis of municipal sludge from Nutrient removal systems and determine whether or not the unbiodegradable particulate organics from the AS system remains unbiodegradable in the AD system. This study focuses on including P into the steady state AD model of NDBEPR As system WAS into the steady state plant-wide model.

CHAPTER FOUR

CHARACTERIZATION PROCEDURE AND STOICHIOMETRIC PART OF THE AD MODEL

The development of a steady state model describing the anaerobic digestion (AD) of NDBEPR WAS is the primary aim of this chapter and this study. This steady state model would be useful in application for the design and operational evaluation of a BEPR AS system coupled to anaerobic digestion, as is described in Chapters One and Two of this study. However, such a model requires that the characteristics of the feed, be it PS or WAS, are known. This can be achieved by developing a characterization procedure that determines the feed sludge characteristics as part of the primary aim of this study. To conclude, the primary aim of this project can be divided into two sections which are (a) the characterization of the WAS from the NDBEPR AS system and (b) the development and application of a steady state AD model describing the anaerobic digestion of the NDBEPR WAS. Each of these objectives can then be subdivided to parts or secondary objectives. Figure 4.1 shows a diagram of the layout of this study and Chapter 4.

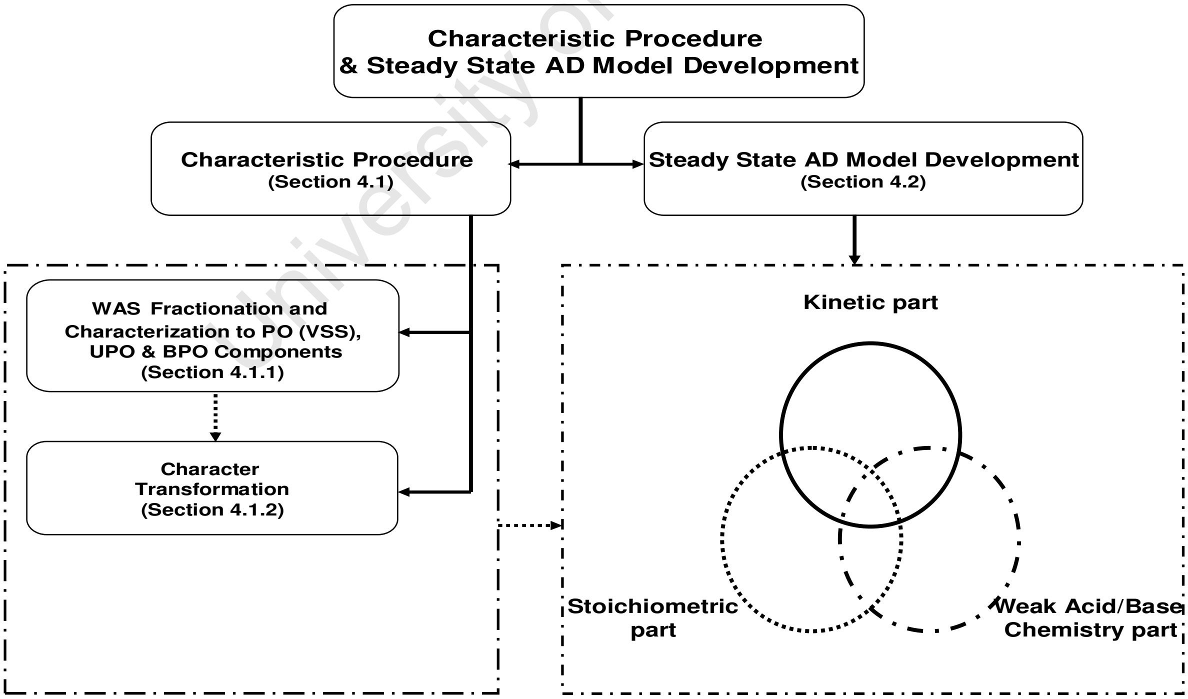


Figure 4. 1: Layout of Characterization Procedure and Model Development

The AD model developed in this project is similar to the steady state AD model developed by Sötemann *et al.* (2005) where a primary settling tank (PST) was coupled to an anaerobic digester. Chapter Two showed that such models comprise three parts, (i) a kinetic part, (ii) a stoichiometric part and (iii) a weak acid/base chemistry part. The kinetic part focuses on the hydrolysis rate of the biodegradable particulate organics and the unbiodegradable fraction. The stoichiometry part focuses on the anaerobic digestion process reactants consumed and products generated in the aqueous and gaseous phases. The weak acid/base chemistry part focuses on the equilibrium chemistry of the inorganic carbon (CO_2) and other weak acid/base systems from which the pH is calculated. Sötemann *et al.* (2005) used the characterization procedure reported by Ekama *et al.* (2006b) to characterize the PS feed to the AD system.

The objectives of, and modelling approaches utilized in, this study are similar to those reported by Sötemann *et al.* (2005) for the anaerobic digestion of primary sludge. However, in this study the Sötemann *et al.* (2005) AD model is extended to include phosphorus in both the stoichiometric and weak acid/base chemistry parts. The weak acid/base chemistry part will assist in the evaluating the likelihood of mineral precipitation but will not be able to quantify this precipitation, if precipitation does occur. The quantification of precipitation is complex and outside the scope of this study. The complexities related to the mixed biomass culture (OHOs & PAOs) and the PAO stored polyphosphate component introduce various unique difficulties that require amendments to the approach used by Sötemann *et al.* (2005).

Firstly, the sludge characterization section (Section 4.1) of this study requires that a characterization procedure be developed that quantifies the elemental composition of NDBEPR WAS. This characterization procedure consists of two steps. The first step involves the conventional characterization of NDBEPR WAS into OHO active, PAO active, OHO endogenous, PAO endogenous and unbiodegradable particulate organics from the influent, by applying conventional activated sludge models such as the Wentzel *et al.* (1990) BEPR and the Ekama and Wentzel, (2004) ISS models. These models require measured data from the influent, aerobic zone and effluent of the UCT MBR AS system, described in Chapter 3, as input variables. In the second step the outcomes from the conventional NDBEPR characterization procedure are transformed with COD/VSS, OrgN/VSS and OrgP/VSS ratios to determine the elemental composition of the NDBEPR WAS in terms of carbon (C), nitrogen (N), hydrogen (H), oxygen (O), phosphorus (P) and counter-ion metals (Me). Each part of the particulate organic (PO) VSS of the

WAS are characterized in the form $C_XH_YO_ZN_AP_B$ while the stored inorganic polyphosphate in the PAOs is characterized as an additional $MePO_3$ compound linked to the PAOs.

The objective is to determine a single elemental composition for the component of NDBEPR WAS that contains store polyphosphate. The reason for this is that the polyphosphate is not integrated into the PAO particulate organics of the NDBEPR WAS but closely associated with it in the sense that it can be released with the PAO BPO during the digestion process. However, from Jardin *et al.* (1994) the kinetic rate that describes the release of the polyphosphate appears to be much faster than the organics hydrolysis rate. To achieve this linked composition the organic particulate component and the inorganic polyphosphate are coupled using linkage factors (q). For linking, the elemental composition of polyphosphate to the biodegradable particulate organics (BPO) compound q_{BPO} is used and in the case of linking in the PAOs compound q_{POA} is used. The results from the characterization part are the empirical stoichiometric formula for NDBEPR WAS in the form $C_XH_YO_ZN_AP_B$. q_{Φ} [$MePO_3$] where Φ refers to the compound with which the linking factor couples. This is the required form of the input variable, substrate composition, to the steady state AD model that will be developed in this chapter.

Secondly, the steady state AD model development section (Section 4.2) describes the extension and modification, as required, of the three parts of the Sötemann *et al.* (2005) model describing the AD of PS to include the phosphorus and the counter-ion metal components related to NDBEPR WAS. For the last part the kinetic rates and constants developed for the hydrolysis of the OHO and PAO BPO are determined by Ikumi *et al.* (2009). The hydrolysis kinetics quantifies the substrate digested and the residual BPO not digested at various sludge ages. The kinetics of polyphosphate degradation is also described in this section. For the second part, the development of the stoichiometry for the biochemical reactions for the anaerobic digestion process of NDBEPR WAS is out lined. This reaction stoichiometry, as described by Sötemann *et al.* (2005), was initially developed by McCarty (1974) and is extended in this study to accommodate the presence of significant concentrations of phosphorus and counter-ion metals related to the stored polyphosphate in the PAOs. The method for extending this stoichiometry is described by McCarty (1975). However, the balanced reaction stoichiometry depends on the form of the products of anaerobic digestion, which in turn is related to the physico-chemical processes occurring within the AD reactor. Therefore, a problem arises because the phosphate weak acid/base system has a pK value at 7.2 (at 35 °C) with the result that the phosphate product is split between HPO_4^{2-} and

$H_2PO_4^-$ depending on the alkalinity contribution of the inorganic carbon system. This problem is addressed by developing a stoichiometric model that is flexible with change in pH and includes both forms of the phosphate product. This will be described in more detail in Section 4.3 below.

In the third part of the steady state model, the predicted results from the stoichiometric part are evaluated to determine the likelihood of mineral precipitation within the digester. Literature from Loewenthal *et al.* (1994) and Musvoto *et al*. (2000) suggest that stuvite is the most likely precipitate to be formed within down stream pipelines and process equipment after the AD of NDBEPR WAS. To evaluate the likelihood for struvite precipitation the ionic product of the aqueous phase ions are determined and compared with the thermodynamic solubility product (K_{spm}) of struvite. If the ionic product (K_{is}) exceeds the K_{spm} for struvite, precipitation is likely to occur. However, this method does not quantify the struvite formed but models developed by Loewenthal *et al.* (1994) and Musvoto *et al.* (2000) and software like Stasoft 4 (Morrison *et al.,* 2000), can be applied for this purpose. The development and inclusion of the third solid phase model that describes and quantifies the mineral precipitants are beyond the scope of this study.

The development of the characterization procedure is dealt with first in this chapter. The reason for this is that the characteristics of NDBEPR WAS are used as input variables to the steady state AD model that therefore provides logical order to this chapter. Finally, to demonstrate the steady state model and characterization procedure, the calculations for the 12 day sludge age AD is included at the end of each AD model part in this chapter.

4.1 Characterization Procedure

As discussed at the start of this chapter, the objective of the characterization part is to determine the elemental composition of each component of NDBEPR WAS in terms of carbon (C), nitrogen (N), hydrogen (H), oxygen (O), phosphorus (P) and counter-ion metals (Me). This is the required form of the reactants used as input variables to the stoichiometric part of the steady state AD model that will be developed Section 4.2 below. Furthermore, it was indicated that this characterization procedure consists of two steps, a conventional VSS characterization or fractionation step and a molar composition determination step from the elemental ratios (e.g. COD/VSS, C/VSS, N/VSS, P/VSS) to the required stoichiometric form $C_XH_YO_ZN_AP_B$.

As described earlier, the general approach to characterization applied in this study exhibit similarities to that reported by Sötemann *et a*l, (2005). However, the mixed biomass (comprising of OHO & PAO active organisms) culture of NDBEPR WAS presented unique difficulties that required amendments and, in some cases, a completely different approach to that used by Sötemann *et al*. (2005).

This NDBEPR WAS organics comprise biodegradable particulate organics (BPO) and unbiodegradable particulate organics (UPO). Insofar as the AS system is concerned, the BPO component consists of the biodegradable parts of PAOs and OHOs. The PAOs contain stored inorganic polyphosphate so the PAOs contain organic and inorganic compounds, which are loosely connected because the polyphosphate is released at a faster kinetic rate than the organic part of the PAOs is hydrolysed during the anaerobic digestion process. The unbiodegradable components comprises of the OHO and PAO unbiodegradable fractions, the OHO and PAO endogenous residual formed in the NDBEPR AS system and the UPO from the influent wastewater that accumulates as VSS in the NDBEPR AS system.

A core objective of the characterization procedure is to determine the elemental composition for each of the components of the NDBEPR WAS. The elemental composition of the BPO component is used as an input variable to the steady state AD model. Although the UPO component is not affected by the AD process its still forms part of the overall composition of the influent and particulate organics of the digester system. Hence, the elemental composition of the UPO component is determined similarly to the BPO component, resulting in the UPO being expressed in the same form as the other components in the AD system. Inline with this objective the elemental composition of the organic part of the PAOs is presented in the form $C_XH_YO_ZN_AP_B$ and that of polyphosphate as [$MePO_3$]. The two components are then linked by the factor (q) which is dependent on the polyphosphate content of the PAOs, yielding a composition in the form $C_XH_YO_ZN_AP_B$. $q_\Phi[MePO_3]$. Because BPO contains PAOs, its elemental composition is presented in the same form. Due to their zero polyphosphate content, the elemental composition of OHOs and UPO is presented in the form $C_XH_YO_ZN_AP_B$ only (i.e. $q_ø = 0$).

The $C_XH_YO_ZN_AP_B$ elemental composition is the required stoichiometric form for all the organic components of the NDBEPR WAS feed for the steady state AD model. However, the UPO components of the waste sludge from the UCT MBR AS system remain in same form as fed if they are not digested. If the UPO from the AS system are not degraded in the AD, then only the biodegradable (AD BPO) components are transformed in the digestion process and so the elemental composition of the BPO are used as input to the stoichiometric part of the steady state AD model, to be developed in Section 4.2, which describes the transformation of the reactants to the digestion products.

4.1.1 WAS VSS Fractionation Process

The initial step in the NDBEPR WAS characterization process involves the application of the BEPR activated sludge model of Wentzel *et al.* (1990) and the ISS model of Ekama and Wentzel, (2004) to determine the various components of this WAS. Measured data from the UCT MBR AS system and the influent wastewater are the input variables to these models. Sötemann *et al.* (2005) determined the elemental composition of ND WAS by using the COD/VSS (f_{cv}) and TKN/VSS (f_N) ratios from the measured data of the aerobic zone of a MLE AS system. In this study the COD/VSS (f_{cv}), TKN/VSS (f_N) and TP/VSS (f_P) of the PO, BPO, UPO, PAOs and OHOs components of WAS are determined from a combination of measured data and results attained from the steady state AS models. Furthermore, the polyphosphate (f_{XBGPP}) and PAO biomass P content (f_{XBGPBM}) and the OHOs P content (f_{XBHPBM}) are determined and used in the characterization of polyphosphate and in determining the linkage factor to couple the organic and inorganic polyphosphate part of the PAOs.

The VSS fractionation procedure uses measured data from the influent and UCT MBR AS system and the COD, VSS, TKN, and TP measurements on the NDBEPR WAS to determine the f_{cv}, f_N and f_P ratios for some of the components of this WAS. To determine these ratios for the other components the COD, VSS, TKN, and TP measurements are used as input variables to the steady state AS models and the resulting characteristics are then used to determine the f_{cv}, f_N and f_P ratios for these specific components.

4.1.1.1 Measured Data and System Parameters for UCT MBR system

Analytical measurements (measured data) were preformed on samples taken from the influent wastewater, the experimental UCT AS system and the AS system effluent as described in Chapter 3. For each sample, analysis is preformed to determine the VSS composition of the total (unfiltered) and soluble (0.45 micrometer membrane filtered) measurements. Measurements conducted were the COD, TKN, FSA, TP, Ortho-P, TSS, VSS, the counter-ion metals Mg, K and Ca. Details of all the samples collected at the various sample points are given in Chapter 3.

A summary of the averages of the measured data from the influent and AS system for each wastewater batch fed to the MBR UCT AS system during the investigation, are presented in Chapter Five. To evaluate the quality of measured data mass balances are performed for COD, Nitrogen, Phosphorus and metals over the UCT MBR AS system. The desired percentage balances are within a range of 80 % to 120% but same sewage batches have mass balances outside this range.

The system parameters of the AS system were kept constant throughout the duration of the experimental investigation. The temperature was controlled at 20 ^{o}C. The system volume was constant at 75 litres and the flow rate at 150 litres/day.

4.1.1.2 Characterizing the NDBEPR WAS

This section explains the characterization of the NDBEPR WAS to mass concentration, mass fraction ratios and in the final step to molar stoichiometric values. To achieve this, measured data and in some cases assumed values are used as input variables to NDBEPR WAS fractionation calculation from the BEPR steady state model.

Firstly, the WAS is fractionated to determine the active PAOs and OHOs mass, endogenous mass and the inert mass from the application of the Wentzel *et al.* (1990) model. However, this model and the ISS model requires measured input variables. Some of these input variables were determined in Section 4.1.1.1. Others are obtained from measurement on the NDBEPR WAS.

This fractionation process is then extended to determine the BPO and UPO compositions of the NDBEPR WAS by grouping the biodegradable and unbiodegradable parts of the PAOs and OHOs. Next, the N, C and P content of each BPO and UPO component is calculated. Some reasonable assumptions are made to determine the carbon content due to lack of accurate analytical measurements for this element that will be later evaluated with carbon mass balances over the AD system. The organically bound P content of each unbiodegradable component (the endogenous residue of the OHOs and PAOs, the unbiodegradable part of the active OHOs and

PAOs) and the biodegradable component (the biodegradable part of the OHOs and PAOs) is assumed to be the same (i.e. 0.03 mgP/mgVSS) and the polyphosphate content of the PAOs is determined from the measured NDBEPR system P removal. Finally, the ISS content of the WAS is determined with the Ekama and Wentzel, (2004) ISS model (i.e. 0.15 mg ISS/ mg OHO VSS and 3.286 mg ISS/mgP polyphosphate, which is equal to 0.35 x 3.286 = 1.15 mgISS/mgPAOVSS, at a PAO polyphosphate content of 0.35 mgP/mgPAOVSS).

The particulate component concentration of the NDBEPR WAS, which is the sum of all the VSS and ISS concentrations, is very high because of the high TSS concentration in the MBR UCT AS system (~10gTSS/ℓ). In contrast, the soluble component concentration of the WAS is very low and has a negligible effect on overall COD, N, P and C composition of the NDBEPR WAS fed to the AD. Therefore, the fractionation characterization procedures described in this section primarily focus on the particulate components of the NDBEPR WAS because of its dominance on the overall composition of the WAS.

A. Determining the Organic Particulate components of NDBEPR WAS

The fractionation of the NDBEPR WAS into its organic particulate component is the most important step in the whole characterization procedure because it affects the products generated in the AD system. As stated earlier, if the UPO remains unchanged, then this does not effect the dissolved and gaseous products of AD, but it does of course affect the effluent particulate products because it is the main part of the outflow particulate organics. Consequently, the main objective is to characterize the particulate organics (PO) of the WAS into the BPO and UPO components by firstly determining the active and endogenous OHO and PAO and inert concentration of the NDBEPR WAS by application of the Wentzel *et al.* (1990) model.

As described in Section 2.2.2, the active part of NDBEPR WAS consists of PAOs (X_{BG}) and OHOs (X_{BH}). The presence of SCFA in the anaerobic zone promotes the growth of PAOs within the UCT NDBEPR AS system. Equations E2.2a and E2.2b, described in Section 2.2.4, are used to determine the OHO and PAO active mass components of NDBEPR WAS. Next, the endogenous residue produced by the OHO and PAO active mass components (X_{EH} & X_{EG}) are determined using Equations E2.2c and E2.2d. Finally, the inert mass of the NDBEPR WAS are determined using Equation E2.2e. The units for these organic components are in mgVSS per litre of WAS.

The overall PO VSS (X_V) is the sum of the active, endogenous and inert masses as illustrated by Equation E2.3a. An example of a mixed OHO and PAO culture design is published by Wentzel *et al.* (1990) (page 33 to 34, Water SA, Vol.16, No.1) that demonstrates the application of this steady state BEPR AS model. The equations applied in this VSS fractionation model, Eqn E2.2a to e, were described in Section 2.2.2 and the results from the application of this model is shown in the characterization example of Section 4.1.3 below.

The analytical measurement obtained from the experimental UCT MBR system operated during this investigation had a higher VSS concentration in the aerobic zone than in the anoxic and anaerobic zone of the system. The active, endogenous, inert and total VSS concentration determined with the above procedure relate to the system averages over the BEPR AS system and not the actual concentrations of the mixed liquor (WAS) from each of the zones within the AS configuration. To determine the specific concentrations in each of the zones, the VSS mass fractions that relate the reactor VSS mass to the system VSS mass (= to the system volume x average VSS concentration) for each zone of the UCT MBR AS system are given by Ramphao *et al.* (2004). These VSS mass fractions relate the actual VSS concentration of a specific zone to the system average VSS concentration. The Equation E 4.1 describes this as follows.

$$f_{m(aer)} = \frac{MXv_{aer}}{\bar{M}Xv_{sys}} = \frac{Xv_{aer}}{\bar{X}v_{sys}} \qquad \textbf{(E4.1)}$$

where: $f_{m(aer)}$ = aerobic mass fraction

MXv_{aer} = measured VSS mass of the aerobic zone

MXv_{sys} = $Q_w.Xv_{sys}$ = Calculated VSS mass of MBR AS system using E2.3a

This aerobic mass fraction is used to determine the X_{BH}, X_{EH}, X_{BG}, X_{EG}, X_{inert} and X_v concentrations in the aerobic zone, and hence also in the waste flow from the VSS masses in the MBR UCT system obtained from the Wentzel *et al.* (1990) BEPR model.

Next, with the X_{BH}, X_{EH}, X_{BG}, X_{EG}, X_{inert} and X_v components of the WAS known, these are grouped to determine the BPO and UPO components of the NDBEPR WAS. The UPO component of this WAS is determined as described in Section 2.2.5. For the AS system, the UPO is the sum of X_{inert} and the endogenous concentration of the PAOs and OHOs (X_{EG} and X_{EH}) and the unbiodegradable constituent of the active PAOs and OHOs. The unbiodegradable residual of the active OHO is accepted to be 8% of the active VSS as in the case of aerobic digestion (Mebrahtu *et al.,* 2008). This has been shown to be valid in anaerobic biodegradability studies of ND system WAS (with no PAOs) by Ekama *et al.* (2006b) and will be checked in this investigation. Concerning the PAOs, their unbiodegradable residual has only been determined in the aerobic batch test and a value f_{EG} of 0.25 was measured by Wentzel *et al.* (1989) in long-term aerobic digestion tests of enhanced PAOs cultures.

This raises an issue of debate on the conceptual model of the endogenous behaviour of the PAOs. For the OHOs, there are two conceptual models for the endogenous behaviour, death regeneration and endogenous respiration models (Dold *et al.,* 1980). Each have different kinetic and stoichiometric constants for the OHOs associated with them, i.e. the endogenous respiration rate (b_H) is 0.24/d and its associated unbiodegradable residue f_{EH} = 0.2, and for the death regeneration model the OHO death rate (b'_H) is 0.62/d and its associated unbiodegradable OHO residue (f'_{EH}) is 0.08. Under aerobic conditions, an activated sludge system batch test produces identical results e.g.

$$X_{EH} = f_{EH} b_H X_{BH} = 0.2 \times 0.24 \times X_{BH} = 0.048 X_{BH} \qquad \textbf{(E4.2a)}$$

and

$$X_{EH} = f'_{EH} b'_H X_{BH} = 0.08 \times 0.62 \times X_{BH} = 0.048 X_{BH} \qquad \textbf{(E4.2b)}$$

The steady state model (WRC, 1984; Henze *et al.*, 1987) and Activated Sludge Model No.3 (ASM3) use the endogenous respiration values and ASM1 and 2 uses the death regeneration values. However, the question that arises is which value is the correct value to use for anaerobic digestion? Ekama *et al.* (2006a) found that f'_{EH} = 0.08 predicts a better UPO fraction for anaerobic digestion than f_{EH} = 0.2. So f'_{EH} = 0.08 is the appropriate value to use for the OHOs in this research.

However, what conceptual model and what endogenous residue value should be used for the PAOs? A death regeneration model for PAOs is not used. The endogenous respiration model is used in both the steady state and dynamic kinetic models of Wentzel *et al.* (1990) and ASM2

(Henze *et al.,* 1995). The reason that a death regeneration model for PAOs is not used is possibly due to the complexity that such a model brings to PAO behaviour, e.g. when PAOs die what happens to the PHA and polyphosphate storage products? They would have to be released to the bulk liquid and taken up by the new generation of PAO grown from the substrate of the dead ones. However, the PAOs can only take up PHA with VFAs as substrate, which is not produced in the aerobic or anoxic zones from BPO released by the dead PAOs. Consequently, endogenous respiration is the only viable approach because it involves growth only on VFAs taken up in the anaerobic reactor as described in Section 2.2.2. This is probably also the reason why death regeneration was abandoned in ASM3 because ASM3 involves uptake and storage products only before growth. However, the question remains, should the UPO of the PAOs (f_{EG}) for the digestion be 0.08, the same as for OHOs, or 0.25 in conformity with the endogenous model for the PAOs? Both values will be tested to see which gives the best unbiodegradable fraction as measured on the anaerobic digester. While this is inconsistent with the activated sludge model for the PAOs, it will be accepted initially that f_{EG} = 0.08, the same as for the OHOs. A case for this value is the other two stoichiometric constants for the PAOs are the same as the OHOs, (i.e. f_{cv} = 1.48 mgCOD/mgVSS and Y_G = 0.45 mgVSS/mgCOD).

From the above Eq E4.2c it is given that the NDBEPR WAS UPO concentration in terms of COD (from Equation E4.1),

$$S_{up(AS)} = \left[X_{inert} + \left(X_{E.H} + X_{E,G}\right) + 0.08\left(X_{B,G} + X_{B,H}\right)\right] f_{cv} \qquad \textbf{(E4.2c)}$$

Where f_{cv} is determined from the measured COD/VSS ratio of the long sludge age AD ($R_s \geq 60$ days) system effluent that is accepted to comprise only of the UPO component. This is done because the COD/VSS of the different components of the NDBEPR WAS could not be measured individually.

With the UPO concentration determined as described above and the PO concentration obtained from measurements on the influent sludge, the BPO concentration is determined from the difference between the PO and UPO components.

B. Determining the Nitrogen Content of each Component

The nitrogen characterization of the NDBEPR WAS are based on the measured nitrogen content of WAS from the aerobic zone of the UCT system and the waste sludge from the AD system. The overall particulate organic (PO) nitrogen content is determined from the difference between the unfiltered and filtered (using a 0.45μm membrane filter) TKN measurements of the aerobic zone of the UCT MBR system. Next, the nitrogen content of the UPO is determined. Because the UPO and BPO components cannot be separated for the AS system, the N content of the effluent sludge from the 60 day R_s AD system was taken to be the N content of the UPO component. The BPO nitrogen content was then determined from the difference of the PO and UPO nitrogen contents. The nitrogen content of each component is used to determine the TKN/VSS (f_N) or TKN/COD ratios of the individual components, which is needed to calculate the molar elemental compositions.

C. Determining the Carbon Content of each Component

To achieve the full elemental composition for each component of NDBEPR WAS, the carbon content of each individual component needs to be known. However, carbon is not a commonly measured element in wastewater analysis. Samples of NDBEPR WAS from the UCT AS system and the 60d sludge age AD system were collected, dried at 70 to 90 °C and then sent to an external laboratory for total organic carbon (TOC) analysis. However, the results from these analyses were found to be inconsistent and inaccurate to use reliably. Even the preparation drying method could result in carbon loss from the sample. The use of these results within this study was abandoned.

As a result, the f_C (TOC/VSS) for the combined particulate organic (PO or VSS) and UPO was assumed to be 0.52 and 0.51 respectively. These assumptions were made based on the f_C (mgC/mgVSS) reported by Ekama (2009) based on studies by Ekama *et al.* (2006b), Volcke *et al.*(2006) and others, as described in Section 2.2.7.6. These carbon fractions were validated in this investigation through a carbon mass balance over the entire experimental setup for the NDBEPR WAS AS and AD systems. The BPO carbon fraction is determined by difference between the PO and UPO components carbon fractions.

D. Determining the Organic and Stored Inorganic Phosphorus Content of each component

This step focuses on determining the phosphorus (P) content of the OHOs and PAOs. The P content of the PAOs is extended to differentiate between the P content related to the polyphosphate and that contained by the cell bound P of the PAOs. This is also important for the mixed weak acid/base chemistry of the AD system. This is also important for the mixed weak acid/base chemistry of the AD system in that released organic P does not generate alkalinity but released polyphosphate does.

In determining the all bound P of PAOs and OHOs some reasonable assumptions need to be made for the P content of the various components of NDBEPR WAS that is then characterized to conform to the measured values. It is assumed that all bound organically P for the OHO and PAO components is 0.033 mgP/acVSS concentration. This is the same as that found by Wentzel *et al.*(1989), as described in Section 2.2.1 and 2.2.2 (Chapter 2). The same P content is applied to the UPO component in conformity with Wentzel *et al.* (1989). The stored polyphosphate of the PAOs can vary depending on the extent of anoxic P uptake in the anoxic zone of the AS system. This is described in more detail in Section 2.2.2 of this work. Therefore, the PAO P content related to the stored polyphosphate was not assumed at a fixed concentration of 0.35 (0.38 – 0.03 all bound P) as was found in Wentzel *et al.* (1990) for pure cultures, but determined for every steady state period. The store phosphorus content of the PAOs was determined from the application of E2.4 described in Section 2.2.4 where ΔP refers to the P removal, i.e. change in TP concentration between the influent and the effluent. Hence, the polyphosphate content of the PAOs was determined from the P removal performance of the UCT NDBEPR AS system. The f_{up} used as an input variable to Equation E2.4 are determined from Equation E2.3a.

E. Determining the ISS concentration of each component

The presence of the stored polyphosphate within the PAOs results in an increased inorganic suspended solid content of the NDBEPR WAS. The inorganic suspended solids (ISS or X_{Io}) component of NDBEPR WAS is determined from the application of ISS model described by Ekama and Wentzel, (2004). This ISS model requires three parameters to be known, i.e. the influent ISS concentration (X_{Io}) which can be measured and the ISS content of the PAOs (f_{iPOA})

and OHOs (f_{iOHO}) which can only be indirectly calculated from E4.3a and E4.3b as described in Ekama and Wentzel, (2004). Ekama and Wentzel, (2004) found that the ISS of the organic part of the PAOs (f_{iPAOBM}) is the same as the ISS of the OHOs (f_{iOHO}) at 0.15 mg ISS/mg OHO or PAO VSS. This is shown in E4.3b. Additionally, the ISS contents of the PAOs (f_{iPOA}) consists also of the ISS of the stored inorganic polyphosphate (f_{iPAOPP}) shown by Equations E4.3a below,

$$f_{iPAO} = f_{i\,PAOBM} + f_{i\,PAOPP} \qquad \textit{(mg ISS/mg VSS)} \qquad \textbf{(E4.3a)}$$

and

$$f_{iOHO} = f_{i\,PAOBM} = 0.15 \qquad \textit{(mg ISS/mg OHO or POAVSS)} \qquad \textbf{(E4.3b)}$$

Ekama and Wentzel, (2004) found the PAO ISS (f_{iPAO}) to be 1.3 mg ISS/mg PAOVSS when the PAO P concentration was 0.38 mgP/mgPAOVSS. Polyphosphate is entirely inorganic and therefore the ISS content of the PAOs are found to be nine times higher than that of the OHOs for this 0.38 mgP/mgPAOVSS P content. When this high ISS content of the PAOs is related to the P content a ratio of 3.28 mgISS to an mg polyphosphate P is achieved. This value is close to the 3.23 used in ASM2 and 2d and that measured in the enhanced PAO cultures (3.19), Ekama and Wentzel, 2004. This is shown in Equation E4.3c,

$$\frac{(f_{iPAO} - f_{iPAOBM})}{(f_{XBGP} - f_{XBGPBM})} = 3.28 \approx 3.23\{ASM\,2\} \qquad \textit{(mgISS/mgP)} \qquad \textbf{(E4.3c)}$$

In the case of the BEPR AS system of this investigation, it was found that the influent ISS had a small effect on the reactor ISS mass. With this type of AS system, the major influencing factor on the reactor ISS mass is the active PAO biomass and specifically the P content of the PAOs.

4.1.1.3 Composition of Polyphosphate

Next, the focus is directed onto the composition of polyphosphate itself. This is covered in three steps that are (i) the elemental composition of the polyphosphate, (ii) determining the linkage factor ($q_ø$) that couples polyphosphate and the organic part of the PAO biomass and then to the BPO component, in its elemental composition form, and (iii) determining the mass fraction of the metal components of polyphosphate in terms of the PAO VSS concentration. The above stated steps assist in characterizing and quantifying the polyphosphate component and helps in balancing the counter-ion metals and phosphate elements of the AD process stoichiometry.

A. Characterization of Polyphosphate

The inorganic polyphosphate structured orthophosphate polymer of chain length of a few monomers to several hundred linked with energy-rich phosphoanhydride bonds as discussed in Section 2.2.3. Furthermore, Section 2.2.3 reviewed work by Miyamoto-Mills *et al.* (1983), Arvin *et al.* (1985) and Comeau *et al.* (1985) that focused on the elemental ratios that exist between the phosphate and charge balancing counter-ion metal components of polyphosphate, in the form of P : K^+: Mg^{2+} : Ca^{2+} where the P represents PO_3^-. The average molar ratio P: Mg: K: Ca, as an average of the three studies above, was found to be 1: 0.275: 0.295: 0.05 respectively. This polyphosphate composition yield an ISS/P ratio of 3.19 which is close to that found by Ekama and Wentzel, (2004), mentioned above.

In this section the results from the analytical measurements, as shown by Table 3.1 (Chapter 3), are utilized to determine the molar ratio P: Mg: K: Ca during the testing of each AD sludge age. Samples of WAS taken from the aerobic zone of the UCT MBR AS system were digested, as described in Section 3.3.1.e (Chapter Three), and sent for Mg, K and Ca anlysis by atomic absorption spectrophotometry. Theoretically, the measured metals concentrations should yield a charge balance with respect to the phosphate component. To achieve this, the metal components are grouped together and represented by a generic metal with a positive charge $Me^{\beta+}$. It is known that the phosphate component (PO_3^-) of polyphosphate has a one negative charge. To form a charge neutral polyphosphate compound the combined metals ($Me^{\beta+}$) should follow a molar arrangement that results in a one positive change to counter balance the one *ve*- charge of the PO_3^- component. This is shown in Figure 4.2 below,

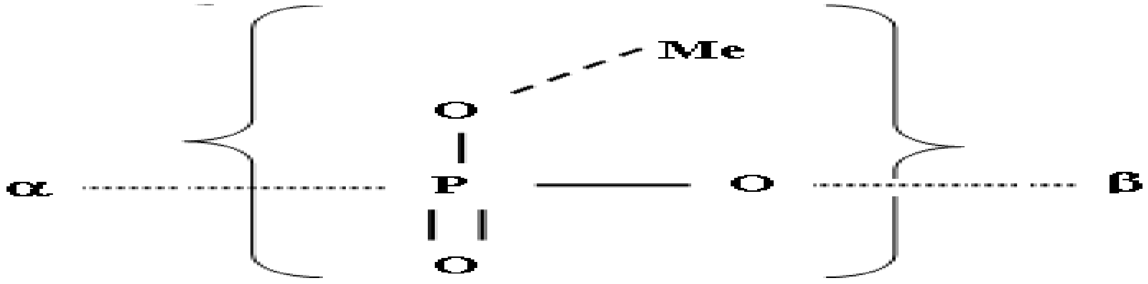


Figure 4. 2: Single charge natural polyphosphate monomer including counter-ion metals)

However, the measured metal concentrations did not result in exactly one positive charge per P and so the Me/P ratio was adjusted to ensure the metals charge was one positive +/P. The extent of such an adjustment should not be significant (charge varied less than 10%) and is only done to correct experimental error. The metal charge can be determined as follows.

$$ve+ = 2b + c + 2d \qquad \textbf{\textit{(E4.4a)}}$$

Where b, c and d refers to the molar ratios (P: Mg: K: Ca) of Mg, K and Ca respectively and *ve+* the charge on the generic metal Me. For example, if we consider the charge produced from the molar ratio P: Mg: K: Ca of 1: 0.275: 0.295: 0.05 obtained from the studies reviewed in Chapter 2, the charge on Me^+ is:

$$ve+ = (2 \times 0.275) + (0.295) + (2 \times 0.05) = 0.945 \qquad \textbf{\textit{(E4.4b)}}$$

Increasing each metal by the same proportion results in the adjustment of the molar ratio Mg: K: Ca to 0.291: 0.312: 0.053. Finally, relating one mole of phosphate to one mole of generic metal with the adjusted metal fractions results in the following Equation E4.4c:

$$Me^+ + H_2PO_4^- \Leftrightarrow MePO_3 + H_2O \qquad \textbf{\textit{(E4.4c)}}$$

B. Linking the polyphosphate to the PAO and BPO components

The objective of this part is to attain a single elemental composition for NDBEPR WAS that couples the elemental composition of inorganic stored polyphosphate and the organic cell mass of the PAOs. The reason for this is that although the stored polyphosphate is not integrated into the particulate organics of the PAOs it is enclosed by it. However, while the organically bound components are digested at the kinetic rate of hydrolysis, the kinetic rate describing the release of the P from polyphosphate is much faster so the polyphosphate needs to be kept distinct but linked to the PAOs and BPO. To achieve this linked elemental composition for PAOs and BPO containing PAOs, the elemental composition of the inorganic polyphosphate and cell mass PO are coupled using a linkage factor (q). Although the polyphosphate concentration doesn't change, the linkage factors changes depending on whether the polyphosphate is linked to the PAOs only or the total BPO, which would include the biodegradable organics of the OHOs. This is done because it has to be accepted that the BPO of the OHOs and PAOs are hydrolysed at the same rate. These linkage factors are therefore specific to the context it is used, e.g. q_{PAO} is used to link the polyphosphate to the PAOs elemental composition while q_{BPO} is used to link the polyphosphate to the BPO compound.

Theoretically, this linking process simply relates the phosphate content of the polyphosphate to the P content of the organic part in a mass ratio to each other. The units of the P mass ratio in the PAO link are mgP/mgPAOVSS while in the case of the BPO link it is mgP/mgBPOVSS. This is shown by Equations E4.5a and E4.5b,

$$q_{PAO} = \frac{f_{XBGPP}}{f_{XBGPBM}} \times B_{PAO} = \frac{X_{BGPP}}{X_{BGPBM}} \times B_{PAO} \qquad \textbf{\textit{(E4.5a)}}$$

$$q_{BPO} = \frac{X_{BGPP}}{X_{BGPBM} + X_{BHPBM}} \times B_{BPO} \qquad \textbf{\textit{(E4.5b)}}$$

Where B refers to the value of the subscript on the organic P in $C_XH_YO_ZN_AP_B$

In this way a single elemental composition is obtained for the components with stored polyphosphate as a fraction of the total VSS concentration.

C. Mass fractions of the Metal components

This Section focuses on determining the mass fraction for the counter-ion metals, Mg (f_{XBGMg}), K (f_{XBGK}) and Ca (f_{XBGCa}). This assists in quantifying the counter-ion metal content of the NDBEPR

WAS and is used to perform mass balances of these components over the AD system to evaluate the extent and release rate during the AD process. To achieve this, equations are needed to determine the mass fraction of these metals in terms of the VSS of PAOs. This is achieved by utilising the P: Mg: K: Ca molar ratios described above as follows:

$$f_{XBGMg} = f_{XBGPP}\left(\frac{MW_{Mg}}{MW_P}\right)n_{R(Mg)} \quad \textbf{(E4.6a)}$$

$$f_{XBGK} = f_{XBGPP}\left(\frac{MW_{K}}{MW_P}\right)n_{R(K)} \quad \textbf{(E4.6b)}$$

$$f_{XBGCa} = f_{XBGPP}\left(\frac{MW_{Ca}}{MW_P}\right)n_{R(Ca)} \quad \textbf{(E4.6c)}$$

where MM_P, MM_{Mg}, MM_K and MM_{Ca} refer to the molar mass and $n_{R(Mg)}$, $n_{R(K)}$ and $n_{R(Ca)}$ refer to the molar ratio to P of Mg, K and Ca.

The molar weight of a single polyphosphate component can be determined from the molar.

$$MM_{Me} = n_{R(Mg)} \cdot MM_{Mg} + n_{R(K)} \cdot MM_K + n_{R(Ca)} \cdot MM_{Ca} \quad \textbf{(E4.6d)}$$

4.1.2 Transformation to Elemental Composition

As discussed in Chapter 2, the ratio based characteristics of the WAS, described above in Section 4.1.1, are not in the molar based form required for the stoichiometric part of steady state AD model.

Section 2.2.6 describes the method used by Ekama (2009) to characterize PS and NDWAS while Section 2.2.7.5 covered the method used by Volcke *et al.* (2006) to characterize ND WAS to its elemental composition in the form $C_XH_YO_ZN_AP_B$. The outcomes of both these methods are the same, although, different symbols are used for the mass ratios. For example, Ekama (2009) refers to COD/VSS as f_{cv} while Volcke *et al.* refer to this variable as α^{COD}. In this study, the symbol used by Ekama (2009) will be used and the overall procedure (Section 2.2.6) will be the basis of the procedure applied in this study.

The procedure described by Ekama (2009) incorporates organically bound phosphorus (bio-P). This is further extended to include polyphosphate of PAOs. Equations E2.6e in Section 2.2.6 defining f_{cv} are extended to include bio-P and the compound charge. This is shown by Equation E4.7a below,

$$f_{CV} = 8\left(\frac{4}{12}f_C + f_H - \frac{2}{16}f_O - \frac{3}{14}f_N + \frac{5}{31}f_P - f_{charge}\right) \qquad \textbf{\textit{(E4.7a)}}$$

Where: f_C, f_N and f_P refer to TOC/VSS, OrgN/VSS and Org.P/VSS respectively. However, f_H and f_O are usually not measured so transforming these two ratios in terms of measured ratios yields,

$$f_O = \frac{16}{18}\left(1 - \frac{1}{8}f_{CV} - \frac{8}{12}f_C - \frac{17}{14}f_N - \frac{26}{31}f_P\right) \qquad \textbf{\textit{(E4.7b)}}$$

$$f_H = \frac{2}{18}\left(1 + f_{cv} - \frac{44}{12}f_C + \frac{10}{14}f_N - \frac{71}{31}f_P\right) \qquad \textbf{\textit{(E4.7c)}}$$

Being mass ratios, the sum of all five mass ratios (f_C, f_N, f_O, f_H and f_P) should be equal to 1 as described in Section 2.2.7.5 Equation E2.7.

With the values of the mass ratios known, the subscripts X, Y, Z, A and B in the generalised elemental composition $C_XH_YO_ZN_AP_B$ for the organic part (VSS concentration) of UPO, BPO, PAOs and OHOs can be determined. To achieve this, the Equations E2.5a to c, stated in Section 2.2.6, are extended to include P and an extra equation added to determine the value of subscript B. The extension process resulted in the following equations shown below:

$$X = \frac{f_C}{12}\left(\frac{Y + 16Z}{1 - f_C - f_N - f_P}\right) \qquad \textbf{\textit{(E4.8a)}}$$

$$A = \frac{f_N}{14}\left(\frac{Y+16Z}{1-f_C-f_N-f_P}\right) \qquad \textbf{\textit{(E4.8b)}}$$

$$B = \frac{f_P}{31}\left(\frac{Y+16Z}{1-f_C-f_N-f_P}\right) \qquad \textbf{\textit{(E4.8c)}}$$

Where:

$$Z = \frac{Y}{2}\left(\frac{1-\frac{1}{8}f_{cv}-\frac{8}{12}f_C-\frac{17}{14}f_N-\frac{26}{31}f_P}{1+f_{cv}-\frac{44}{12}f_C+\frac{10}{14}f_N-\frac{71}{31}f_P}\right) \qquad \textbf{\textit{or}} \qquad \textbf{\textit{(E4.8d)}}$$

$$Z = \frac{Y\times f_O}{16 f_H} \qquad \textbf{\textit{(E4.8e)}}$$

The molar elemental composition can be expressed with respect to any of its constituents. Selecting Y = 7 as a constant yield the X, Z, A and B values with respect to H_7. The results of this calculation yields in the organic components of the NDBEPR WAS expressed in their elemental composition. These equations are applied to any of the components of NDBEPR WAS to yield the numerical values for X, Y, Z, A and B in the molar elemental composition $C_XH_YO_ZN_AP_B$.

The final step in this procedure is to incorporate the polyphosphate component to the PAOs expressed first with respect to the PAOs (q_{PAO}), in the format $C_XH_YO_ZN_AP_B.q_{PAO}[MePO_3]$, and then with respect to the biodegradable particulate organics (q_{BPO}) and PO or VSS (q_{PO}).

4.1.3 Characterization Example

This example demonstrates the application of the characterization procedure described in Section 4.1. It utilizes the measured data from the experimental investigation at the 12 day sludge age (R_s) steady state operation of the AD and wastewater batch number 14 fed to the UCT MBR AS system during this experimental period. This calculation example follows the steps as described above in the characterization procedure. Appendix C presents the results of the VSS fractionation calculation for the UCT MBR NDBEPR AS system for the target influent COD concentration of

800 mg COD/l some assumed wastewater characteristics. It combines the Wentzel *et al.*, (1990) NDBEPR and Ekama and Wentzel, (2004) ISS models with the UCT system MBR mass fraction equations in terms of system volumes and recycle ratios of Ramphao *et al.* (2004).

4.1.3.1 Fractionation of the VSS to its components

A. Analytical Measurements and System parameters and constants

The averages of the NDBEPR AS system data set measured during the 12 day steady state AD sludge age period (Sewage Batch 14) are presented in Table 4.1 and the system parameters and constants are presented in Chapter 3. Some of these averages are used an input variables in the fractionation procedure.

Table 4.1: Measure Average Influent, WAS & Effluent (Sewage Batch 14)

Character	Conc.	Influent	WAS	Effluent
	Units		Aerobic	
COD (total)	***mgCOD/l***	763.2	9355.4	36.26
COD (Soluble)	***mgCOD/l***	277.0	36.26	36.26
TKN (total)	***mgN/l***	62.41	550.5	5.60
TKN (Soluble)	***mgN/l***	54.88	5.60	5.60
FSA	***mgN/l***	51.13	1.85	1.848
TP (total)	***mgP/l***	55.1	866.6	20.34
TP (Soluble)	***mgP/l***	51.90	20.34	20.34
OrthoP	***mgP/l***	51.56	18.56	18.56
TSS	***mg/l***		8595.9	
VSS	***mg/l***		6482.4	
ISS	***mg/l***		2113.5	
Mg (Total)	***mg/l***	101.0	235.7	84.17
Mg (Soluble)	***mg/l***	101.0	89.2	84.17
K (Total)	***mg/l***	99.7	401.5	89.90
K (Soluble)	***mg/l***	99.7	95.0	89.90
Ca (Total)	***mg/l***	15.7	50.7	11.67
Ca (Soluble)	***mg/l***	15.7	12.33	11.67

i. Mass Balance over the AS system

The measured data in Table 4.1 are used to check the mass balances over the UCT MBR AS system for the COD, N, P and counter-ion metals (Mg, K and Ca). This is done to check mass continuity over the AS and AD systems to assess data quality. Table 4.2 presents the results from the mass balance checks over the UCT MBR AS system during the experimental investigation of sewage batch Batch 14 (12 day R_s AD). The calculation procedure to determine these mass balances is described in Appendix B1.

Table 4. 2: Mass Balance for COD, Nitrogen, Phosphorus and Counter-ion Metals

COD	Nitrogen	Phosphorus	Magnesium	Potassium	Calcium
109.6%	**81.3%**	**95.3%**	**89.0%**	**102.0%**	**83.9%**

ii. Determining the feed wastewater and WAS characteristics from the measurements

Firstly, the characteristics of the influent wastewater are determined (unbiodegradable soluble and particulate COD fractions, f_{usi} and f_{upi}) from the measured data presented in Table 4.1. To achieve this, the unbiodegradable particulate fraction of the influent (f_{upi}) needs to be determined using Equation E2.3a described in Section 2.2.4. The measured particulate organic (PO) VSS concentration from the aerobic zone of the UCT MBR AS system and the other required influent concentrations, presented in Table 4.1 are input variables to Equation E2.3a to yield the influent f_{usi} and f_{upi}. Similarly, the influent nitrogen and phosphorus characteristics are also determined and presented in Table 4.3.

Table 4. 3 : Characterization of Wastewater (Influent to UCT MBR AS system)

COD Characterization								
S_{ti}	S_{bp}	S_{bs}	S'_{bsi}	S_{up}	S_{us}	S_{b}	S_{u}	S_{ai}
763.16	357.34	240.72	240.72	128.84	36.26	598.06	165.10	200.00
Nitrogen Characterization								
N_{ti}	N_{ai}	N_{oi}	N_{obsi}	N_{ousi}	N_{obpi}	N_{oupi}	N_{obi}	N_{oui}
62.41	51.13	11.28	3.75	3.75	0.76	7.53	0.12	11.28
Phosphorous Characterization								
P_{ti}	P_{ai}	P_{oi}	P_{obsi}	P_{ousi}	P_{obpi}	P_{oupi}	P_{obi}	P_{oui}
55.11	45.50	5.70	2.65	1.78	0.55	11.72	3.20	6.50

The wastewater characterization procedure also fractionates the NDBEPR WAS into its five organic components i.e. OHO and PAO active biomass, OHO and PAO endogenous residue and unbiodegradable particulate organics from the influent (X_I) which together make up the measured particulate organics (PO) or VSS concentration. In terms of the AS system, these are grouped into biodegradable (BPO) and unbiodegradable (UPO) organic concentrations.

Next, the COD/VSS (f_{cv}), C/VSS (f_C), N/VSS (f_N) and P/VSS (f_P) ratios of the overall PO for the NBBEPR WAS from the aerobic reactor (zone) of the UCT MBR and UPO estimated from the 60 day anaerobic digester are determined from measured data. The 60 day AD measured data is presented in Appendix A.2.7. Since accurate measured data for the total organic carbon (TOC) could not be obtained these values were assumed similar to that found by Ekama (2009) for ND AS systems VSS (PO) mass. This ND AS system VSS mass consists primarily of OHOs, which support this assumption in the context that OHOs from various AS system have similar elemental compositions. Furthermore, this assumption is extended to the organic part of the PAO cell mass which is assumed to have the same elemental composition as the OHO cell mass. The OrgC/VSS or f_C ratio for the overall organic particulate (PO) is assumed to be 0.52 gC/gVSS and for the UPO 0.51 gC/gVSS. This is determined from the averages of the Ekama (2009) studies described in Section 2.2.7.1. The COD/VSS (f_{cv}), TKN/VSS (f_N) and P/VSS (f_P) are obtained from measurements are presented in the Table 4.4 below,

Table 4. 4: Characterization of NDBEPR WAS (Batch14)

Component	f_{cv}*	f_N*	f_P*	f_C**
	COD/VSS	OrgN/VSS	OrgP/VSS	TOC/VSS
PO (WAS from Aerobic Zone)	1.45	0.093	0.126	0.52
UPO(60 day AD)	1.43	0.050	0.033	0.51
Measured Ratios * and Assumed Ratios **				

B. Characterization of the PO components of WAS

i. Fractionation of the active, endogenous and inert mass of NDBEPR WAS

As indicated in Section 4.1.1.2a, the outcome of the wastewater characterization and VSS fractionation model of by Wentzel *et al.* (1990) is the active (X_{BG} and X_{BH}) and endogenous (X_{EG} and X_{EH}) mass of the PAOs and OHOs and the inert mass (X_{inert}) VSS contained within the NDBEPR WAS. However, the results obtained from the application of the model are the system average masses for UCT MBR AS system. To determine the concentrations in the aerobic zone the zone of UCT MBR AS system, the equations of Ramphao *et al.* (2004) are applied, which use the volume fractions of the different zones and the recycle ratios (Section 4.1.1.2) to determine the VSS concentration in the aerobic reactor of the UCT BMR system. The VSS fractionation and concentration results for the aerobic zone for Sewage Batch 14 are as shown in Table 4.5 below,

Table 4. 5: The Active, Endogenous and Inert Concentrations of NDBEPR WAS(Sewage Batch 14)

Active Mass		Endogenous Mass		Inert Mass	PO
X_{BG} (PAO)	X_{BH} (OHO)	X_{EG} (PAO)	X_{EH} (OHO)	X_{inert}	X_V
mgVSS/l	*mgVSS/l*	*mgVSS/l*	*mgVSS/l*	*mgVSS/l*	*mgVSS/l*
2050.1	**1254.5**	**204.5**	**600.6**	**2372.7**	**6482.4**

The concentrations in Table 4.5 are then grouped into UPO and BPO of the NDBEPR WAS as described in Section 4.1.1.2a accepting that the unbiodegradable fraction of the OHOs and PAOs (f_{EH} and f_{EG}) is 0.08 (8%) for both. This means that 92% of the OHOs and PAOs is biodegradable (BPO) and the UPO is given by the sum of 8% of the OHO and PAO biomass, the OHO and PAO endogenous residue (X_{EH} & X_{EH}) and the influent particulate organics (X_{inert}, X_I), i.e. the UPO of

the WAS in terms of COD and VSS concentrations can be determined using Equation E4.2. The BPO is determined from the difference between the PO, determined from the measured data in the first step of this example, and UPO components VSS and COD concentrations.
This is presented in Table 4.6 below,

Table 4. 6: The UPO and BPO components (Batch 14)

UPO		BPO	
COD conc.	VSS conc.	COD conc.	VSS conc.
mgCOD/l	*mgVSS/l*	*mgCOD/l*	*mgVSS/l*
4920.0	**3442.1**	**4446.9**	**3073.3**

The UPO component constituted 53 % of the total PO of NDBEPR WAS for Batch 14 (12 day R_s) of the experimental investigation.

ii. Characterization Organic and Inorganic phosphorus and the Counter-ion Metal components

The organic phosphorus content of the PO component is determined as described in section 4.1.1.2 d above. Two methods are used in this study to determine the P content of the PO component. (1)The phosphorus content of the OHO active mass (f_{XBHPBM}) for a ND AS fed the same wastewater as the UCT MBR system is determined. Consequently, it is assumed that the P content of the OHOs from the ND AS system is the same as that for the UCT MBR system and that the organically bound P content of the PAOs are the same as that of the OHOs. (2) The organically bound P content of the active, endogenous and inert VSS masses of the BEPR AS system is taken to be the same as the stated by Wentzel *et al.* (1990) at 0.033 mgP/mgavOHO VSS and the additional P removal achieved by the NDBEPR system is attributed to polyphosphate content of the PAOs. The organically bound P content for both methods were found to be similar (0.025 to 0.035 mgP/mgOHOVSS).

The P content of the endogenous and inert VSS masses and unbiodegradable part of the active mass are incorporated in $X_{P(UPO)}$ and as a mass fraction $f_{P(UPO)}$. The P content of the stored inorganic polyphosphate (f_{XBGPP}) is determined using Equation E2.4, described in Section 2.2.4. The results and the P mass fractions of all the VSS components results based on Methods 1 and 2 are presented in Table 4.7a and 4.7b.

Table 4. 7a&b: Phosphorus Bound or Enclosed Character of each PO Component (Method 1&2)

a: Phosphorus Bound or Enclosed Character of each PO Component (Method 1)					
PAOs			**OHOs**	**UPO**	**PO**
f_{XBGPBM} (mgP/mgPAOVSS)	**f_{XBGPP}** (mgP/mgPAOVSS)	**f_{XBGP}** (mgP/mgPAOVSS)	**f_{XBHPBM}** (mgP/mgOHOVSS)	**$f_{P(UPO)}$** (mgP/mgUPOVSS)	**f_{P}** (mgP/mgVSS)
0.036	0.337	0.372	0.036	0.036	0.260
X_{BGPBM}	**X_{BGPP}**	**X_{BGP}**	**X_{BHPBM}**	**$X_{P(UPO)}$**	**$X_{P(BPO)}$**
mgP/l	*mgP/l*	*mgP/l*	*mgP/l*	*mgP/l*	*mgP/l*
72.9	689.9	762.8	44.6	122.4	798.0

b: Phosphorus Bound or Enclosed concentrations of each PO Component (Method 2)					
PAOs			**OHOs**	**UPO**	**PO**
f_{XBGPBM}	**f_{XBGPP}**	**f_{XBGP}**	**f_{XBHPBM}**	**$f_{P(UPO)}$**	**f_{P}**
(mgP/mgPAOVSS)	**(mgP/mgPAOVSS)**	**(mgP/mgPAOVSS)**	**(mgP/mgOHOVSS)**	**(mgP/mgUPOVSS)**	**(mgP/mgVSS)**
0.033	0.345	0.38	0.033	0.033	0.260
X_{BGPBM}	**X_{BGPP}**	**X_{BGP}**	**X_{BHPBM}**	**$X_{P(UPO)}$**	**$X_{P(BPO)}$**
mgP/l	*mgP/l*	*mgP/l*	*mgP/l*	*mgP/l*	*mgP/l*
67.65	706.50	774.16	41.40	112.20	798.00

Next, the linkage factor (q_{Φ}) that couples of the inorganic polyphosphate elemental composition of the biodegradable part of the PAOs and BPO (containing PAOs) to the organic parts is determined as described in Section 4.1.1.3b. The linkage factor coupling the organic component of the PAOs and BPO with its stored polyphosphate, q_{PAO} and q_{BPO}, are determined from Equation E4.5a and E4.5b respectively. The results for q_{PAO} and q_{BPO} so obtained are 1.35 and 0.84 respectively.

Next, the molar ratios of the counter-ion metals, Mg^{2+}, K^{+} and Ca^{2+} to one mole of P for each metal, in $MePO_3$ and BPO are determined from measured data as described in Section 2.2.3. Note that the charge ratio of Me^{+} to PO_3^{-} must be at one and if this is not the case, the ratios need to be adjusted to comply. This procedure is covered in Section 4.1.1.3a. The mass fractions of the counter-ion metals are determined using Equations E4.6a to E4.6c as described in Section 4.1.1.3c. These results are presented in Table 4.8

Table 4. 8: Mass and Molar ratios of Counter-ion Metals (PAOs and BPO)

Molar ratio to Polyphosphate			
$\mathbf{n}_{R,G(P)}$	$\mathbf{n}_{R,G(Mg)}$	$\mathbf{n}_{R,G(K)}$	$\mathbf{n}_{R,G(Ca)}$
1.00	0.278	0.358	0.044
Mass fraction to PAOs VSS conc.			
f_{XBGPP}	$f_{XBGP(Mg)}$	$f_{XBGP(K)}$	$f_{XBGP(Ca)}$
0.337	0.072	0.151	0.243
Molar ratio to BPO			
$\mathbf{n}_{R,BPO(P)}$	$\mathbf{n}_{R,BPO(Mg)}$	$\mathbf{n}_{R,BPO(K)}$	$\mathbf{n}_{R,BPO(Ca)}$
1.000	0.240	0.309	0.039

4.1.3.2 Calculating the Molar Elemental Composition

The results from the VSS fractionation method are used to determine the molar elemental composition of all the organic components of NDBEPR WAS in the form $C_XH_YO_ZN_AP_B$. This is then extended to include the elemental composition of the inorganic polyphosphate ($MePO_3$) to obtain a single composition for the particulate organics (PO = Biodegradable + Unbiodegradable) and the unbiodegradable particulate organics (UPO). This procedure is described in Section 4.1.2.

Firstly, the mass ratios (fractions) of oxygen (f_O) and hydrogen (f_H) need to be determined for all the components of the NDBEPR WAS. These are calculated from the measured COD, N and P and assumed C to VSS ratios. This is achieved from the application of Equations E4.7a to E4.7c. The results for f_C, f_N, f_O, f_H and f_P are summarised in Table 4.9 below, for the three different particulate components of NDBEPR WAS.

Table 4.9: Composition Matrix for each Component of NDBEPR WAS (Batch 14 - 12)

PO					
f_{cv}^{*}	f_{N}^{*}	f_{P}^{*}	f_{C}^{**}	f_{H}	f_{O}
1.44	0.084	0.036	0.52	0.057	0.30
UPO					
f_{cv}^{*}	f_{N}^{*}	f_{P}^{*}	f_{C}^{**}	f_{H}	f_{O}
1.429	0.049	0.036	0.51	0.057	0.35
BPO					
(determined from the difference of PO and UPO)					
f_{cv}^{*}	f_{N}^{*}	f_{P}^{*}	f_{C}^{**}	f_{H}	f_{O}
1.447	0.124	0.036	0.53	0.056	0.25
**** Measured Ratios & ** Assumed Ratio***					

Next, with mass fractions, the X, Y, Z, A and B values of the elemental compositions in the form $C_XH_YO_ZN_AP_B$ for the three organic components of NDBEPR WAS are calculated by applying Equations E4.8a to E4.8f. Finally, the inorganic polyphosphate component is added to the organic part of PAOs by means of the linkage factor (q_{Φ}). This procedure is described in Section 4.1.2. The results for each component is summarised in Table 4.10.

Table 4.10: Elemental Composition of NDBEPR WAS (Batch 14 - 12)

PO
$C_{5.33}H_7O_{2.34}N_{0.74}P_{0.14}$. 0.36[$MePO_3$]
UPO
$C_{5.21}H_7O_{2.65}N_{0.45}P_{0.14}$
BPO
$C_{5.46}H_7O_{1.99}N_{1.07}P_{0.13}$. 0.76[$MePO_3$]

No elemental composition data of NDBEPR WAS could be found in the literature with which to compare the compositions obtained in this investigation. However, Ekama (2009) presents some composition data for primary sludge (PS) biodegradable (BPO) and unbiodegradable organics (UPO).

If a range for the biomass composition is established based on the molar composition of carbon it is found that the BPO or biomass compositions range from $C_{4.8}H_7O_2N_{0.77}$ (Dold *et al.,* 1980) to $C_{5.67}H_7O_2N_{0.865}$ (Ekama, 2009). On this basis only, the elemental composition of the NDBEPR WAS organic component, for Sewage Batch 14 (12 days AD R_s test), are within of this range. Detailed discussions in this regard are reported in Chapter 5 of this work.

4.2 Development of a Anaerobic Digestion Stoichiometric Model

This section presents a systematic account of the development of a steady state model that describes the anaerobic digestion of the BPO components of NDBEPR WAS. The development of this steady state model is the primary objective of this investigation. Chapter 2, Section 2.3, discussed the supporting background needed for the development of this model. However, as stated at the start of this Section, the development of this model is not separate from the wastewater characterization, VSS fractionation and molar elemental composition (reactant) determination procedures because this AD model requires the reactant input variables in molar stoichiometric form.

At this point, the elemental compositions of the BPO and UPO components of NDBEPR WAS have been determined. This is the required form for the input variables to steady state AD model that will be developed in this Section. Initially it will be assumed that the UPO component of the NDBEPR WAS is the same for the AS system as for the AD system. However, this assumption will be tested by determining the UPO of the AD system from the AD system data, i.e. from regression curves representing all the measured COD removals attained at the various AD steady state sludge ages. This plots are used to determine the UPO of the NDBEPR WAS as well as the proportion of the BPO utilized in the AD and constitutes the kinetics (first) part of the AD model based on COD mass balanced hydrolysis kinetics.

The stoichiometric (second) part of the AD model relates the concentration of BPO utilized during the AD process to the quantity of products formed. In the case of the Sötemann *et al.* (2005) AD model, the PS feed was digested to generate methane (CH_4), carbon dioxide (CO_2), ammonium (NH_4^+), bi-carbonate (HCO_3^-) and anaerobic biomass ($C_5H_7O_2N$). The McCarty (1974) AD model, used by Sötemann *et al*. (2005) is extended in this section to include the phosphate (P_T) and metal (Me) products formed during the digestion of NDBEPR WAS. Furthermore, this model should be flexible to changes in the form of the AD products to changes in the pH of the AD environment. Additionally, the model results should reflect measured results of the AD products in two phases (excluding biomass growth), the aqueous and gaseous phases. However, this steady state AD stoichiometric model will exclude the prediction of precipitation that may occur within the AD system because of the three phase weak acid/base chemical reactions. If mineral precipitation does not occur, the model should predict the AD products within reasonable accuracy to the measured values.

To achieve the extension of the steady state AD model of Sötemann *et al.* (2005), the method described by McCarty (1975), as discussed in Section 2.3.2 is applied. In adding P, cognizance needs to be taken of the $H_2PO_4^-$ / HPO_4^{2-} pK value (~7.0) near the operating pH range of the experimental anaerobic digesters. This aspect introduces some complexity because now the ortho-P and inorganic carbon systems affect the digester pH. Therefore, in the application of the McCarty (1975) method the AD reaction stoichiometry developed will need to recognize both phosphorus species $H_2PO_4^-$ and HPO_4^{2-}. At any constant phosphate concentration within the AD system, a change in the pH within the range found for this experimental investigation will result in changes in the $H_2PO_4^-$ and HPO_4^{2-} concentrations of this system. These changes in $H_2PO_4^-$ and HPO_4^{2-} concentrations compensate for each other because the total phosphate concentration remains constant. This problem is solved by splitting the ortho-P generated into f x $H_2PO_4^-$ and (1-f) HPO_4^{2-}, which implies a fixed pH depending on the f value. The gaseous CO_2 and CH_4 set the pCO_2, which together with the dissolved CO_2 (HCO_3^- or $H_2CO_3^*$ Alk.) also imply a certain pH value where the $H_2CO_3^*$ Alk. is the difference between the total Alk. (of the inorganic carbon and ortho-P systems) and the ortho-P subsystem. The f value at which the pH meets the requirements for both the inorganic carbon and ortho-P subsystems is the pH established in the digester.

Furthermore, in cases where the ionic product of the aqueous phase ions exceeds the thermodynamic solubility product (K_{spm}) of mineral precipitation then precipitation of those minerals are likely to occur. So for the purpose of completeness, the weak acid/base part of the AD model should include mineral precipitation as part of the AD products. The precipitation formed are those most likely to occur at the prevailing conditions of digestion i.e. calcium and magnesium carbonates and phosphates. However, this is beyond the scope of this study and it is therefore recommended that other models such as those of Musvoto *et al.* (2000), Loewenthal *et al.* (1994) or Stasoft 4 be used to quantify the precipitation formed based on the results obtained from the stoichiometric part of the steady state AD model which assumes infinite solubility of the anions and cations. Therefore, this AD model does not predict or quantify precipitation products but the ionic products of the aqueous phase concentrations can be determined and compared with the thermodynamic solubility product (K_{spm}) of specific precipitation. The precipitation potential is discussed in Section 2.4.4.

4.2.1 Developing the Stoichiometric part of the AD model for NDBEPR WAS

As earlier stated, the steady state stoichiometric model is developed using the methods described by McCarty (1975). The steady state AD model developed by Sötemann *et al.* (2005) is extended in this section to incorporate phosphorus and the counter-ion metals related to polyphosphate. The resultant steady state model can be applied to the anaerobic digestion of NDBEPR WAS. However, the extended steady state AD model will require flexibility in the ortho-P species formed to model pH.

First, the mass balanced redox half reactions of substrate electron (and H^+) donation are determined for each of the phosphate products (HPO_4^{2-} and $H_2PO_4^-$). These are presented in Equation E4.9a and E4.9b i.e.

$$\begin{aligned} &C_X H_Y O_Z N_A P_B .q[MePO_3] + (2X - Z + A + 2B)H_2O \rightarrow (X - A + 2B + q)CO_2 + \\ &+ ANH_4^+ + (B+q)HPO_4^{2-} + (A - 2B - q)HCO_3^- + qMe^+ + \gamma_S(H^+ + e^-) \end{aligned} \qquad \textit{(E4.9a)}$$

And,

$$\begin{aligned} &C_X H_Y O_Z N_A P_B .q[MePO_3] + (2X - Z + A + 3B)H_2O \rightarrow (X - A + B)CO_2 \\ &+ ANH_4^+ + (B+q)H_2PO_4^- + (A - B)HCO_3^- + qMe^+ + \gamma_S(H^+ + e^-) \end{aligned} \qquad \textit{(E4.9b)}$$

Where γ_s is the number of e^- donated per mole of organic and described in E4.13a below. The e^- donated by the organics are used for two biological processes: (1) anabolism, which is the generation of all mass, and (2) Catabolism which is the generation of energy to synthesize the cell mass from some of the substrate material (anabolism).

So next, the mass balanced reaction stoichiometry describing the anabolic process (R_a) half reaction is determined. The active biomass in the AD reactor is described as $C_kH_lO_mN_nP_p$ and not $C_5H_7O_2N$ as used in Equation E2.15 of Section 2.3.2. However, the subscript of the P component of the elemental composition of the biomass was determined to be 0.124 if it is assumed that the

P content of the active biomass is 0.033 of the active VSS and k, l, m and n are assumed to be 5, 7, 2 and 1. This translates in the elemental composition of the active biomass of the AD system being $C_5H_7O_2N_1P_{0.124}$. This is done using the procedure described in Section 4.2.2. Equation E4.9c refers to the uptake $H_2PO_4^-$ for AD biomass growth while Equation E4.9d refers to the uptake HPO_4^{2-} for AD biomass growth:

$$R_a = \begin{bmatrix} (k-n+p)\frac{\gamma_S}{\gamma_B}CO_2 + (n-p)\frac{\gamma_S}{\gamma_B}HCO_3^- + n\frac{\gamma_S}{\gamma_B}NH_4^+ + p\frac{\gamma_S}{\gamma_B}H_2PO_4^- \\ +\gamma_S\left[H^+ + e^-\right] \rightarrow \frac{\gamma_S}{\gamma_B}C_kH_lO_mN_nP_p + (2k-m+n+3p)\frac{\gamma_S}{\gamma_B}H_2O \end{bmatrix} \qquad \textbf{\textit{(E4.9c)}}$$

and

$$R_a = \begin{bmatrix} (k-n+2p)\frac{\gamma_S}{\gamma_B}CO_2 + (n-2p)\frac{\gamma_S}{\gamma_B}HCO_3^- + n\frac{\gamma_S}{\gamma_B}NH_4^+ + p\frac{\gamma_S}{\gamma_B}HPO_4^{2-} \\ +\gamma_S\left[H^+ + e^-\right] \rightarrow \frac{\gamma_S}{\gamma_B}C_kH_lO_mN_nP_p + (2k-m+n+2p)\frac{\gamma_S}{\gamma_B}H_2O \end{bmatrix} \qquad \textbf{\textit{(E4.9d)}}$$

Where γ_B is the e^- donating capacity of the AD biomass organics and is described in E4.13b

Under anaerobic conditions the e^- acceptor for the catabolic process is CO_2. So the stoichiometry describing the catabolic process (R_c) half reaction is given by Equation E4.9e describing the e^- acceptor half reaction for catabolic pathway as follows,

$$R_c = \left[\frac{\gamma_S}{8}CO_2 + \gamma_S\left[H^+ + e^-\right] \rightarrow \frac{\gamma_S}{8}CH_4 + \frac{2\gamma_S}{8}H_2O\right] \qquad \textbf{\textit{(E4.9e)}}$$

To balance the COD, the e^- donated by the organics must be equal to the electrons captured into new all mass (anabolism) and transferred to the e^- acceptor CO_2. If a fraction E of the e^- are new cell mass and (1-E) passed to e^- acceptor CO_2 then:

$$R = R_d - (1-E)R_a - ER_c \qquad \textbf{\textit{(E4.10)}}$$

Where E refers to the sludge produced per day per COD utilized per day and is described by equation E4.11 below

$$E=\frac{V_d\left(Z_{BAD}+Z_{EAD}\right)}{Q_i\left(S_{bi}-S_{be}\right)R_s}=\frac{Y_{AD}\left(1+f_{AD}b_{AD}R_S\right)}{\left[1+b_{AD}R_s\left(1-Y_{AD}\left\{1-f_{AD}\right\}\right)\right]}$$ ***(E4.11)***

A generalised stoichiometric model (R) is derived for the phosphate products $H_2PO_4^-$ and HPO_4^{2-} using the Equation E4.10. These stoichiometric models are presented as Equations E4.12a and E4.12b,

$$C_XH_YO_ZN_AP_B.q[MePO_3]+\left(2X-Z+A+2B-E\frac{\gamma_S}{\gamma_B}(2k-m+n+2p)-\frac{2\gamma_S}{8}(1-E)\right)H_2O\rightarrow$$

$$\left(X-A+2B+q-E\frac{\gamma_S}{\gamma_B}(k-n+2p)-\frac{(1-E)\gamma_S}{8}\right)CO_2+\left(\frac{\gamma_S}{8}(1-E)\right)CH_4+\left(E\frac{\gamma_S}{\gamma_B}\right)C_kH_lO_mN_nP_p$$

$$+\left(A-nE\frac{\gamma_S}{\gamma_B}\right)NH_4^++\left(B+q-pE\frac{\gamma_S}{\gamma_B}\right)HPO_4^{2-}+\left(A-2B-q-E\frac{\gamma_S}{\gamma_B}(n-2p)\right)HCO_3^-+qMe^+$$

(E4.12a)

and,

$$C_XH_YO_ZN_AP_B.q[MePO_3]+\left(2X-Z+A+3B+q-E\frac{\gamma_S}{\gamma_B}(2k-m+n+3p)-\frac{2\gamma_S}{8}(1-E)\right)H_2O\rightarrow$$

$$\left(X-A+B-E\frac{\gamma_S}{\gamma_B}(k-n+p)-\frac{(1-E)\gamma_S}{8}\right)CO_2+\left(\frac{\gamma_S}{8}(1-E)\right)CH_4+\left(E\frac{\gamma_S}{\gamma_B}\right)C_kH_lO_mN_nP_p$$

$$+\left(A-nE\frac{\gamma_S}{\gamma_B}\right)NH_4^++\left(B+q-pE\frac{\gamma_S}{\gamma_B}\right)H_2PO_4^-+\left(A-B-E\frac{\gamma_S}{\gamma_B}(n-p)\right)HCO_3^-+qMe^+$$

(E4.12b)

Where γ_S and γ_B refers to the electron donating capacity of the substrate (e^- / mol) and biomass (e^-/ mol) respectively. These parameters can be determined using equations E4.13a and E4.13b as shown below,

$$\gamma_S=4X+Y-2Z-3A+5B$$ ***(E4.13a)***

And

$$\gamma_B=4k+l-2m-3n+5p$$ ***(E4.13b)***

At this stage it would be relevant to note that although this stoichiometric model has been developed for BPO that include PAOs, thus including the elemental composition of polyphosphate as part of the overall elemental composition of the BPO, it can be applied also to BPO of WAS that does not contain stored polyphosphate. In this case, the linkage factor (q_{Φ}) for the BPO substrate or reactant is zero. This eliminates the polyphosphate component from the stoichiometric part of the AD model. Also only the elemental composition of the BPO components is input to the stoichiometric model because these are the only components that are digested during the AD process. The elemental compositions of the PO and UPO were determined from the measured data as the means to calculate the composition of the BPO by difference.

Furthermore, in the form presented above, the phosphate product $H_2PO_4^-$ and HPO_4^{2-} is taken to be independent of each other and it is assumed that both $H_2PO_4^-$ and HPO_4^{2-} is known. However, these phosphate products are directly related to each other and dependent on the aqueous phase equilibrium chemistry that exists within the AD reactor environment. Therefore, the physico-chemical aspects of the AD environment need to be incorporated in the stoichiometric model.

4.2.2 Including the physico-chemical processes

Contrary to the anaerobic digestion of ND WAS and PS, where the weak acid/base chemistry sub-systems of the products of digestion is dominated by the inorganic carbon species only, the weak acid/base chemistry for the anaerobic digestion products of NDBEPR WAS are dominated by the phosphate subsystem also. The phosphate sub-system has a pK value close to the normal operating pH of the anaerobic digester. The concentrations of the HPO_4^{2-} and $H_2PO_4^-$ species varies in the AD system depending on the $H_2CO_3^*$ alkalinity supplied by the inorganic carbon system. Consequently, to predict the AD pH, the weak acid/base chemistry of both the inorganic carbon and ortho-P systems needs to be recognized.

The influence of the inorganic carbon and ortho-P subsystems on the weak acid/base chemistry and pH of the AD process is a function of the sludge age of the system. The BPO from the NDBEPR WAS contain large quantities of stored inorganic P in the form of polyphosphate and although the carbon content of the WAS is still significantly larger than the P content in terms of mass concentration, the release rate of the C and P components during the digestion process differ. The organically bound C, N and P components are released at the kinetic rate of the hydrolysis process while the inorganic P content of the WAS is released at a kinetic rate that is much faster than that of hydrolysis. In anaerobic digestion batch tests that were preformed during this study, reported in Appendix D, it was observed that all the polyphosphate P is released within 7 days. The organic components of BPO takes significantly longer to hydrolyse and digest then this. Consequently, high aqueous P concentrations arise already at short sludge ages, but the sludge age of the AD system increases, the impact of the inorganic carbon system increases relative to the phosphate system as increased BPO are hydrolysed and digested. This behaviour is shown in more detail in Section 5.3.1 b of this study.

4.2.2.1 Incorporation of the weak acid/base chemistry

To incorporate the aqueous weak acid/base chemistry into the AD model describing the AD of NDBEPR WAS, a $H_2PO_4^-$ / HPO_4^{2-} relative fraction (f) is included that relates the P components to the pH via the equilibrium chemistry of the system. The bi-carbonate and two phosphate species are the dominant aqueous species that govern the normal operating pH of the AD system.

Defining the f value in terms of pH and the pK_{p2} dissociation constants (Equation E2.19e) that relates $H_2PO_4^-$ and HPO_4^{2-}, yields,

$$\left[H_2PO_4^-\right] = f.P_t = f\left[B + q - pE\frac{\gamma_S}{\gamma_B}\right] \qquad \textbf{\textit{(E4.14a)}}$$

Where $P_t = [H_2PO_4^-] + [HPO_4^{2-}]$. Then from Eq. 2.19e :

$$\left[H_2PO_4^-\right] = \frac{P_t}{1+10^{pH-pK'p2}} \qquad \textbf{\textit{(E4.14b)}}$$

So:

$$f = \frac{1}{1+10^{pH-pK'p2}} \qquad \textbf{\textit{(E4.14c)}}$$

Similarly (1-f) for the HPO_4^{2-} term is

$$(1-f) = \frac{1}{1+10^{pK'p2-pH}} \qquad \textbf{\textit{(E4.14d)}}$$

This *ƒ* relationship (which assumes that the H_3PO_4 and PO_4^{3-} species concentration are ≈ 0 at the normal operational pH of the AD system) relates the substrate WAS to each of the phosphate species, HPO_4^{2-} and $H_2PO_4^-$. From the *ƒ* relationship of HPO_4^{2-} and $H_2PO_4^-$ if *ƒ* = 1 than $H_2PO_4^-$ is at its maximum (with HPO_4^{2-} being zero) and if *ƒ* = 0 the reverse is true. The pH of the AD is calculated iteratively by varying *ƒ*, which varies with pH, the HCO_3^- concentration (≈ to the $H_2CO_3^*$ Alk. and the pCO_2). The HCO_3^- concentration and pCO_2 are then used to calculate the pH in the usual way for non-P dominated ADs. The *ƒ* value at which the pHs for the P and IC species is equal is the correct *ƒ* value. Equations 4.12a and b are combined by adding (1-*ƒ*) x E4.12a for HPO_4^{2-} and *ƒ* x E4.12b for $H_2PO_4^-$, then the mass balanced stoichiometry will generate a specific Ortho-P (P_t) concentration split between HPO_4^{2-} and $H_2PO_4^-$ i.e.

$$
\begin{aligned}
&C_X H_Y O_Z N_A P_B . q_\theta [MePO_3] + \left(2X - Z + A + (2+f)B + fq - E\frac{\gamma_S}{\gamma_B}(2k - m + n + (2+f)p) - \frac{2\gamma_S}{8}(1-E) \right) H_2O \rightarrow \\
&\left(X - A + (2-f)B - E\frac{\gamma_S}{\gamma_B}(k - n + (2-f)p) - \frac{(1-E)\gamma_S}{8} \right) CO_2 + \left(\frac{\gamma_S}{8}(1-E) \right) CH_4 + \left(E\frac{\gamma_S}{\gamma_B} \right) C_k H_l O_m N_n P_p \\
&+ \left(A - nE\frac{\gamma_S}{\gamma_B} \right) NH_4^+ + f\left(B + q - pE\frac{\gamma_S}{\gamma_B} \right) H_2PO_4^- + (1-f)\left(B + q - pE\frac{\gamma_S}{\gamma_B} \right) HPO_4^{2-} + qMe^+ \\
&+ \left(A - (2-f)B - (1-f)q - E\frac{\gamma_S}{\gamma_B}(n - (2-f)p) \right) HCO_3^-
\end{aligned}
$$

(E4.15)

The inorganic C and P mixed weak acid/base chemistry part of the AD model does not describe the formation of mineral precipitation during the digestion process. The development or incorporation of models describing mineral precipitation within the AD system is beyond the scope of this study. Nevertheless, the aqueous phase products of digestion effectively at infinite solubility can be utilized as input variables to the models developed by Loewenthal *et al*. (1994) or Musvoto *et al.* (2000) to include the third solid phase for quantifying the precipitation products from the AD of NDBEPR WAS.

At the implementation stage of the steady state AD model it is important to differentiate between the units of the variables in concentration, e.g. mgCOD/l or mgVSS/l, and daily flux, e.g. mmol/d, in the three parts of the steady state AD model. The incorrect use of units will result in incorrect results.

4.2.2.2 Hydrolysis Kinetics from Ikumi *et al.* (2009)

Sections 4.2.1 and 4.2.2 above describe the development of the reaction stoichiometry and mixed weak acid/base chemistry part of the AD model for NDBEPR WAS. These are the second and third parts of the steady state AD model. The first part is the kinetics that describes the hydrolysis rate of the BPO components of NDBEPR WAS. The hydrolysis rate defines the concentration of BPO utilization, which via the stoichiometry, is directly related to the production rate of AD products from the organic components of NDBEPR WAS. However, the production rate of the AD products related to the store polyphosphate is significantly higher than the hydrolysis rate. Consequently, it was found that the AD products related to polyphosphate are present in high concentrations relative to the organically bound products at short sludge ages, because of the higher polyphosphate P release rate. Nevertheless, NDBEPR WAS contains high concentrations of the organically bound C components and the products related to these organic C components at longer sludge ages exceed the concentration of the products related to polyphosphate due to the higher % BPO hydrolyzed at longer sludge ages.

The hydrolysis kinetic model is used to determine the quantity of the NDBEPR WAS BPO that is hydrolyzed and utilized during the anaerobic digestion process. In this project, the hydrolysis kinetic model was developed in the parallel study by Ikumi *et al.* (2009) while the kinetics of polyphosphate degradation is described in this study. A summary of the study by Ikumi *et al.* (2009) is given below.

To determine the hydrolysis kinetics rate for residual BPO, Sötemann *et al.* (2005) described hydrolysis as the first and slowest bioprocess in the AD of sewage sludge organics. The rate of the hydrolysis process is therefore equal to the rate that the AD products are produced in the AD environment.

Ikumi *et al.* (2009) applied the method of Sötemann *et al.* (2005) to determine the hydrolysis kinetic constants. Fistly, after taking due account of the influent and effluent VFA concentration, the residual (not degraded) BPO COD concentration (S_{bpe}) is calculated from the measured influent and effluent COD concentration (S_{ti} and S_{te}) for an assumed unbiodegradable particulate COD fraction ($f_{WAS,up}$).

$$S_{bpe} = \frac{S_{te} - S_{tpi}\left[f_{up} + E(1-f_{up})\right]}{(1-E)} \qquad \textbf{(E4.16a)}$$

This S_{bpe} concentration is independent of the hydrolysis rate equation and is a fuction of the E value which depends on the acedogen yield coeffiecnt ($Y_{AD} = 0.113$), endogenous respiration rate ($b_{AD} = 0.04$) and the unbiodegradable fraction ($f = 0$) and the system sludge age/retention time ($R_h = R_s$) i.e.

$$E = \frac{Y_{AD}\left(1 + f_{AD} b_{AD} R_s\right)}{\left[1 + b_{AD} R_s\left(1 + (1-f)Y_{AD}\right)\right]} \qquad \textbf{(E4.16b)}$$

S_{bpe} known, Z_{AD} and the volumetric hydrolysis rate (r_h) can be calculated from:

$$Z_{AD} = \frac{Y_{AD}\left[\left(1 - f_{WAS,up}\right)S_{tpi} - S_{bpe}\right]}{\left[1 + b_{AD} R_s\left(1 - (1-f)Y_{AD}\right)\right]} \qquad \textbf{(E4.16c)}$$

Where rh can be determined as shown in Table 2.5:

$$r_h = K_H S_{bp} \qquad \textbf{(E4.16d)}$$

With Sbpe, ZAD and rh known, the kinetic constants in the different hydrolysis rate equations can be calculated i.e.

i) First order :

$$r_h = K_H S_{bpe} \qquad \textbf{(E4.16e)}$$

ii) First order specific

$$r_h = \frac{K_m S_{bpe}}{K_s + S_{bpe}} Z_{AD} \qquad \textbf{(E4.16f)}$$

iii) Monod

$$r_{HYD} = \left[\frac{K_m \bullet S_{bp}}{K_S + S_{bp}} \right] \bullet Z_{AD} \qquad \textbf{(E4.16g)}$$

iv) Saturation:

$$r_{HYD} = \frac{K_M \left(S_{bp} / Z_{AD} \right)}{K_S + \left(S_{bp} / Z_{AD} \right)} Z_{AD} \qquad \textbf{(E4.16h)}$$

For the first order and specific first orderkinetics, different K_h and K_H rates were obtained at different sludge ages, increasing with increase in sludge ages. This was also found by Sötemann *et al.*(2005) and they calculated the coefficient of variation of the different K_h and K_H rates obtained at different sludge ages. They also noted that if different unbiodegradable fractions (f_{up}) were selected, different K_h and K_H rates and coefficients of variation were obtained. They accepted that the f_{up} value for which the coefficient of variation were a minimum were the best estimate of the f_{up} for the hydrolysis rate. Slightly different minimum coefficient of variation values were obtained for the first order (K_h) and specific first order (K_H) hydrolysis kinetics. This was also the case in this (Ikumi *et. al.,* 2009) investigation.

For the Monod and Saturation kinetics, the equations are linearized with three methods i.e. Lineweaver-Burke, Double reciprocal and Eadie-Hofstee (Lehninger, 1977) methods and the results correlated over the range of sludge ages of the Ads, to obtain the K_m, K_s and K_M, $K_{S'}$ values and a linear correlation coefficient R^2. The f_{up} value that gives the highest R^2 value was accepted to be the vbest estimate the f_{up} and its associated K_m, K_s and K_M, $K_{S'}$ values were accepted to be the best hydrolysis rate constants. The different hydrolysis kinetic equations give slightly different f_{up} fractions but they varied in a sufficiently narrow range (2 to 3%) to give a good estimate for the $f$up fraction of the digested sludge. Also, the $f$up value obtained from the first order and first order specific rates were closely similar to those obtained from the Monod and Saturation kinetic rates.

On application of the Monod equation, it was found that where there was a change in influent COD concentration (S_{tpi}), the K_s value (K_{s1}) should change to maintain the correct fraction of influent biodegradable particulates (S_{bpi}) removed at the same sludge age.

This is presented in Figure 4.3.

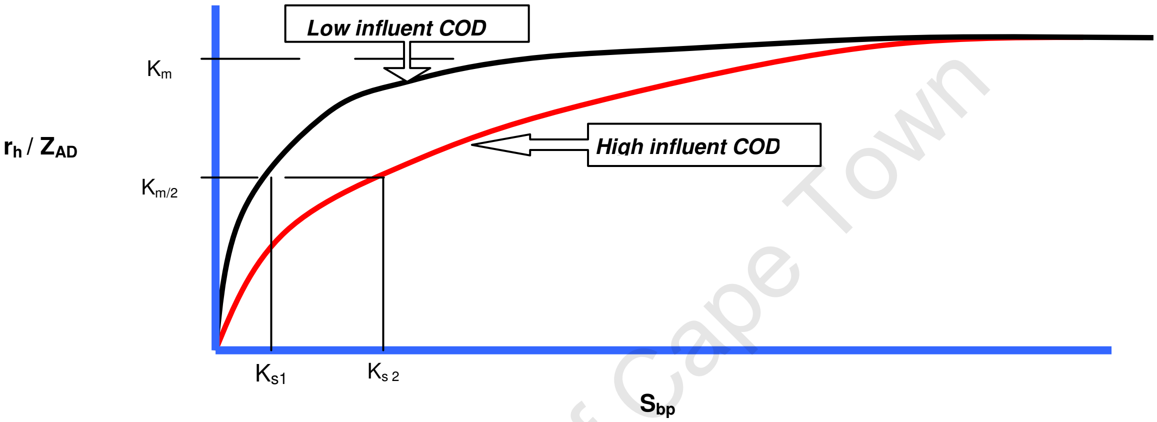


Figure 4.3: Plot of BPO utilisation to determine Monod kinetics (Ikumi *et al.*, 2009)

The K_m value did not change because it is influenced by the fraction of COD removal with change in sludge age rather than changes by in S_{tpi} concentration. Therefore a fractionion K_s value was set as a reference Ks and used to determine the actual K_s values in propotion with a change in the S_{bpi} concentration. This problem does not arise with Saturation kinetics because the growth limiting concentration is expressed as a ratio to the acedogen biomass concentration.
This is described in equation E4.16c below,

$$Ks_{actual} = \left[\frac{Ks_{control}}{Sbpi_{control}}\right] \bullet Sbpi_{actual} \qquad \textbf{\textit{(E4.16i)}}$$

Table 4.11a present the correlation coefficients determined for the Monod, Saturation and First Order kinetic rate equations over the f_{up} range found to give the highest coefficient of variation and correlation.

Table 4. 11a, b & c: Consider the Correlation Coefficients, Hydrolysis Rates and Kinetic Constants

4.11a: The Correlation Coefficients determined for the different rate expressions based on the expected f_{up} range			
f_{up}	**Monod Kinetics**	**Saturation Kinetics**	**First Order Kinetics**
0.51	1.000	0.950	0.979
0.52	1.000	0.971	0.978
0.53	0.997	0.989	0.977
0.54	0.988	0.999	0.976
0.55	0.968	0.995	0.974
0.56	0.923	0.958	0.971
0.57	0.827	0.851	0.968
0.58	0.626	0.612	0.965

4.2.2.3 Summary of Kinetic Constants for the AD of NDBEPR WAS

The hydrolysis kinetic constants for the first order rate (K_h), the specific first order rate (K_H), the Monod (K_m & K_s) and the saturation (K_M & K_S) were determined from the measured data obtained for the experimental NDBEPR WAS anaerobic digester unit. The three-linearization methods (Lineweaver, Double Reciprical and Eadie Hofsee) gave consistently good correlation coefficients in the determination of kinetic constants for both the Monod and Saturation kinetics. The kinetic constants are presented in Tables 4.11a and 4.11b.

4.11b: Experimentally determined hydrolysis rates for different rate equations for NDBEPR WAS AD					
Short Sludge ages (10 to 25 days)					
Volumetric hydrolysis rate		**Spec. Volumetric hydrolysis**		**First order kinetics**	
r_{HYD} Slope	***r_{HYD} Intercept***	***Spec. r_{HYD} Slope***	***Spec. r_{HYD} Intercept***	***K_h slope***	***K_h intercept***
-0.001	0.044	-0.036	1.571	0.002	0.041

4.11c: Experimentally determined kinetic constants used in the AD of NDBEPR WAS							
Obtained for longer R_s (25 to 60 days)							
First order Specific kinetics		Monod kinetics			Saturation Kinetics		
K_H Slope	K_H intercept	K_m	K_s	$K_m/2K_s$	K_M	K_S	$K_M/2K_S$
0.114	-0.386	0.822	0.05	8.198	0.866	1.682	0.257

The above tables show that the experimentally determined K_m value for the AD of NDBEPR WAS is 0.822.

4.2.2.4 Hydrolysis kinetics of polyphosphate (P and Me release rate)

The kinetics of polyphosphate hydrolysis is handled differently to the hydrolysis rate of the BPO. The reason for this is that in this investigation, the experimental anaerobic digester was not operated at a steady state $R_s < 10$ days. This was done to allow sufficient time for WAS BPO hydrolysis. Izzett and Ekama (1992) found that primary sludge (PS) AD systems failed at around 6 days sludge age due to insufficient BPO hydrolysis to sustain the AD biomass consortium. Previous studies on the AD of WAS suggested that an $R_s > 10$ days is adequate for a stable operation of these anaerobic digesters. Although a significant quantity of the biodegradable organics may have been digested at an $R_s < 10$ days by the hydrolysis and acidogenesis processes, the symbiotic relationship between the acidogenic and methanogenic organisms are likely not balanced at these low sludge ages. If the pH of the AD system decreased below 6 due to insufficient alkalinity generation via ammonia release, the system will fail. An AD process diagram is shown in Figure 2.5.

The kinetic rate for complete degradation of polyphosphate is less than 7 days as described by Jardin *et al.* (1994) and will later be confirmed by Figure 5.9 f to h from the batch tests of this investigation. At the shortest sludge age of this study (10 days) all stored polyphosphate had been hydrolysed and released to the bulk liquid of the anaerobic digester. It is therefore concluded that all the polyphosphate contained by the BPO component of the NDBEPR WAS is released to the bulk liquid at all of the steady state sludge ages of this investigation (all ≥ 10 days). This is much faster than the hydrolysis of the BPO components of the NDBEPR WAS which is completely hydrolysed only at very long sludge ages like 60 days.

To determine the polyphosphate hydrolysis release rate, and separate this component from the BPO hydrolysis rate the molar fluxes for the total BPO (J_{BPO}) and utilized BPO ($J_{BPO(U)}$) components are incorporated into the elemental composition of the substrate of reactant used in the steady state stoichiometric model. This is presented in E4.16j below,

$$J_{BPO(U)} \cdot C_X H_Y O_Z N_A P_B . q_{\phi} . \frac{J_{BPO}}{J_{BPO(U)}} \left[MePO_3 \right] \qquad \textbf{\textit{(E4.16j)}}$$

These molar fluxes are determined in the example at the end of Section 4.2. The same result would be achieved if the hydrolysis and stoichiometry of polyphosphate were considered separately from that of the WAS BPO, i.e. extract all the q_{Φ} terms from Eq. E4.15 as an independent stoichiometric equation, then q is the mol of polyphosphate in the PAOs that are all released.

4.2.3 Anaerobic Digestion Model Application Procedure and Example

This section describes the procedure for applying the stoichiometry part of the AD model developed in Section 4.2.1. It also describes the application of the BPO hydrolysis kinetic part of the AD model of Ikumi *et al.* (2009), as well as the kinetic rate of polyphosphate hydrolysis explained in Section 4.2.3c. These descriptions are supported by an example that shows the results obtained from the application of the model. This example continues from the characterization example of Section 4.1.3, where the NDBEPR WAS was characterized to its elemental composition of its particulate organic (PO, S_{tp}), UPO (S_{up}) and BPO (S_{bp}) components. Furthermore, these components of the NDBEPR WAS were also quantified to mass (mgVSS/ℓ or mgCOD/l), molar (moles/ℓ) concentrations, and the molar composition of each component.

The first step is to determine the quantity of BPO utilized (S_{bp} utilized), in concentration units, during the anaerobic digestion process at a specific steady state sludge age. This is determined from the application of the hydrolysis kinetic part of the AD model developed by Ikumi *et al.* (2009). Application of hydrolysis kinetic model yields the residual BPO (S_{bpe}) and the BPO (S_{bp})

utilized is the difference between the influent and effluent sludge BPO COD concentration (S_{bpi} – S_{bpe}). The stoichiometric model is then applied to change the utilized BPO (converted from the COD to mole units) to the products formed during AD.

The anaerobic digester used in this study was a flow through CSTR unit, operated on a daily batch fed basis, as stated in Section 3.2.4.1. The R_s (solid retention time or sludge age) and hydraulic retention time of a flow through CSTR system is the same, resulting in the particulate and dissolved components having the same retention time in the system. Knowing the AD system type, the retention times of the content and the molar masses of each component, the feed rate for each component of the WAS substrate can be determined as a molar flux (J_Φ in moles/d, where J refers to molar flux and Φ refers to the particular component). This is the required unit for the input variables used in the application of the stoichiometry part of the AD model.

The units of the products from the stoichiometry part of the AD model such as AD biomass ($C_5H_7O_2N_1P_{0.124}$), CH_4 and CO_2 gas, HCO_3^-, NH_4^+, Me^+ (includes Mg^{2+}, K^+ and Ca^{2+}) and the phosphates, HPO_4^{2-} and $H_2PO_4^-$ are in molar flux (mmol/d) . The concentrations of the $H_2PO_4^-$ and HPO_4^{2-} and hence the P system alkalinity generated is dependent on the pH. As the system pH is unknown, the system pH has to be calculated iteratively as explained earlier. This is demonstrated in this Section below.

Some precipitates, mainly Mg and Ca carbonate and phosphate minerals may form within the AD system. The occurrence or not of these minerals within the AD system can be determined from the relevant dissolved AD products but the mixed weak acid/base chemistry part of the AD model does not quantify the precipitants. Furthermore, if precipitation does occur some of the experimental AD system observed measurements would differ significantly from the predicted ones from the AD model which does not include mineral precipitation. In addition, because the model does not quantify mineral precipitation, it is difficult to compare the predicted dissolved concentrations with all the measured ones.

4.2.3.1. Application of the Kinetic Model to determine Utilized Biodegradable Particulate Organics

The input variable to the hydrolysis kinetic model is the BPO COD concentration of the NDBEPR WAS. With the hydrolysis kinetic rate constants known, the residual BPO (S_{bpe}) is determined as described above. Next, the difference between the influent and effluent (residual) BPO COD is the utilized BPO (S_{bp} utilized). This is shown in Equation E4.17 below,

$$S_{bp}(utilised) = S_{bpi} - S_{bpe} \qquad \textbf{\textit{(E4.17)}}$$

The model predicted results for the S_{bpi}, S_{bpe} and S_{bp} (utilized), for the 12 day sludge age are presented in Table 4.12.

Table 4.12: Kinetic Model Results for Residual & Utilized BPO

UPO	BPO			
Total	***Influent S_{bpi}***	***Measure S_{bpe}***	***Predict S_{bpe}***	***Utilized S_{bp}***
mgCOD/l	*mgCOD/l*	*mgCOD/l*	*mgCOD/l*	*mgCOD/l*
4920.0	4446.9	1736.6	1757.2	2641.9

The S_{bp} utilized is input to the stoichiometric part of the AD model. The effluent sludge from the experimental AD system at the different sludge ages contains the unbiodegradable COD (S_{up}), the residual biodegradable COD (S_{bpe}) and the AD biomass COD (Z_{AD}) all determined from the hydrolysis kinetic model.

4.2.3.2. Application of the Stoichiometric Model to determine AD products (No Precipitants)

Next, the stoichiometry part of the AD model is applied to determine the AD products for the 12 day R_s AD system. The S_{bp} (utilized) from the kinetic model above is one of the input variables. The other is the molar elemental composition of the BPO as determined in the characterization example above, which serves also to change the units of the S_{bp} (utilized) from mass COD concentration (mgCOD/l) to a molar flux ($J_{BPO(U)}$ in mmoles/day).

To convert the units to mmoles/d, the utilized BPO COD concentration [S_{bp} utilized in mgCOD/l] is first changed to utilized BPO VSS concentration (mgVSS/l) and divided by the molar mass of the BPO (MM_{BPO}) to yield mmol/l. Next, the sludge age and volume of the AD system are used to determine the molar flux ($J_{BPO(U)}$) as shown in Equation E 4.18a below,

$$J_{BPO(U)} = \frac{X_{BPO(U)} \times Q_I}{MM_{BPO}} \tag{E4.18a}$$

where: $J_{BPO(U)}$ = Molar flux of the utilized BPO (mmoles/day)

$X_{BPO(U)}$ = Utilized BPO (mgVSS/l)

MM_{BPO} = Molar mass of the BPO components (mgVSS/mmol)

$Q_W = Q_I$ = Volumetric flow rate through the CSTR (l/d) = V_{AD}/R_s

To determine the molar flux of the BPO (J_{BPO}) and the utilized BPO concentration ($X_{BPO(U)}$) Equation E4.18 is changed to the influent BPO VSS concentration (X_{BPO}).

Next, the fluxes of the influent and utilized BPO and the BPO molar elemental composition are inserted into the stoichiometry part of the AD model shown in Equation E4.18b.

$$\left(J_{BPO(U)}\right)\left(\begin{array}{l}
C_X H_Y O_Z N_A P_B . q_\theta\left(\dfrac{J_{BPO}}{J_{BPO(U)}}\right)\left[MePO_3\right]+ \\
\left(2X - Z + A + (2+f)B + fq\left(\dfrac{J_{BPO}}{J_{BPO(U)}}\right) - E\dfrac{\gamma_S}{\gamma_B}(2k - m + n + (2+f)p) - \dfrac{2\gamma_S}{8}(1-E)\right)H_2O \leftrightarrow \\
\left(X - A + (2-f)B - E\dfrac{\gamma_S}{\gamma_B}(k - n + (2-f)p) - \dfrac{(1-E)\gamma_S}{8}\right)CO_2 + \left(\dfrac{\gamma_S}{8}(1-E)\right)CH_4 + \\
\left(E\dfrac{\gamma_S}{\gamma_B}\right)C_k H_l O_m N_n P_p + \left(A - nE\dfrac{\gamma_S}{\gamma_B}\right)NH_4^+ + f\left(B + q\left(\dfrac{J_{BPO}}{J_{BPO(U)}}\right) - pE\dfrac{\gamma_S}{\gamma_B}\right)H_2PO_4^- \\
+ (1-f)\left(B + q\left(\dfrac{J_{BPO}}{J_{BPO(U)}}\right) - pE\dfrac{\gamma_S}{\gamma_B}\right)HPO_4^{2-} + q\left(\dfrac{J_{BPO}}{J_{BPO(U)}}\right)Me^+ \\
+\left(A - (2-f)B - (1-f)q\left(\dfrac{J_{BPO}}{J_{BPO(U)}}\right) - E\dfrac{\gamma_S}{\gamma_B}(n - (2-f)p)\right)HCO_3^-
\end{array}\right) \tag{E4.18b}$$

The elemental composition of the NDBEPR WAS BPO for the 12 day R_s (Batch 14) is $C_{5.46}H_7O_{1.99}N_{1.07}P_{0.13}.0.76[MePO_3]$ as determined in the characterization example of Section 4.1.3. The molar fluxes, $J_{BPO(U)}$ and J_{BPO}, were determined above and *E* is determined in Equation E4.11 and, Y_s and Y_B in Equations E4.13a and E4.13b. The only unknown remaining in Equation E4.18b is the *ƒ* factor for calculating the digester pH.

Solving for the system pH with the *ƒ* factor is iterative because it involves both the inorganic C and P systems. The inorganic C products CO_2 in the gas phase and HCO_3^- in the aqueous phase exist in equilibrium that is pH dependent in the identical way as for negligible P concentration AD systems. However, the phosphate concentration system (HPO_4^{2-} and $H_2PO_4^-$) also generate alkalinity which change the dissolved CO_2 (HCO_3^-) and gaseous CO_2 concentrations. These phosphate components exist in a pH dependent equilibrium with each other. However, CH_4 is essentially insoluble and therefore does not exist in a gaseous–dissolved equilibrium that is pH dependent. So the methane concentration of the stoichiometry part of the AD model was selected as the constant to simultaneously solve for the pH and the quantities of the AD products that are pH dependent.

To solve the pH and the quantities of the AD products that are pH dependent the following procedure was followed,

1. In the first step, an equation is derived that relates the CH_4 to the CO_2 in the gas and aqueous phases. This is done by relating the partial pressure of the CO_2 (pCO_2) from E4.18c to that in E4.18d resulting in E4.18e, as shown below.

$$pCO_2 = \frac{[CO_2]_g}{[CH_4]_g + [CO_2]_g} \qquad \textbf{(E4.18c)}$$

and,

$$[H_2CO_3] = pCO_2 \times K_H \qquad \textbf{(E4.18d)}$$

Given that

$$[CH_4]_g = [CO_2]_g \left(\frac{K_H}{[H_2CO_3]} - 1 \right) \qquad \textbf{(E4.18e)}$$

where: pCO_2 = The partial pressure of CO_2
K_H = Henry's Law Constant
$[CO_2]_g$ and $[CH_4]_g$ = The gas concentration (mmoles/l)
$[H_2CO_3]$ = The aqueous phase dissolvedCO_2 (mmoles/l)

2. In the second step, $[H_2CO_3]$ is related to $[HCO_3^-]$ through the chemical equilibrium equation from K_{C1}. This resultant equation is shown in E4.18f

$$[H_2CO_3] = [HCO_3^-](10^{pK_{c1}-pH}) \qquad \textbf{\textit{(E4.18f)}}$$

3. E4.18f is substituted in E4.18e resulting in E4.18g. This relates $CH_{4\,(g)}$, $CO_{2\,(g)}$ and HCO_3^-

$$[CH_4]_g = [CO_2]_g\left(\frac{K_H}{[HCO_3^-](10^{pK_{c1}-pH})} - 1\right) \qquad \textbf{\textit{(E4.18g)}}$$

4. Then Substituting the specific solution for the AD products from the stoichiometry which include the f value from E4.18b for $CH_{4\,(g)}$, $CO_{2\,(g)}$ and HCO_3^- into Eq. E4.18g incorporate f in Eq. E4.18g. This equation is then solved for f through an iteration procedure.

The above procedure simultaneously predicts pH and quantifies the AD products that are pH dependent. However, it was found that the predicted pH is different from that observed. This difference can be attributed to mineral precipitation that takes place inside the AD system while the steady state model excludes mineral precipitation.

The steady state AD model equation E4.18b is applied to determine the H_2O utilisation and the product generation of the anaerobic digestion of NDBEPR WAS. Although E4.18b is large and complex, the application is less complex because each component in the model is determined individually. The complexity arises from the size of the model as presented in E4.18b, which includes 10 components. These components consist of two reactants, the elemental composition of the NDBEPR WAS BPO and the H_2O utilized in the reaction, and 8 AD products, the AD active biomass ($C_5H_7O_2N_1P_{0.124}$), $CO_{2\,(g)}$, $CH_{4\,(g)}$, $HCO_3^-{}_{(aq)}$, $NH_4^+{}_{(aq)}$, $Me^+{}_{(aq)}$, $HPO_4^{2-}{}_{(aq)}$ and $H_2PO_4^-{}_{(aq)}$.

However the counter-ion metal component Me^+ is a combination of 3 metals i.e. Mg^{2+}, K^+ and Ca^{2+} i.e. approximately 0.27 mol Mg, 0.22 mol K and 0.12 mol Ca per mol P.

The theoretically predicted results are presented in Table 4.13, below. The overall comparisons of the measured and predicted results are discussed in detail in Chapter 5.

4.2.3.3. Comparing the Model Predicted Results to the Experimentally Measured Results

The model predicted results for the example calculation are compared to the experimentally observed results in this section. Some AD product component are referred to in their measured form i.e. FSA instead of NH_4^+ (as is predicted) and others are transformed in terms of their units i.e. HCO_3^- is changed to H_2CO_3* Alkalinity (as $mgCaCO_3$).

The AD system alkalinity is described by the Eq. E2.21d reported in Section 2.4.2. However, because the expected operational range of the pH of the AD system is between 6.6 and 8.0, some of the components of the carbon, phosphate and ammonium species remain negligibly small in this pH range resulting in Eq. E4.19 below (for use in this study),

$$H_2CO_3 / H_3PO_4 / NH_4^+ Alk = \left[HCO_3^-\right] + \left[H_2PO_4^-\right] + 2\left[HPO_4^{2-}\right] \tag{E4.19}$$

The experimentally measured and theoretically predicted results are presented in Table 4.13 below.

Table 4. 13: AD Measure vs. Model Predicted Results

Character	Measurement Units	Measured	Predicted
COD (total)	***mgCOD/l***	6702.6	6747.5
VSS	***mgVSS/l***	4737.7	4603.0
TKN (total)	***mgN/l***	551.6	550.9
FSA	***mgN/l***	120.2	206.8
TP (total)	***mgP/l***	906.0	919.4
Ortho-P	***mgP/l***	525.4	753.8
Mg (Soluble)	***mg/l***	23.80	198.64
K (Soluble)	***mg/l***	355.75	322.89
Ca (Soluble)	***mg/l***	43.35	45.12
pH		6.80	7.30
H_2CO_3* Alkalinity	***mg as $CaCO_3$/l***	274.0	251.0
H_3PO_4 Alkalinity	***mg as $CaCO_3$/l***	431.0	1722.5
CH_4	***mmol/d***	50.21	50.83
CO_2	***mmol/d***	27.49	33.95
Carbon in CH_4	***mgC/l***	374.15	412.46
Carbon in CO_2	***mgC/l***	204.70	264.70
COD removed	***mg/l***	2652.9	2439.8
Possibility of Struvite Prec. (Pred. - Measure)	***moles/l***	6.19	
	moles/l	7.37	
	moles/l	7.29	

The COD, TKN, TP, K and Ca concentrations determined from the application of the steady state model compare well with those measured. Furthermore, the measured CO_2 and CH_4 gas flux (moles/day) are acceptably closely predicted by the stoichiometric model. However, variations are observed in the theoretically predicted Mg, ortho-P and FSA concentrations compared with those observed from the experimental investigation at the 12 day sludge age (R_s). The predicted concentrations are much greater than those measured. On further evaluation of components that vary and the differences in quantities between the measured and predicted results, struvite formation is suspected. This can be confirmed by determining the struvite precipitation potential as discussed in Section 2.4.4 and will be described in more detail below.

4.2.3.4. Determining the struvite precipitation potential

As described in Section 4.2.2.1 the stoichiometry results are the products of AD in the aqueous and gaseous phases (two phase model) and as such some of these results may not be directly comparable with the measured results when precipitation takes place (three phase system). The struvite precipitation potential can be determined from the results of the model as described in Section 2.4.4. If this method indicates possible precipitation, the precipitation can be quantified using the precipitation models. From literature, the most probable precipitant that can occur is struvite and this relates to a difference between the aqueous phosphate, magnesium and ammonium concentrations of the measured and calculated results.

This precipitation potential of the experimental AD setup and the products determined from the application of the steady state model are determined from the method described in Appendix B3. The input variables to this are the FSA, Mg and PO_4^{3-} concentrations of the AD system. The FSA and Mg concentration are obtained directly from measurements or the results of the steady state model. However, the PO_4^{3-} concentration is attained from the weak acid/base chemistry equilibrium equations E2.19 d to f. This is also a dynamic process that refers to the system shifting the equilibrium to replace the PO_4^{3-} in solution to equilibrium when precipitation has occurred. The outcome of the precipitation potential calculation represents the initial potential for struvite formation.

In this case, it is estimated that between 6.19 and 7.37 mmoles of struvite per day possibly formed. The precipitation potential calculation for struvite can be used to confirm whether conditions existed within the AD environment for struvite formation. This and other outcomes from the experimental measurement vs. theoretically predicted results will be presented and discussed in Chapter 5.

4.2.3.5. A diagram describing the anaerobic digestion process

Figure 4.4 is included to provide a visual impression of the changes in solid, aqueous and gas phases that take place during the anaerobic digestion of NDBEPR WAS.

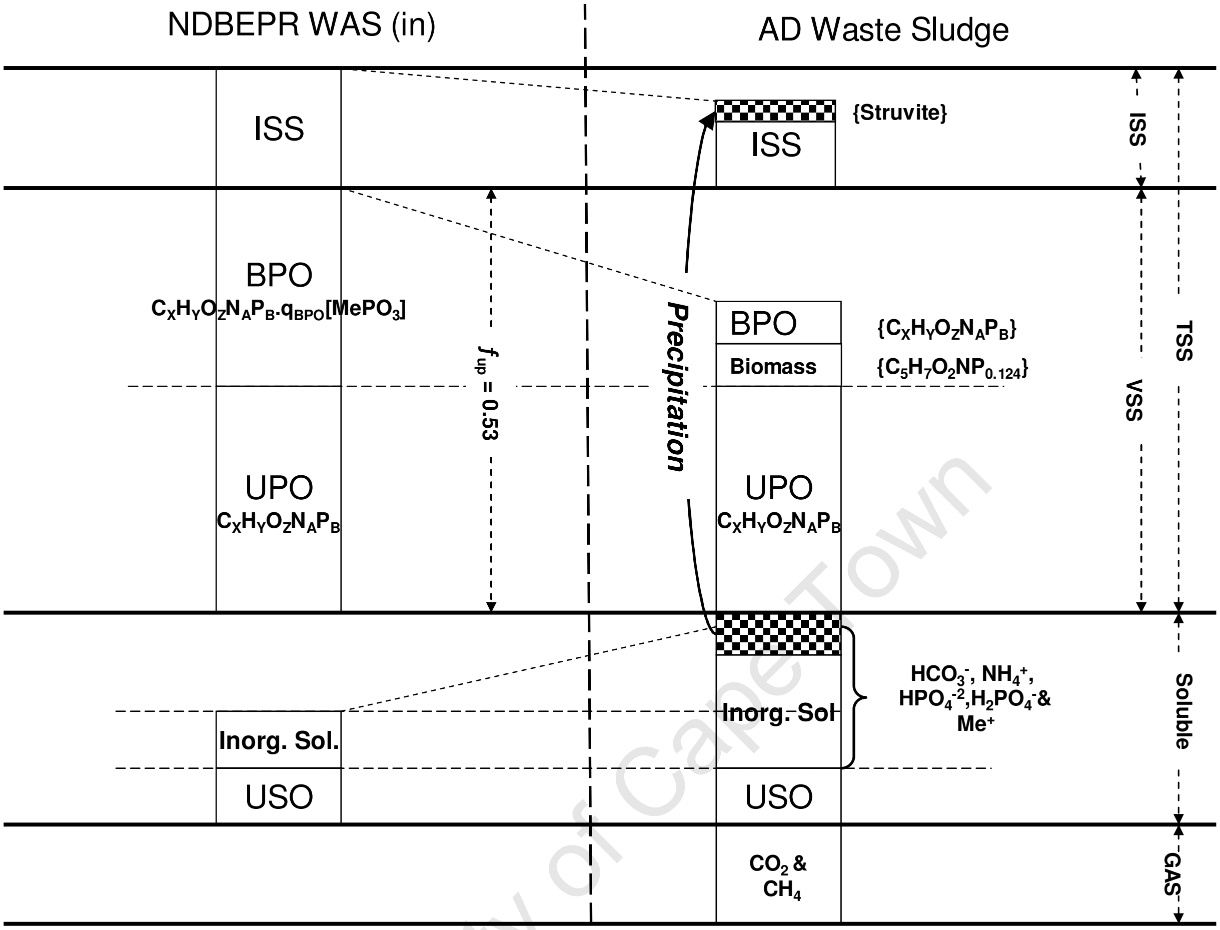


Figure 4.4: Diagram describing the Anaerobic Digestion of NDBEPR WAS

The highlighted section shows the components of struvite (based on the assumption that struvite is the only mineral precipitate formed) in the soluble form. Polyphosphate hydrolysis reduces the ISS and increase the dissolved inorganics. The arrow indicating precipitation shows that when struvite forms, it adds to the ISS in the AD system. Another important process shown is that the residual BPO in the AD effluent (waste) sludge does not contain polyphosphate as this is all released at $R_s < 10$ days.

4.2.3.6. Comparing the Unbiodegradable Particulate Organics (UPO) of WAS

One of the aims of this study is to compare UPO component (S_{upi}) determined for the AS system and used as the UPO fraction of the influent WAS with the UPO fraction measured in the AD system operated at a long enough sludge age so that only the UPO (and a little AD biomass) remained in the effluent sludge. The UPO fraction measured on the 60 day AD was applied to the feed of the 12 day steady state AD. Then the UPO fraction determined from the wastewater characterization and AS VSS fractionation procedure is compared with those obtained from the AD hydrolysis model and 60 day sludge age AD system to investigate whether or not unbiodegradable organics from the AS system remain unbiodegradable in the AD system. The S_{up}, based on the AS system, are determined by applying Equation E4.2c, in terms of COD concentration as described in Section 4.1.1.2a. The UPO in terms of VSS concentration is determined by using Eq. E4.2a also but excluding the COD/VSS ratio (f_{cv}).

To determine the S_{bp} utilized (BPO in terms of COD concentration) during anaerobic digestion, the residual S_{bpe} has to be determined first for the specific R_s. This is done by applying the steady state hydrolysis kinetic models presented in Section 4.2.3, which requires the S_{bp} or BPO component of the WAS to be known. The S_{bpi} is determined from an initial f_{up} estimate as explained in Section 4.2.3 above, i.e.

$$S_{bpi} = S_{ti} - S_{up(AD)} \quad \text{or} \quad f_{up(AD)}.S_{ti} \quad \text{where} \quad f_{up(AD)} = \frac{S_{up}}{S_{tb}} \qquad \textbf{\textit{(E4.19)}}$$

The results in terms of COD and VSS concentrations for the UPO and BPO are presented in Table 4.14 below. For the 12d AD system, the UPO obtained from the AS system and the AD system are quite similar.

Table 4.14: The UPO (AS & AD) and BPO (determined by difference)

Unit Operation	UPO		BPO	
	COD conc.	VSS conc.	COD conc.	VSS conc.
	mgCOD/l	*mgVSS/l*	*mgCOD/l*	*mgVSS/l*
Activated Sludge	4920.0	3442.1	4446.9	3073.3
Anaerobic Digestion	5226.4	3661.1	4129.0	2808.6

Comparison and discussion of all the measured and calculated UPO and BPO results will the covered in Chapter Five (Results and Discussion). The utilized BPO (S_{bp}) at the different AD sludge ages are also discussed in Chapter 5.

4.3 Application Boundaries

During the development of the steady state AD model, some parameter limitations were incorporated. These limitations result in boundaries of application of this model.

This steady state AD model was developed for WAS with high particulate organics (PO) content and low soluble organic concentrations, both biodegradable, BSO, and unbiodegradable, USO. Therefore, it is not known how NDBEPR WAS with high BSO and USO concentrations will change the hydrolysis kinetic rate and stoichiometry of this model. The kinetics of polyphosphate hydrolysis and polyphosphate related products release is approached differently from the organics hydrolysis rate within the AD model. The hydrolysis of polyphosphate is complete in less than 7 days as described by Jardin *et al.* (1994) and the batch tests done for this purpose in this investigation. At the shortest sludge age of this study (10 days) all polyphosphate was hydrolysed and released to the bulk liquid. It was therefore concluded that all the polyphosphate contained by the BPO component of the NDBEPR WAS is released to the bulk liquid at all of the steady state sludge ages (10 to 60 days) within this study. The polyphosphate hydrolysis was setup so that all phosphate from polyphosphate is released at all R_s of this study. However, if the R_s of the AD is less than 7 days, which is not very likely in practice, accepting complete polyphosphate release as in this study would not be valid.

The extended stoichiometric part of the AD model does not predict precipitation formation within the AD system treating NDBEPR WAS. However, the precipitation potential of the AD products in the aqueous phase were tested by determining the aqueous phase ionic products and comparing these with the thermodynamic solubility product (K_{spm}) of the mineral precipitant struvite, which is most likely to form under the AD conditions. While the potential for mineral precipitation in the experimental AD system based on precipitation potential calculations was assessed, quantifying mineral precipitation was beyond the scope of this Masters Degree Research project. The mineral precipitation phase can be included in the steady state AD model developed using data from this study. Furthermore, models from previous studies by Loewenthal *et al.* (1994), Musvoto *et al.* (2000) and van Rensburg *et al.* (2003) can be applied using the inorganic soluble products from this AD model stoichiometry as input variables.

4.4 Closure

This chapter presented the development of the procedure by which NDBEPR WAS is characterized in its elemental composition in the form $C_XH_YO_ZN_AP_B$. $q_{PAO}[MePO_3]$. This was achieved by utilizing analytical measurements as input values to conventional steady state AS models that fractionates the VSS into its five components. These results were then grouped to the required biodegradable and unbiodegradable forms for use as input to the steady state AD model. The calculation procedure was demonstrated with the average data from sewage Batch 14 fed to the UCT MBR NDBEPR system with the WAS fed to the 12 day sludge age AD system. In Chapter 5 (Results and Discussion), the results obtained for the sewage batches 3 to 14 and the AD sludge ages 10 to 60 days will be reported and then further discussed.

This chapter described the development of the stoichiometry part of the AD model for anaerobic digestion of NDBEPR WAS. The fractionation and composition of the UPO for the AD reactor were obtained from experimental measurements at a steady state sludge age of 60 days. The kinetic constants for the hydrolysis rate of BPO were determined by Ikumi *et al.* (2009) for the AD of NDBEPR WAS and were applied to determine the residual BPO not hydrolysed and that utilized during the AD process. Some of the results from the steady state AD model were used as input variables to determine whether or not the ionic products of the aqueous phase AD products indicate the possibility of mineral precipitant formation. However, the steady state model results do not quantify the mineral precipitants formed inside the AD system during the normal operation. The inclusion of the precipitation phase is beyond the scope of this study.

The example calculation in this chapter indicated that the UPO determined from the AS system ISS characterization matched quite closely that measured in the 60 day R_s AD. This shows that the UPO of the AS remains unbiodegradable within the AD system. However, in this chapter this is only demonstrated for the sewage batch 14. A more general conclusion can only be made when the UPO of all other AS batches are determined and evaluated in Chapter 5.

CHAPTER FIVE
RESULTS AND DISCUSSIONS

This chapter presents and discusses the experimentally measured (observed) and model determined (predicted) results from the UCT membrane (MBR) NDBEPR AS system and the anaerobic digester fed the WAS from this system. The measured and predicted results from this study are discussed in context of increasing AD sludge age. Where available, the results are also compared with findings reported in the literature. However, before the experimentally measured data are used as input variables to the AS and AD models they are evaluated by performing mass balance checks over the experimental AS and AD systems.

The experimental measurements collected in this study were obtained from the UCT MBR AS system and the anaerobic digester coupled to it as shown in Figure 3.1. The setup of these units was described in detail in Chapter Three. The AS system was fed 12 sewage batches (3 to 14) over the duration of the experimental investigation over a period starting in July 2007 and ending in November 2008. Sewage Batches 1 and 2 were fed during the start up period of the experimental investigation to achieve steady state operation of the AS system. Because the measured data for these 2 batches were irregular they were excluded from the data of this study. As previously described in Chapter Three, the UCT AS system was operated at a steady state sludge age of 10 days throughout the duration of the experimental investigation. The results from the AS system are named according to the sewage batch number fed during the sampling period starting at Sewage Batch 3 up to Sewage Batch 14 for the overall experimental investigation period. For instance, the 12 day AD sludge age (R_s) example used in Chapter Four, refers to the AD system operated at a steady state R_s of 12 days but the sewage batch fed to the UCT MBR AS system during this period was Sewage Batch 14. The sewage batches fed to the AS system during the different AD sludge ages are listed in Table 5.1.

The AD system was fed the WAS from the UCT AS system. The AD system was operated at 7 different steady state sludge ages (R_s). At each steady state sludge age, AD performance data were measured. These measured data sets were named according to the steady state R_s of the AD system. The AD system was operated at 10, 12, 18, 20, 25, 40 and 60 day sludge age. Five of these AD steady state R_s experimental data sets i.e. 10, 18, 25, 40 and 60 day sludge age, were used to calibrate the AD model and the two (12 and 20 R_s) conducted at the end of the investigation were used to validate the AD model.

This chapter firstly evaluates the quality of the experimentally measured data sets for the AS and AD systems. This is done by performing material mass balances over the experimental systems for each sewage batch in the case of the AS system and for each steady state R_s in the case of AD system. This is followed by presenting the results of the AS system WAS characterization described in Section 5.2. The elemental compositions of each component of the NDBEPR WAS, i.e. the PO, BPO and UPO, are also determined for each AD sludge age in this section. The BPO elemental composition is then used as one of the input variables to the stoichiometry part of the AD model developed in Chapter Four. Finally, Section 5.3 presents and discusses the measured, calculated and predicted results from the anaerobic digester.

5.1 Material Mass Balances

Material mass balances were preformed on the experimentally measured data over the AS and AD systems for COD, N, P, Mg, K and Ca. For the AS system sewage batch average data were used for this. For the AD system the different sludge age average data were used. Furthermore, carbon material mass balances were performed at the different sludge ages for the AD system based on the carbon produced by the AD system in the form of CO_2 (dissolved and gaseous) and CH_4 and the carbon content of the BPO component of the WAS, where the carbon content of the BPO components was determined by difference from assumed C content of the VSS (PO) and UPO components, at 0.52 and 0.51 respectively. These mass balances help evaluate the quality of the measured data sets based on mass continuity of the specific measured component over the system. The calculation procedures to determine the mass balance for component are described in Appendix B1.

Table 5.1 presents the name of each experimental data set, the start and end dates of the period, the number of samples collected and analysed during the period and the Appendix where this data are listed.

Table 5. 1: Batch No., Experimental Period, Operational Unit, Number of Samples and Measured

Sewage	AD SS	Date		Number of Sample		Measured Data Reported	
Batch No.	**Sludge age**	**Start**	**Complete**	**AS**	**AD**	**AS**	**AD**
Batch 3	**None**	17-Jul-07	25-Jul-07	5	None	Appendix A.1.1	None
Batch 4	**None**	31-Jul-07	8-Aug-07	5	None	Appendix A.1.2	None
Batch 5	**None**	11-Sep-07	21-Sep-07	6	None	Appendix A.1.3	None
Batch 6	**None**	23-Sep-07	14-Oct-07	6	None	Appendix A.1.4	None
Batch 7	**None**	25-Oct-07	13-Nov-07	6	None	Appendix A.1.5	None
Batch 8	**None**	20-Nov-07	29-Nov-07	5	None	Appendix A.1.6	None
Batch 9	**None**	20-Dec-07	31-Dec-07	6	None	Appendix A.1.7	None
Batch 10	**18 Day**	31-Mar-08	8-Apr-08	5	10	Appendix A.1.8	Appendix A.2.3
Batch 11	**60 Day**	2-Jun-08	12-Jun-08	6	10	Appendix A.1.9	Appendix A.2.7
Batch 12	**40 Day**	25-Jun-08	4-Jul-08	5	10	Appendix A.1.10	Appendix A.2.6
Batch 13	**25 Day**	18-Aug-08	28-Aug-08	5	10	Appendix A.1.11	Appendix A.2.5
Batch 14	**10 Day**	26-Oct-08	2-Nov-08	5	10	Appendix A.1.12	Appendix A.2.1
Batch 14	**12 Day**	26-Oct-08	2-Nov-08		6		Appendix A.2.2
Batch 14	**20 Day**	26-Oct-08	2-Nov-08		6		Appendix A.2.4

5.1.1 Mass balance on the UCT membrane Activated Sludge system

A summary of the mass balances performed over the UCT MBR AS system for Sewage Batches 3 to 14 are presented in Table 5.2a. These mass balances were performed on the experimentally measured data sets for the COD, N, P and the polyphosphate counter-ion metals, Mg, K and Ca from the NDBEPR AS system. These mass balances compare the exiting fluxes via the effluent and waste sludge flows of a specific component with its influent flux via the influent flow. For reliable results these mass balances should be as close to 100% as possible.

Table 5. 2 a & b: UCT Membrane AS Material Mass Balances

5.2a :UCT Membrane AS Material Mass Balances						
Sewage	**Components of % Mass Balance**					
Batch No.	**COD**	**TKN**	**TP**	**Mg**	**K**	**Ca**
Batch 3	97%	109%	90%	***Used Batch 6 measurements***		
Batch 4	102%	112%	95%			
Batch 5	96%	109%	98%			
Batch 6	92%	131%	94%	81%	101%	82%
Batch 7	91%	108%	94%	***Used Batch 6 measurements***		
Batch 8	95%	112%	95%			
Batch 9	105%	98%	95%			
Batch 10	101%	101%	96%	77%	102%	102%
Batch 11	92%	115%	97%	100%	101%	100%
Batch 12	102%	120%	94%	88%	102%	105%
Batch 13	99%	92%	105%	86%	102%	109%
Batch 14	110%	81%	95%	89%	102%	84%

The COD mass balances determined for the different sewage batches fed to the AS system vary within 10% from the target 100% balance throughout the duration of the experimental investigation. These COD balances are in fact better than several other studies on NDBEPR AS systems at UCT (Ekama and Wentzel, 1999) and so are acceptable mass balances for the COD concentration and OUR measurements. The TP mass balance over the AS system varies within an acceptable 5% range from the target. The COD and TP mass balances, which are the most important for this study, are presented graphically in Figures 5.1a and 5.1b below.

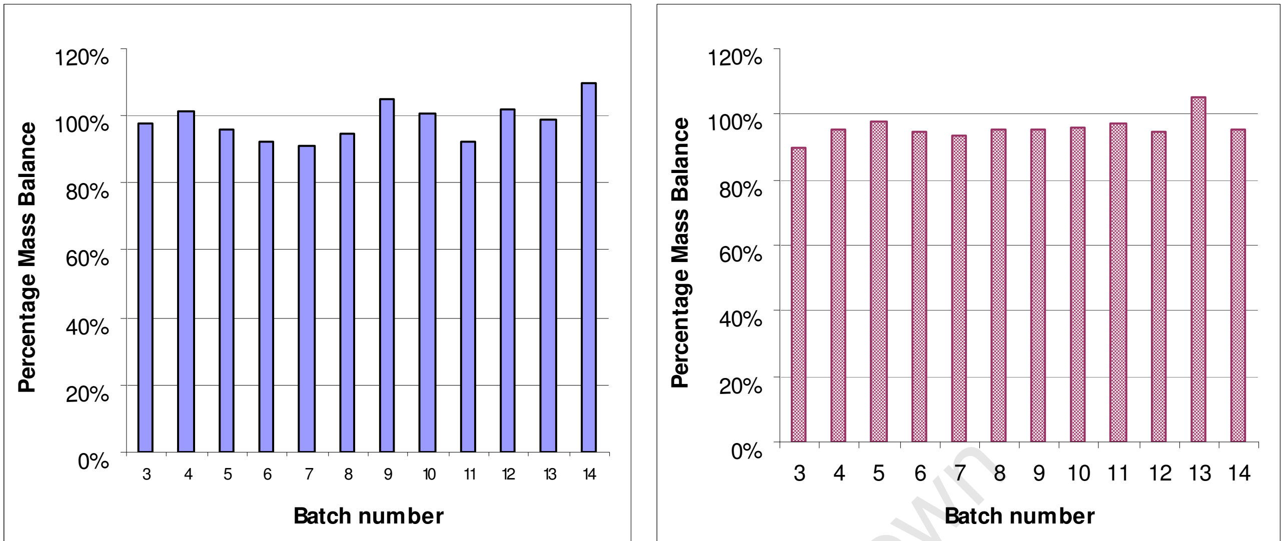


Figure 5.1a: Activated Sludge COD Mass Balance

Figure 5.1b: Activated Sludge TP Mass Balance

Figure 5. 1*a & b: The COD and TP Mass Balances as per Sewage Batch.*

The variation of the COD mass balance shown in Figure 5.1a is reasonably consistent around a 100% balance. The overall average of the COD mass balance over the 12 sewage batches is 98.5%.

The TP mass balance shown in Figure 5.1b also remains fairly constant throughout the experimental period. The range of the mass balance results are between 90% (Batch 3) and 105% (Batch 13). The overall average TP mass balance was 96% for the AS system through out this experimental investigation. Once again, these mass balance results are acceptable considering the high dilution required (20 x) to measure the TP of the WAS.

The N mass balance varies significantly but for the most part still remained within a 20% range of 100%. This larger target range was set because the N balance is very sensitive to the recycle ratio from the aerobic to the anoxic reactors of the AS system. If the nitrate concentration is in error by say 0.5 mgNO_3-N/ l in the aerobic reactor, this can make a 5% difference to the N mass balance over the AS system because the estimate of the nitrate concentration denitrified in the anoxic reactor will change by that much. The N balance for Sewage Batch 6 was the only mass balance outside the 20% range and initially this was the reason why Sewage Batch 6 was be used as the10 day R_s test for the AD system. Provide the N content of the VSS (f_N) is close to

0.10 mgN/mgVSS, the N balance is the least important in the project because the nitrate denitrified in the UCT system is of little concern for the anaerobic digester. What is important for the digester is the N composition of the AS which was directly measured on the WAS. Although this means that the N mass balance of Sewage Batch 6 is acceptable for the AD model at the 10 day AD test sludge age, this trail was already repeated at the stage that this data was found to be acceptable for use.

The counter-ion metals, Mg, K and Ca in the AS system were only tested on the AS system when the AD system was tested. The sample preparation procedure for these metals was similar to that of the TKN analysis as described in Section 3.3. The dilution ratio requirements for these samples were very larger. Consequently, errors in the dilution and analysis could have caused some of the inconsistencies in the measured results determined for these metals. The mass balances results varied within 20% of the 100% balance for most sewage batches, which were regarded acceptable for these measurements, because the mass balance is dependent on a small difference between two large (influent and effluent) concentrations.

Overall, the quality of the data collected from the UCT membrane AS system during this investigation were regarded to be reasonably consistent and good for the COD and TP, and although more varied for the N and polyphosphate counter-ion metals these also are acceptable. Where relevant, the mass balances results will be taken into account when comparing the predicted results, which are based on 100% mass balances relative to the measured influent results to the AS and AD systems.

5.1.2 Mass balances over the Anaerobic Digester

Table 5.2b presents results from the mass balances performed over the anaerobic digestion system at the various steady state sludge ages. These mass balance results are evaluated and discussed in detail below. Similar to the UCT AS system, mass balances for the COD, TKN, TP, TC and counter-ion metal (Mg, K and Ca) fluxes entering and existing the AD system are presented in Table 5.2b.

5.2b: Anaerobic Digester Material Mass Balances								
Data Set	**AD SS**	**Components of % Mass Balance**						
Application	**Sludge Age**	**COD**	**TKN**	**TP**	**TC**	**Mg**	**K**	**Ca**
Model Calibration	**10 Day**	100%	108%	105%	91.7%	96%	77%	85%
	18 Day	99%	98%	100%	91.7%	102%	80%	80%
	25 Day	100%	100%	87%	92.2%	103%	91%	91%
	40 Day	98%	104%	106%	92.1%	80%	84%	85%
	60 Day	98%	87%	93%	92.1%	98%	101%	86%
Model Validation	**12 Day**	101%	108%	104%	90.3%	107%	98%	86%
	20 Day	104%	106%	104%	96.7%	116%	93%	85%

The COD and TP mass balances are shown graphically in Figures 5.1c and d. This is done because the experimentally measured data for these parameters are used in the calibration and validation of the steady state AD model. A large deviation in the mass balance of the COD, N and P components would influence the concentrations of the calculated COD utilisation during the anaerobic digestion of NDBEPR WAS. Inconsistencies in the mass balance obtained for the experimentally measured COD results can negatively affect the results determined from the application of the steady state AD model and as a direct consequence also the result for the products of digestion.

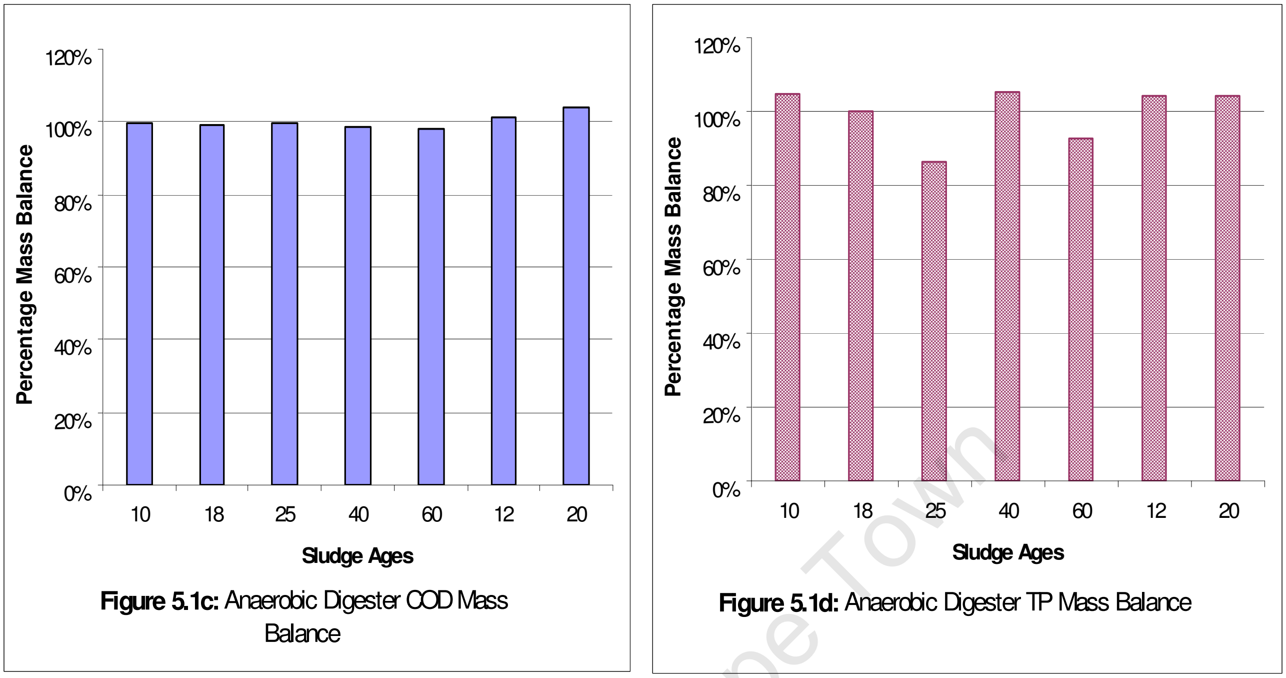


Figure 5.1c: Anaerobic Digester COD Mass Balance

Figure 5.1d: Anaerobic Digester TP Mass Balance

Figure 5.*1c & d: The Anaerobic Digestion COD and TP Mass Balances*

The COD mass balance over the AD system deviate only a maximum of 3% from the target 100%. This very good mass balance result shows the COD measured data are reliable and acceptable for calibrating and validating the steady state AD model. The TP mass balance varied much more but still is within 10% of the100% balance for most steady states. The TP mass balance exception is the 25 day steady state R_s at only 87% TP recovery. This inconsistent result for the TP mass balance will be considered in context of the general trend of the actual TP measurement obtained for all the steady state sludge ages during the investigation (the sequence of the AD sludge ages in Figures 5.1c and d is the chronological order of the sludge ages at which the AD was operated).

The TKN, Mg, K and Ca mass balance results are shown in Figures 5.1 e, f, g and h respectively.

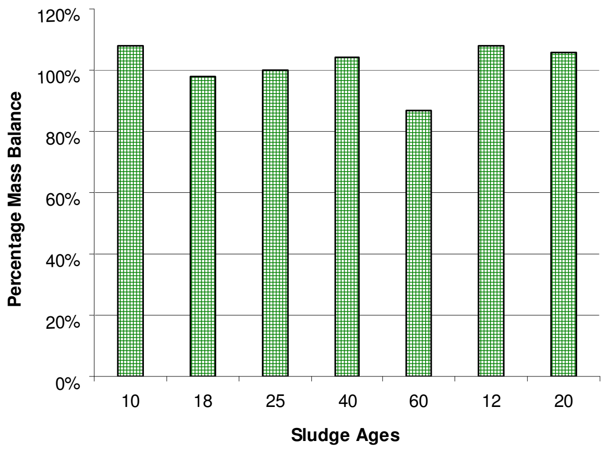


Figure 5.1e: Anaerobic Digester TKN Mass Balance

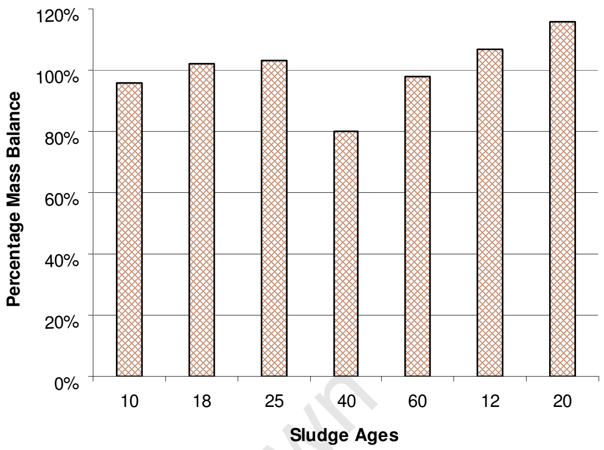


Figure 5.1f: Anaerobic Digester Mg Mass Balance

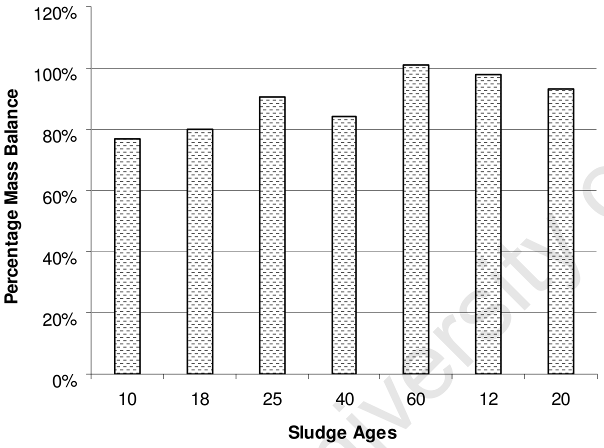


Figure 5.1g: Anaerobic Digester K Mass Balance

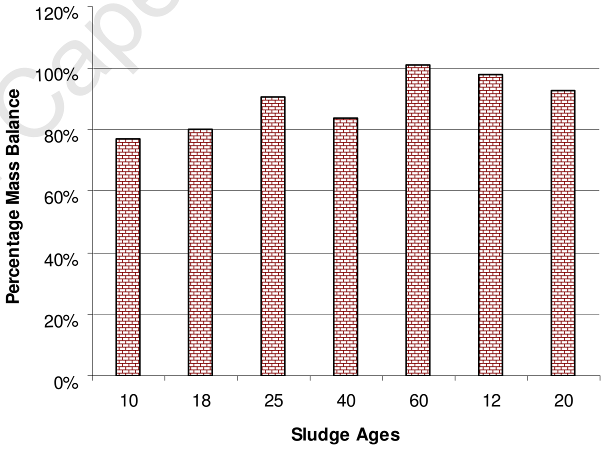


Figure 5.1h: Anaerobic Digester Ca Mass Balance

Figure 5.*1e, f, g & h: The Anaerobic Digestion TKN, Mg, K and Ca Mass Balances*3

The TKN mass balance for all steady state sludge ages deviate less than 10% from the 100% target balance except for the 60 days steady state R_s. However, a 13% deviation is still acceptable and has been considered in the calibration process of the steady state model. The component mass balance for Mg is consistently close to the 100% except for the 40 day steady state R_s at 80%. The K and Ca mass balances were found to vary between the 80% to 100% range for most sludge ages. The mass balance deviations will be considered when the measured and predicted data for these components are compared. Since, the TKN and metal components are not used as calibration components for the steady state model for the AD of NDBEPR WAS, their impact on the model is not significant. The mass balances for these components are therefore acceptable for the purpose of this study.

Also, material mass balance was performed for the carbon fractions allocated to some the measured data on the AD system only. This was done to evaluate whether the Carbon (C) fractions (f_C) assumed in Section 4.1.1.2c, for the VSS (PO) (0.52) and UPO (0.51) components and then calculated for the BPO were acceptable. The carbon mass content of the influent to the AD system was determined from the carbon content (f_C, mgC/mgVSS) of the VSS concentration and the H_2CO_3* Alk. of the influent WAS. In the case of the WAS and biogas exiting the AD system, the carbon content of the UPO, residual BPO, effluent H_2CO_3* Alk., CH_4 and CO_2 gas were determined. The anaerobic digestion biomass also contains C but this component of the effluent sludge could not be directly measured and so could not be included to this mass balance. However, based on the AD model predicted results the carbon content of the AD biomass contributes at most 4% of the carbon content of the effluent from the AD system. Furthermore, this carbon balance would be adversely affected if carbon based mineral precipitation (like $CaCO_3$ or $MgCO_3$) occurs within the AD system. Figure 5.1i below shows the carbon mass balance (based on assumed f_C allocated to the VSS (PO) and UPO).

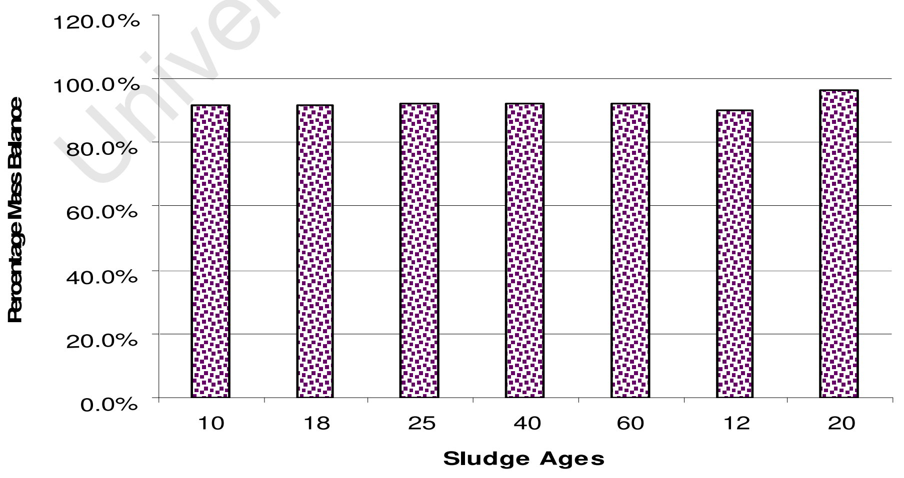


Figure 5.1i: Anaerobic Digester Carbon (C) Mass Balance

Figure 5.*1i: The Anaerobic Digestion Carbon [C] Mass Balances*

The C mass balance over the AD system has a mean balance of 92.7% and deviates less than 10% from the target 100%. Although the C content of the biomass was excluded from this carbon balance, this accounts for only about 3% less on the deviation. These are good mass balance results for the C content of the measured data and so are reliable and acceptable for use in the steady state AD model. These Carbon mass balance results confirmed the mass fraction (f_C) assumed for the VSS and UPO components as justification and acceptable for this study.

5.2 WAS VSS fractionation and Elemental Composition Calculation

Section 5.2 presents and discusses the results determined of the UCT MBR AS system. The procedure to determine these results is described in Section 4.1. The results from the influent and NDBEPR WAS characterization as described in Section 4.1.1.1 and 4.1.1.2 a to c is presented in Section 5.2.2a to c in this section. The results of the elemental composition calculation described in Section 4.1.2 is presented in Section 5.2.2d of this chapter. The results obtained from the VSS fractionation procedure are evaluated against the measurements of the influent wastewater that most significantly affect them. The influent wastewater unbiodegradable particulate COD fraction (f_{upi}) obtained from the VSS fractionation is compared with the values obtained on previous studies.

The results from the VSS fractionation calculation with the Wentzel *et al.* (1990) steady state NDBEPR AS model and the ISS model are presented and discussed. These results relate to the calculated active, endogenous and inert masses of the NDBEPR WAS from the AS system for Sewage Batches 3 to 14. The results for the extended characterization to determine the PO, UPO and BPO components for each of the sewage batches are presented and discussed thereafter in Section 5.2.2. Finally, the PO, UPO and BPO components of the VSS are transformed to their elemental compositions that include carbon, hydrogen, nitrogen, oxygen and phosphorus of the organic particulate components. The elemental compositions of the relevant PO components are extended to include the inorganic polyphosphate elemental composition. The elemental compositions in the form $C_XH_YO_ZN_AP_B$ so determined for each of the components for the different Sewage Batches and elemental compositions in the form $C_XH_YO_ZN_AP_B.q_{BPO}[MePO_3]$ for the BPO components.

The full array of analytical measurements are presented in Appendix A1 for the experimental AS system and listed in individual tables based on the sewage batch number. The averages for the Sewage Batches were determined and are presented in rows for the specific sewage batch number.

5.2.1 AS influent (wastewater) characterization and VSS fractionation

The results for the analytical measurements and characterization of the influent are presented in this section. The mean measured COD, TKN and TP concentrations (mg/l) for each sewage batch are shown in Table 5.3a. Figure 5.2 shows a plot of the measured average influent COD concentration and target influent COD. Also, Table 5.3a presents the COD fractions for the influent unbiodegradable particulate organics COD (f_{upi}), unbiodegradable soluble organics COD (f_{usi}) and the readily biodegradable COD (f_{tbsi}) all with respect to the total COD (S_{ti}).

Table 5.3a: ***Influent Characteristics***

Sewage	S_{ti}	N_{ti}	P_{ti}	f_{upi}	f_{usi}	f_{tbsi}
Batch No.	*mgCOD/L*	*mgN/L*	*mgP/L*			
Batch 3	**843.8**	**77.2**	**61.1**	**0.17**	**0.04**	**0.33**
Batch 4	**795.0**	**76.3**	**51.1**	**0.22**	**0.06**	**0.27**
Batch 5	**792.0**	**74.6**	**50.6**	**0.21**	**0.01**	**0.34**
Batch 6	**826.7**	**45.0**	**55.6**	**0.19**	**0.04**	**0.32**
Batch 7	**753.9**	**44.1**	**59.5**	**0.25**	**0.03**	**0.33**
Batch 8	**699.6**	**65.9**	**55.1**	**0.25**	**0.06**	**0.34**
Batch 9	**754.9**	**68.8**	**61.2**	**0.19**	**0.04**	**0.36**
Batch 10-18	**790.5**	**45.0**	**57.0**	**0.18**	**0.04**	**0.37**
Batch 11-60	**826.7**	**45.0**	**55.6**	**0.19**	**0.04**	**0.32**
Batch 12-40	**794.5**	**46.2**	**55.3**	**0.16**	**0.02**	**0.30**
Batch 13-25	**751.4**	**52.4**	**59.0**	**0.19**	**0.05**	**0.37**
Batch 14-10	**763.2**	**62.4**	**55.1**	**0.17**	**0.05**	**0.32**

The measured readily biodegradable (f_{tbsi}) and the unbiodegradable soluble (f_{usi}) COD fractions are used as input variables to the steady state BEPR AS model to fractionate the NDBEPR WAS

VSS. The unbiodegradable particulate COD fraction (f_{supi}) is varied until the calculated mass of VSS in the UCT MBR AS system matches that measured. Once the correct f_{upi} is found, the VSS is also correctly fractionated into its active (OHO and PAO), endogenous (OHO and PAO) and inert (X_I) components.

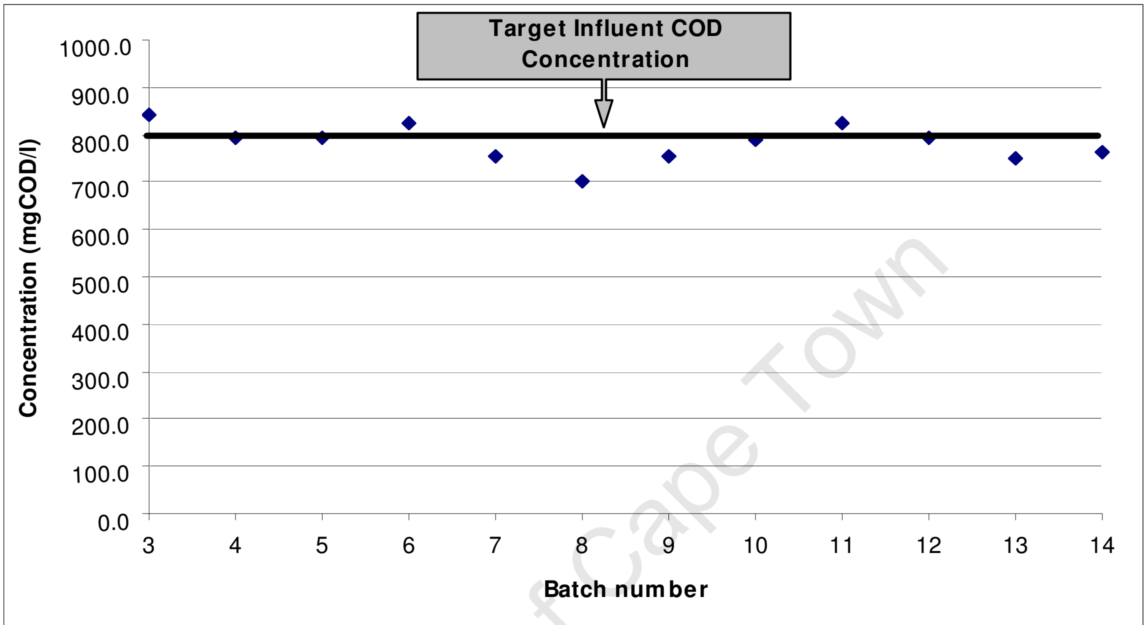


Figure 5.2: Influent COD concentration

Figure 5. 2: Influent COD concentrations

The target influent COD concentration to the UCT MBR AS system was set at a concentration of 800 mg COD/l that is made up of 600 mgCOD/l of real wastewater and 200 mgCOD/l of sodium acetate. The measured average influent COD for the AS system for all the sewage batches was 782.7 mgCOD/l with a standard deviation of 40 mgCOD/L. 92% of the feed sewage batches are within 50 mgCOD/L of the target COD. This means that the feed COD content varies less than 10% off the target COD. However, Sewage Batch 8 with an average COD concentration of 700 mgCOD/l falls outside the 10% deviation from the target feed COD concentration. The reason for this is that the sewage collected from the Mitchell's Plain WWTP was only about 500 mg/l before the 200 mgCOD/l Acetate addition. The data collected during this period was not used to calibrate the steady state AD model. As a norm the feed COD concentration to the AS system varied within an acceptable range to establish constant flow and load conditions.

The influent TP remained reasonably consistent throughout the overall duration of the experimental run. The TKN concentration of the influent feed was high at the initial stages of experimentation (Sewage Batches 3 to 5) because NH_4Cl was dosed to the feed during these periods. This was done to maintain an influent TKN / COD concentration ratio of close to 0.1 mgN/mgCOD which was the case for the feed to the MLE system of the parallel investigation by Ikumi *et al.* (2009). As part of the original objectives, the feed characteristics for the UCT and MLE AS systems were kept closely the same to compare the results from these systems. This was a requirement of the studies done in the parallel work by Ikumi et al. (2009). Because the N removal kinetics in the UCT MBR AS system was of negligible importance to this investigation, NH_4Cl dosing to it was stopped from Sewage Batch 2.

The unbiodegradable soluble COD fraction (f_{usi}) of the feed remained small (0.02 to 0.06) and the readily biodegradable COD fraction with respect to the total COD (f_{tbsi}) remained relatively consistent at around 0.33. The influent unbiodegradable particulate COD fraction (f_{upi}) will be discussed in more detail in the next section.

5.2.2 AS WAS VSS Fractionation

The results obtained from the wastewater COD characterization procedure above also give the VSS fractionation results, which are presented and discussed in 4 steps, based on the layout of the procedure described in Chapter 4,

i. The collection and evaluation of the measured data from the aerobic zone of the AS system as described in Section 4.1.1.1.
ii. The fractionation of the WAS from the application of the steady state NDBEPR AS model as described in Section 4.1.1.2.
iii. The quantification of polyphosphate to mass fractions/ratios with the steady state NDBEPR models and determining the elemental composition and linkage factors for polyphosphate as described in Section 4.1.1.3.
iv. The calculation of the elemental composition of the WAS PO, UPO and BPO components and the counter-ion metals (represented by Me) as described in Section 4.1.2.

Some of the measured and calculated results from the application of this characterization procedure are presented in graphs to evaluate the general trends of the data from the UCT MBR

AS system. The trends shown in these plots should ideally be nearly linear due to constant flow and load operation but of course with real wastewater this is not possible so variations are expected due to variations in the characteristics of the sewage batches fed to the AS system throughout the duration of this experimental investigation. These influent sewage batch variations are evident in the graphs shown in Section 5.2.1 above.

A. Analytical measurement data from the Aerobic Zone of the AS system

The averages for each sewage batch for the measurements on samples taken from the aerobic zone of the UCT MBR AS system are presented in Table 5.3b. These measurements are used to determine the f_{cv} (COD/VSS), f_N (OrgN/VSS), f_P (OrgP/VSS) and f_C (TOC/VSS) for the overall PO (particulate organic) VSS of the NDBEPR WAS, which in turn is utilized as the input variables as described in Section 4.1.2 to determine the elemental composition of the PO.

The summary of measured data from the aerobic zone is presented in Table 5.3b according to Sewage Batch numbers. Average results for the COD, VSS, TKN, FSA, TP, Ortho P and the counter-ion metals (Mg, K and Ca) components are listed in Table 5.3b.

Table 5. 3b: Measured Data from Aerobic Zone of AS system (WAS Characterization)

Sewage	COD (S_t)	VSS (X_v)	TKN (N_t)	FSA (N_a)	TP (P_t)	OP (P_{Ortho})	Mg (X_{Mg})	K (X_K)	Ca (X_{Ca})
Batch No.	*mgCOD/L*	*mgVSS/L*	*mgN/L*	*mgN/L*	*mgP/L*	*mgP/L*	*mgMg/L*	*mgK/L*	*mgCa/L*
Batch 3	**10381**	**7067**	**661.4**	**1.79**	**734.5**	**27.4**	***Used Batch 6 measurements***		
Batch 4	**10023**	**6947**	**584.6**	**1.93**	**766.9**	**19.4**			
Batch 5	**10411**	**7184**	**575.4**	**1.84**	**843.0**	**5.9**			
Batch 6	**10201**	**6958**	**601.1**	**2.33**	**796.8**	**18.2**	**280.0**	**400.5**	**54.0**
Batch 7	**10139**	**7103**	**559.2**	**1.87**	**866.7**	**9.4**	***Used Batch 6 measurements***		
Batch 8	**9623**	**6682**	**463.1**	**1.85**	**866.6**	**17.8**			
Batch 9	**9508**	**6794**	**525.8**	**1.34**	**862.0**	**45.4**			
Batch 10-18	**10062**	**6921**	**598.6**	**4.31**	**914.5**	**19.6**	**290.9**	**494.0**	**54.0**
Batch 11-60	**10418**	**7168**	**670.1**	**5.09**	**921.9**	**18.9**	**279.3**	**401.8**	**56.4**
Batch 12-40	**10127**	**6990**	**576.2**	**4.97**	**838.0**	**16.4**	**313.1**	**447.9**	**52.9**
Batch 13-25	**9589**	**6583**	**596.4**	**4.90**	**988.5**	**24.8**	**289.5**	**442.3**	**58.5**
Batch 14-10	**9355**	**6482**	**550.5**	**1.85**	**866.6**	**18.8**	**235.7**	**400.0**	**50.7**

Figures 5.3a and b show the total COD (S_t) and VSS (X_v) of NDBEPR WAS. A S_t of 9986 mgCOD/l with a standard deviation of 374 mgCOD/l and an X_v of 6907mgVSS/l with a standard deviation of 228 mgVSS/l were found for the NDBEPR WAS as averages of all the measurements collected during the experimental investigation period. From the fairly even trend of the plots shown in Figures 5.3a & b it is reasonable to state the UCT AS system was operated at steady state during the investigation. The measured data for the WAS COD and VSS concentrations never exceeded a 10% variation from the system mean. Furthermore, this consistent WAS COD concentration lead to the feed WAS to the AD system being approximately constant and therefore comparable for all steady state AD sludge ages throughout the duration of experimental investigation. No linearization or other trending methods are required when different steady state sludge ages are compared. The total PO VSS concentration (X_v) (shown in Figure 5.3b) is used to determine the mass/VSS ratios (f_{cv}, f_N, f_P and f_C) for the elemental compositions of the PO components.

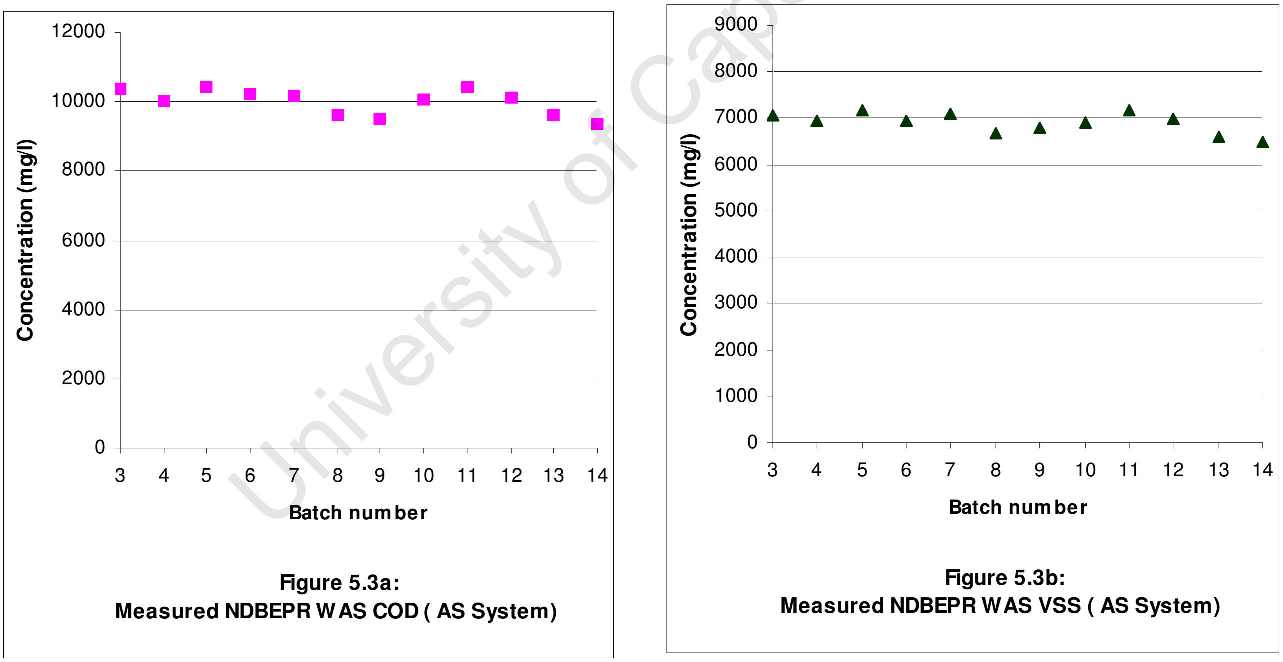


Figure 5.3a:
Measured NDBEPR WAS COD (AS System)

Figure 5.3b:
Measured NDBEPR WAS VSS (AS System)

Figure 5.3 a & b: the measured COD and VSS conc. of the NDBEPR WAS

The unfiltered TKN is virtually equal to the particulate TKN or equivalently organic nitrogen (Org. N) concentration of the solids because the dissolved TKN concentration is less than 1% of the unfiltered TKN and so negligible. The OrgN concentration measurements were found to vary quite considerably between 450 to 700 mgN/l. This could be the result of the inaccurate analytical methods or variable N content of the feed solids or both. The impact of this variable N content of the VSS on the elemental composition of the NDBEPR WAS PO component will be discussed in Section 5.2.2d below.

The sewage batch average measured unfiltered TP concentration results are also found to vary. However, this is the result of variation in the stored polyphosphate content of the PAOs as described in Section 2.2.2. This variation in P uptake and storage will be shown and discussed in Section 5.2.2c that deals with the characterization of polyphosphate. These measured results are also presented there with discussions on the variation of the results in context of the data application.

B. Fractionation of the WAS from the AS system

To fractionate NDBEPR WAS into its different components, the steady state AS model developed by Wentzel *et al.* (1990) was employed. This steady state AS model determines the active and endogenous (PAO and OHO) masses and inert mass composition of the WAS VSS as a consequence of determining the influent unbiodegradable particulate COD fraction (f_{upi}). This model is described in Sections 4.1.1.2 (application) and 2.2.2 (theory). These VSS components are used to determine the biodegradable particulate organic (BPO) and unbiodegradable particulate organic (UPO) components of NDBEPR WAS.

The results from these calculations are presented in Table 5.4a.

Table 5. *4a : Results from Fractionation Characterization computations (Wentzel et al., 1990)* 5

Sewage Batch Number	PAOs (X_{BG})	OHOs (X_{BH})	PAOs (X_{EG})	OHOs (X_{EH})	Inert (X_{Inert})	TSS (X_T)	BPO ($S_{bp(AS)}$)	UPO ($S_{up(AS)}$)	f_{SupAS}
	Active	*Active*	*Endogenous*	*Endogenous*	*inert mass*	*measured*	*AS BPO*	*AS UPO*	
	mgVSS/L	*mgVSS/L*	*mgVSS/L*	*mgVSS/L*	*mgVSS/L*	*mgTSS/L*	*mgCOD/L*	*mgCOD/L*	
Batch 3	2331	1398	220	634	2483	9531	5207	5197	0.50
Batch 4	1778	1255	169	572	3173	9394	4075	5941	0.59
Batch 5	2240	1168	226	566	2984	10335	4664	5786	0.55
Batch 6	2077	1545	218	777	2341	9692	5049	5182	0.51
Batch 7	2029	1009	206	491	3368	10430	3999	6158	0.61
Batch 8	2051	876	201	411	3144	9991	3923	5703	0.59
Batch 9	2283	1097	227	523	2664	9251	4260	5266	0.55
Batch 10-18	2460	1141	244	544	2532	9109	4929	5157	0.52
Batch 11-60	2230	1271	223	611	2833	9725	4746	5642	0.55
Batch 12-40	2087	1497	218	750	2439	10067	4885	5279	0.53
Batch 13-25	2344	1004	234	481	2521	9740	4594	5007	0.53
Batch 14-10	2050	1255	205	601	2373	8648	4447	4920	0.53

The UPO results reported in Table 5.4a represents the unbiodegradable fraction ($f_{up(AS)}$) of the NDBEPR WAS which is accepted to be the $X_{inert,}$ the PAO and OHO endogenous mass (X_{EG} and X_{EH}) and 8% of the active PAO and OHO biomass (X_{BG} and X_{BH}). This method of determining the UPO in terms of COD concentration is described by Eq. E4.2c in Section 4.1.1.2b. The PAO and OHO concentrations in the WAS are presented in Figure 5.4a and the variation of the PAO biomass fraction of the WAS ($f_{avPAO} = X_{BG}/X_v$) with the influent RBCOD concentration variation in Figure 5.4b. The BPO and UPO COD concentrations of the WAS are shown in (Figure 5.5a) and a comparison of the influent unbiodegradable COD fraction (f_{upi}) and the WAS unbiodegradable fraction {$f_{up(AS)}$ = UPO/(UPO+BPO)} is presented in Figure 5.5b.

These graphs are shown to give an assessment of the wastewater characteristics and VSS fractionation of the NDBEPR AS system used for WAS generation in this investigation.

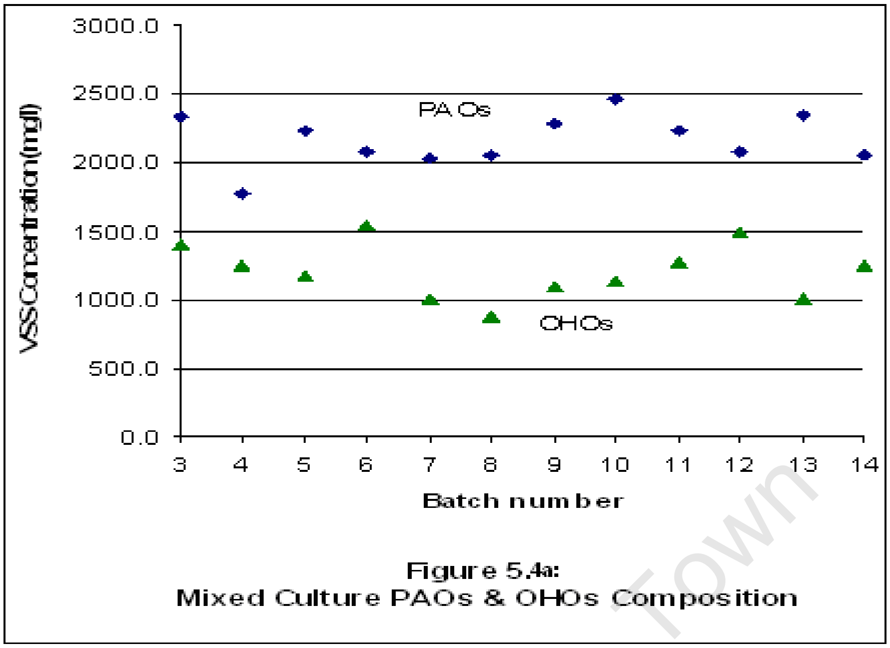


Figure 5.4a: Mixed Culture PAOs and OHOs composition

Literature reports, as discussed in Section 2.2, that the UCT AS system promotes the growth of the PAO population over that of the OHOs population of the system. Figure 5.4a illustrates a high PAO concentration relative to that of the OHOs for each batch through the entire duration of the experimental investigation. This is due to the 200 mgCOD/l acetate dosing to the influent, thereby doubling the influent RBCOD concentration so is in line with theoretical expectation for this configuration. The OHO and PAO active mass fractions vary from batch to batch during the investigation due to the variation in RBCOD concentration in the wastewater itself.

The PAO active fraction variation with influent RBCOD fraction variation is presented in Figure 5.4b. Clearly, as expected from the NDBEPR model the higher the influent RBCOD fraction, the greater the PAO active mass fraction of the VSS (PO).

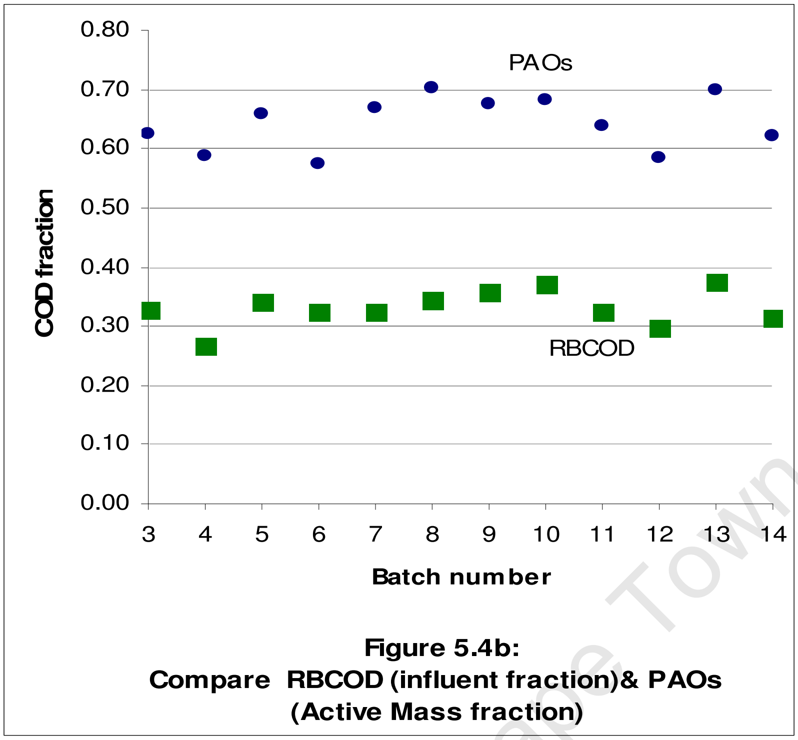


Figure 5.4 b: Comparison of the RBCOD (influent) and PAOs (Active mass) fractions

The active, endogenous and inert masses of the NDBEPR WAS are grouped into two categories, the UPO and BPO components. This characterization procedure is described in Section 4.1.1.2 a. The UPO component relates to the unbiodegradable particulate content of WAS in the UCT AS system. The BPO is then determined from the difference between the overall PO component (measured) and the UPO component (Calculated). These results is listed in Table 5.4a and graphically presented in Figure 5.5a.

In Figure 5.5a it can be observed that for Sewage Batches 3 to 9 there were significant variations in the UPO and BPO COD composition of the NDBEPR WAS even though the overall PO COD composition remained fairly consistent during this time. To visualise these variations of the UPO and BPO components, in a fairly consistent PO concentration, the unbiodegradable particulate content of the influent was plotted with the unbiodegradable fraction of the WAS presented in Figure 5.5b. The UPO components of the WAS varies consistently with the variation in UPO composition of the influent wastewater.

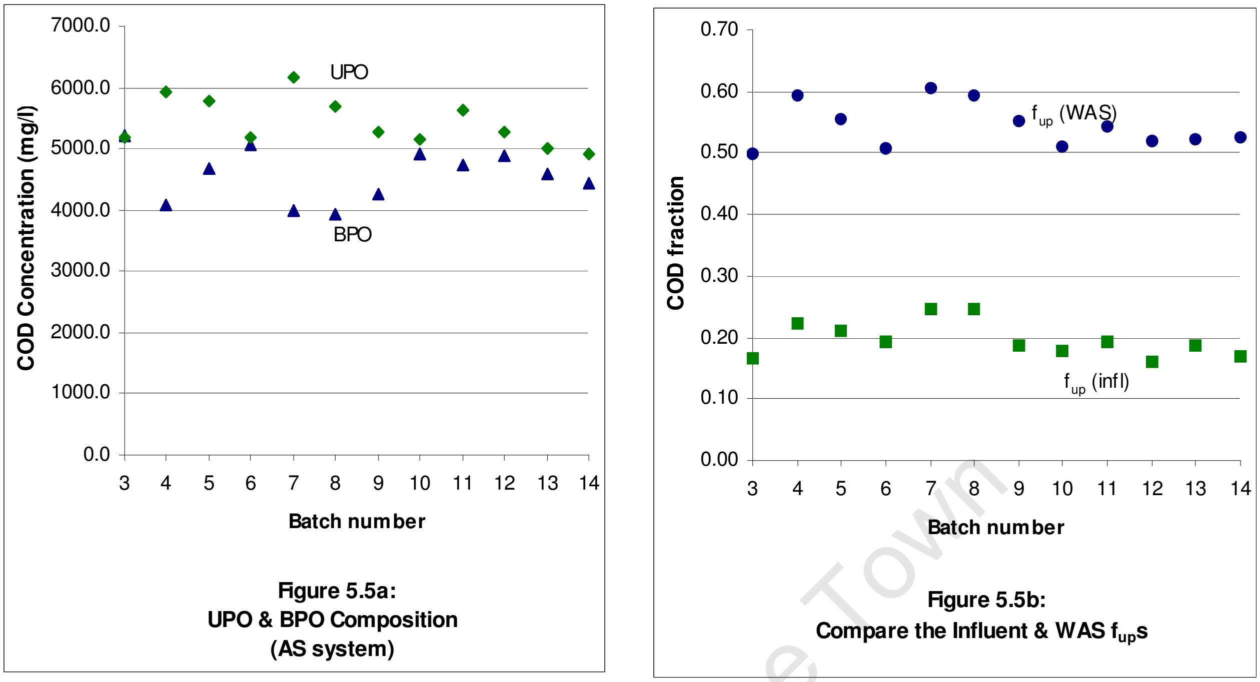


Figure 5.5a:
UPO & BPO Composition
(AS system)

Figure 5.5b:
Compare the Influent & WAS f_{up}s

Figure 5.5 a & b: (a) Compare UPO vs. BPO composition (f) and (b) f_{upi} and $f_{up(AS)}$

Figure 5.5b illustrates a direct relationship between the changes in the f_{upi} and $f_{up(AS)}$. This is in line with theoretical expectation that the influent unbiodegradable organic particulate (UPO) fraction (f_{upi}) becomes enmeshed in the AS and forms part of the overall UPO fraction $f_{up(AS)}$ of the AS system VSS. Therefore, a change in the wastewater f_{upi} is reflected in a change in VSS $f_{up(AS)}$. The measured $f_{up(AD)}$ of the NDBEPR WAS in the AD will compared with this model estimated $f_{up(AS)}$ in a section below that deals with the UPO of the experimental plant wide setup. The UPO fraction ($f_{up(AS)}$) of the NDBEPR WAS fed to the AD reactor during the experimental investigation remains consistent between 0.51 and 0.55. The variation of the UPO in the wastewater is probably a consequence of variations in COD balance due to the method of calculation of the influent UPO fraction (f_{upi}) (finding the f_{upi} that reconciles the calculated VSS mass in the UCT system with that measured),

C. Fractionation of Phosphate in each Component of PO and the Characterization of Polyphosphate

At this stage in the characterization procedure the phosphate content of each component of PO are determined as a mass fraction to the VSS concentration f_P. The procedure was described in

Section 4.1.1.2d and the results obtained from the application of this fractionation procedure is presented and discussed here. The mass fractions TP/VSS presented here are f_P ratios used with the f_{cv}, f_N and f_C mass fractions to characterize the organic part of each component to its elemental composition as described in Section 4.1.2. This section also presents the results for the linkages factors (q_{Φ}) used to couple the elemental composition of the stored inorganic polyphosphate counter-ion metals Mg: K: Ca in Me of the $MePO_3$, to the elemental composition of organic parts of the PAO and BPO (that contain PAOs) components. This method was described in Section 4.1.1.3b.

Table 5.4b presents the results obtained in the phosphorus content of the VSS components in terms of the active mass (X_{BH} & X_{BG}), endogenous mass (X_{EH} & X_{EG}) and inert mass (X_{inert}) of PO VSS in NDBEPR WAS and in terms of the PO (VSS) subdivided into BPO (92% of the OHOs and PAOs) and the UPO (the remainder of the VSS). It also presents the linkage factors (q_{BPO} and q_{PAO}) utilized to produce a single elemental composition PAO and BPO components that contains polyphosphate.

Table 5.4b : Phosphorus Characterization and Linkage Factors

Sewage Batch Number	$X_{P(VSS)}$	f_{TP}	$f_{P(UPO)}$	$f_{P(BPO)}$	$f_{XB(H/G)PBM}$	f_{XBGP}	f_{XBGPP}	q_{PAO}	q_{BPO}
		(in total VSS)	*(in UPO VSS)*	*(in BPO VSS)*	*(in active VSS)*	*(in PAOs VSS)*	*(in PAOs VSS)*	*(link PAOs)*	*(link BPO)*
	mgP/L	*mgP/mgVSS*	*mgP/mgVSS*	*mgP/mgVSS*	*mgP/mgVSS*	*mgP/mgVSS*	*mgP/mgVSS*		
Batch 3	**806.0**	**0.114**	**0.031**	**0.199**	**0.031**	**0.304**	**0.272**	**1.00**	**0.63**
Batch 4	**744.4**	**0.107**	**0.032**	**0.216**	**0.032**	**0.350**	**0.317**	**1.20**	**0.70**
Batch 5	**792.9**	**0.110**	**0.032**	**0.209**	**0.032**	**0.304**	**0.272**	**1.05**	**0.69**
Batch 6	**823.7**	**0.118**	**0.034**	**0.208**	**0.034**	**0.343**	**0.309**	**1.17**	**0.67**
Batch 7	**871.2**	**0.123**	**0.032**	**0.259**	**0.032**	**0.376**	**0.343**	**1.31**	**0.88**
Batch 8	**855.8**	**0.128**	**0.027**	**0.275**	**0.027**	**0.385**	**0.358**	**1.39**	**0.97**
Batch 9	**857.6**	**0.126**	**0.043**	**0.222**	**0.043**	**0.312**	**0.269**	**1.01**	**0.68**
Batch 10-18	**888.2**	**0.128**	**0.034**	**0.228**	**0.034**	**0.322**	**0.288**	**1.08**	**0.74**
Batch 11-60	**876.3**	**0.122**	**0.033**	**0.232**	**0.033**	**0.345**	**0.312**	**1.15**	**0.73**
Batch 12-40	**892.3**	**0.128**	**0.031**	**0.233**	**0.031**	**0.382**	**0.351**	**1.31**	**0.76**
Batch 13-25	**817.6**	**0.124**	**0.035**	**0.224**	**0.035**	**0.308**	**0.273**	**1.01**	**0.71**
Batch 14-10	**865.2**	**0.133**	**0.036**	**0.242**	**0.036**	**0.372**	**0.337**	**1.26**	**0.78**

Sötemann *at el.* (2005) excluded the phosphorus content from the elemental characterization of PS and ND WAS because this content was significantly lower than the other elemental components of the sludge. During the digestion of PS and ND WAS, the quantity of phosphate products of digestion was negligible and as a consequence do not affect the aqueous concentration and pH of the digester liquid. To put this into context, the mass fraction (based on total VSS) of organic P relative to the organic N in PS and ND WAS is more than 6 times lower than in NDBEPR WAS, which can increase if the P mass fraction of UPO is less than the 0.03 assumed for this study. In the case of NDBEPR WAS the total P concentration is actually higher than the organic N concentration (Figure 5.6). Because the phosphorus content of the UPO component does not affect the soluble P products generated during the digestion process, only the P content of the BPO component of the NDBEPR WAS influences the concentration of P released to solution during the AD process.

In Section 4.1.1.2 it was assumed that the organic parts of PAOs and OHOs have the same elemental composition. Hence, if the WAS contains only OHOs, like in the case of ND WAS, the organic N and organic P is closely related (f_N/f_P = 0.10/0.025 = 4). Figure 5.6a shows that the phosphorus content (in terms of mass) of the NDBEPR WAS BPO is greater than the organic N content (f_N/f_P = 0.67). Therefore, the P component will contribute significantly to the aqueous products of digestion with the result that these cannot be neglected in the weak acid/base chemistry part of the AD model.

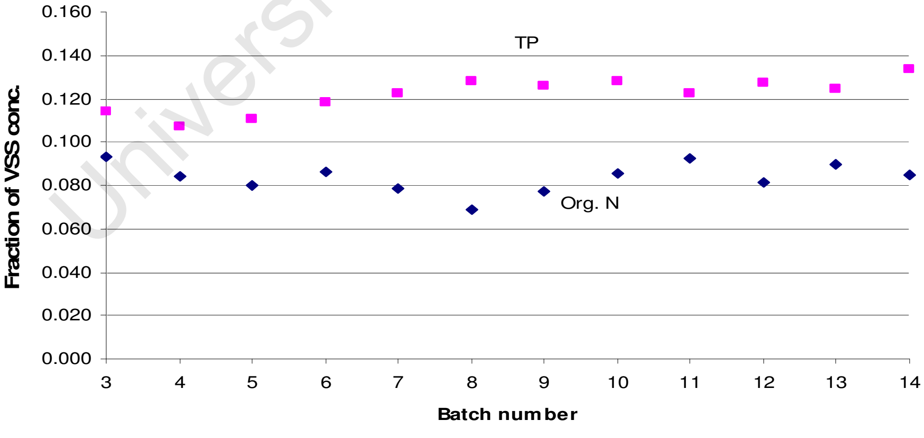


Figure 5.6:
Comparision of TP and Org. N (fraction of VSS conc.)

Figure 5.6: Comparison of TP and Org. N (as fractions of VSS conc.)

Figure 5.7a shows the biomass P, polyphosphate P and the total phosphorus composition of the PAOs, in terms of mass fractions, per sewage batch for the full duration of the experimental investigation. The plots indicate that the organic P content of the PAOs remains fairly consistent which is expected because the PAO biomass is assigned a P content of 0.034mgP/mgPAOVSS but that the polyphosphate content varies significantly. This resulted in significant changes in the total P content of the PAOs. Wentzel *et al.* (1989) state that the maximum total P content of PAOs is 0.38 mgP/mgactivePAOVSS, as described in Section 2.2.4. This yields a maximum polyphosphate content of 0.35 mgP/ mgPAOVSS which Wentzel *et al.* (1989) observed in enhanced cultures of PAOs. In this study, the variation in polyphosphate content of the PAOs is a consequence of the calculation procedure. With the other VSS components assigned a P/VSS ratio of 0.033 mgP/mgVSS, the polyphosphate content of the PAOs is selected such that the calculated P removal matched that measured. The variation in PAO polyphosphate content therefore mirrors the observed variation in the P removal. Figure 5.7b shows the polyphosphate P, biomass P and total P content of the BPO component where the BPO is the sum of the biodegradable part of the OHOs and PAOs (assumed to be 92% of their VSS). With respect to the BPO, the P content is of course lower due to the diluting effect of the biodegradable part of the OHOs. This dilution effect is observed in the linkage factor for the PAO component (q_{PAO}) compared with that of the BPO component (q_{BPO}), i.e. $q_{PAO} > q_{BPO}$.

Next, to obtain the elemental composition for the VSS components that contain the inorganic polyphosphate a method was developed that links the elemental compositions of the organic part to the inorganic polyphosphate part. This method was described in Section 4.1.1.3b. The values for the linkage factor for the PAOs (q_{PAO}) and the BPO (q_{BPO}) are shown in Table 5.4b. Because these factors are related to the polyphosphate content of the PAOs, it varies in the same way as the PAO polyphosphate content with sewage batches. The q_{PAO} varies between 1.0 and 1.39 in this experimental study.

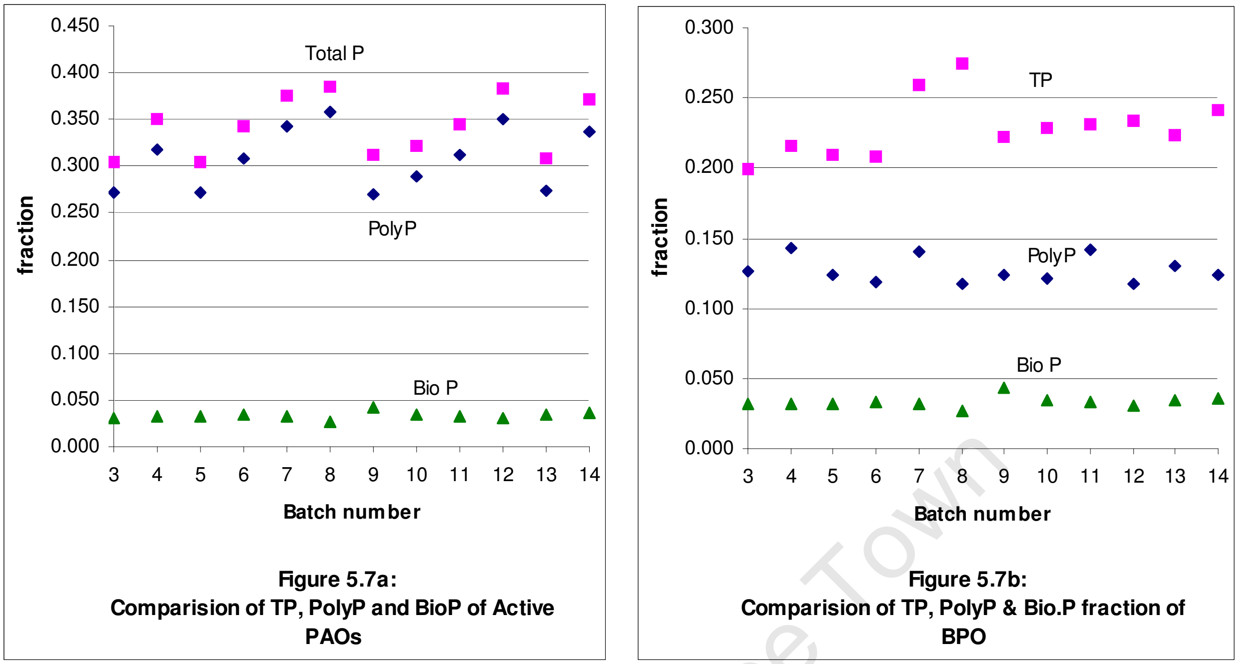


Figure 5.7a:
Comparision of TP, PolyP and BioP of Active PAOs

Figure 5.7b:
Comparision of TP, PolyP & Bio.P fraction of BPO

Figure 5.7a & b: Comparison of TP, PolyP & Bio.P in the PAOs and BPO.

Table 5.4c presents the counter-ion metal mass fractions to the BPO VSS concentration and molar ratios with respect to one mole of polyphosphate. These polyphosphate counter-ion metals function as charge balancing ions for the negative charges on the polyphosphate chain, as described in Section 2.2.3. The procedure to determine these molar ratios are described in Section 2.2.3 (theoretical) and the calculations for the measured Mg, K and Ca concentrations are described in Section 4.1.1.3a.

These results are listed in Table 5.4c.

Table 5.4c : Polyphosphate Counter-ion Metal Characterization (Mg, K and Ca)

Sewage Batch Number	f_{XBGPP}	f_{XBGMe}	f_{XBGMg}	f_{XBGK}	f_{XBGCa}	$n_{R(Mg)}$	$n_{R(K)}$	$n_{R(Ca)}$
	Mass Fraction					Molar Ratio {1: $n_{R(Mg)}$: $n_{R(K)}$:$n_{R(Ca)}$}		
	mgP/mgVSS	*mgP/mgVSS*	*mgP/mgVSS*	*mgP/mgVSS*	*mgP/mgVSS*	*mole ratio to 1mole P of polyp*		
Batch 3	**0.272**	**0.181**	**0.067**	**0.104**	**0.010**	***Used Batch 6 measurements***		
Batch 4	**0.317**	**0.212**	**0.079**	**0.121**	**0.012**			
Batch 5	**0.272**	**0.181**	**0.067**	**0.104**	**0.010**			
Batch 6	**0.309**	**0.206**	**0.076**	**0.118**	**0.011**	**0.32**	**0.3**	**0.03**
Batch 7	**0.343**	**0.229**	**0.085**	**0.131**	**0.013**	***Used Batch 6 measurements***		
Batch 8	**0.358**	**0.238**	**0.089**	**0.137**	**0.013**			
Batch 9	**0.269**	**0.179**	**0.067**	**0.103**	**0.010**			
Batch 10-18	**0.288**	**0.200**	**0.068**	**0.122**	**0.009**	**0.31**	**0.34**	**0.02**
Batch 11-60	**0.337**	**0.242**	**0.072**	**0.151**	**0.019**	**0.28**	**0.36**	**0.04**
Batch 12-40	**0.351**	**0.237**	**0.086**	**0.139**	**0.012**	**0.32**	**0.31**	**0.03**
Batch 13-25	**0.273**	**0.184**	**0.067**	**0.107**	**0.01**	**0.32**	**0.31**	**0.03**
Batch 14-10	**0.337**	**0.242**	**0.072**	**0.151**	**0.019**	**0.28**	**0.36**	**0.04**

The analytical measurements on the AS system to quantify the counter-ion metals were performed during the periods when experimental data was collected for the AD steady state experiments. Although the quality of the data from Sewage Batch 6 for the AS system is acceptable for input in the AD model, the AD test data were discarded because the AD data collected during this period was irregular. However the data collected for the AS system for the same period was fairly consistent and this data were included in the characterization procedure.

The counter-ion metals molar ratio results found for this study vary to some extent but this is probably due to the high dilution and variation of the analytical procedure applied to quantify these components. This procedure is similar to the TKN procedure that includes a sludge acid digestion step, which produces variation in results. Furthermore, the sludge samples are diluted between 125 to 250 times. The source of these expected inconsistencies are described in Section 4.1.3.1a(II). The average polyphosphate to metal molar determined for this study are 1: 0.31: 0.32: 0.03 for P: Mg: K: Ca respectively. This molar ratio was obtained after the measured results were adjusted to account for charge imbalances between the metals and the polyphosphate to ensure that the polyphosphate component has a zero charge. The measured molar ratios without adjustment are 1: 0.289: 0.305: 0.028 for P: Mg: K: Ca respectively, which has a charge of +0.94 versus -1.00 for the PO3. Experimentally this is as good as the literature cited below.

Table 2.1 reviews the results for the molar ratios of studies on polyphosphate by Miyamoto-Mills *et al.* (1983), Arvin *et al.(*1985) and Comeau *et al.(*1985) as described in Section 2.2.3. The average results from these studies are 1: 0.275: 0.295: 0.05 for these counter-ion metals. These results are also not adjusted to ensure a neutral polyphosphate compound (charge +0.94). The average phosphorus to counter-ion metals molar measured in this study (Table 5.4c) is nearly the same as that found in the published studies described in this Section and in Section 2.2.3.

The mass fractions of the metal components are determined using the molar ratios that relate the counter-ion metals to the P content of the polyphosphate. Consequently, the variation in the trend for polyphosphate content of the NDBEPR WAS throughout this experimental investigation is reflected in the variation of the counter-ion metals. This is shown by Figure 5.8.

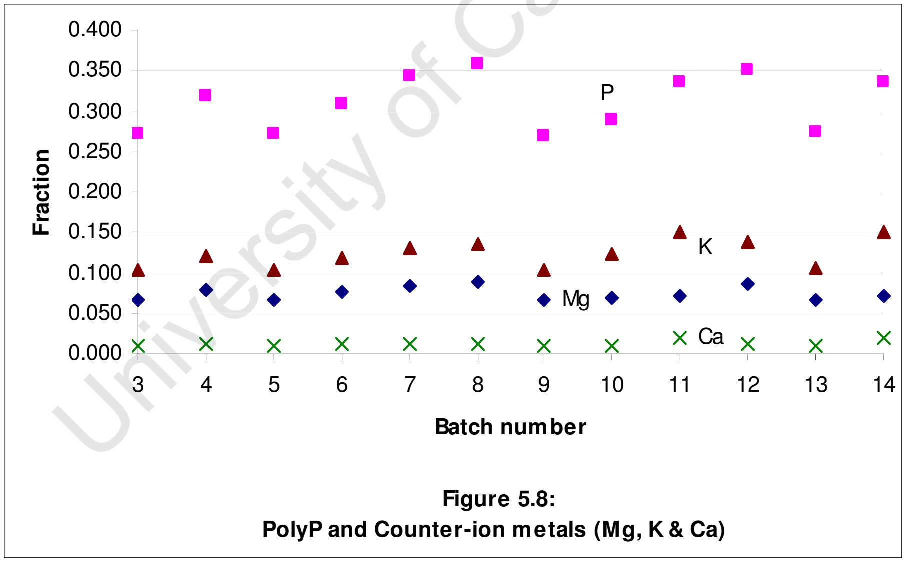


Figure 5.8: Compare Polyphosphate and Counter-ion metal fractions

5.2.3 Transformation to Elemental Composition

This section presents results from the final step in the characterization procedure described in Section 4.1.2. At this stage, the NDBEPR WAS has been fractionated into its active, endogenous and inert VSS fractions and then these VSS fractions were grouped into BPO and UPO components, each with its COD, TKN, TOC, TP and VSS concentration characteristics. Next, these mass fraction ratios (f_{cv}, f_N, f_{cv}, and f_N) are transformed to elemental compositions for the PO VSS, UPO and BPO components in the form $C_XH_YO_ZN_AP_B$. q[$MePO_3$] for the PO VSS and BPO (that include polyphosphate via the PAOs) and $C_XH_YO_ZN_AP_B$ for the UPO. The BPO mass fractions are determined by difference between the PO and UPO, where the PO is based on the measured ratios on the WAS and the UPO on the measured ratios of the 60 day retention time AD effluent.

The f_{cv}, f_C, f_N and f_P mass ratio for the PO VSS, UPO and BPO components are presented in Table 5.5a.

Table 5.*5a : Composition Matrices for each Component of NDBEPR WAS*

Sewage Batch Number	PO VSS				UPO				BPO			
	f_{cv}	f_N	f_P	f_C	f_{cv}	f_N	f_P	f_C	f_{cv}	f_N	f_P	f_C
Batch 3	1.46	0.093	0.031	0.52	1.43	0.051	0.031	0.51	1.50	0.138	0.031	0.53
Batch 4	1.44	0.084	0.032	0.52	1.43	0.051	0.032	0.51	1.44	0.132	0.032	0.53
Batch 5	1.45	0.080	0.032	0.52	1.43	0.051	0.032	0.51	1.47	0.117	0.032	0.53
Batch 6	1.46	0.086	0.034	0.52	1.43	0.051	0.034	0.51	1.50	0.124	0.034	0.53
Batch 7	1.45	0.080	0.032	0.52	1.43	0.051	0.032	0.51	1.48	0.123	0.032	0.53
Batch 8	1.43	0.069	0.027	0.52	1.43	0.051	0.027	0.51	1.44	0.096	0.027	0.53
Batch 9	1.47	0.077	0.043	0.52	1.43	0.051	0.043	0.51	1.52	0.109	0.043	0.53
Batch 10-18	1.45	0.086	0.033	0.52	1.43	0.048	0.034	0.51	1.47	0.127	0.031	0.53
Batch 11-60	1.45	0.093	0.032	0.52	1.43	0.049	0.033	0.51	1.47	0.146	0.030	0.53
Batch 12-40	1.45	0.082	0.030	0.52	1.43	0.047	0.031	0.51	1.47	0.120	0.029	0.53
Batch 13-25	1.44	0.084	0.034	0.52	1.43	0.051	0.036	0.51	1.45	0.121	0.033	0.53
Batch 14-10	1.44	0.084	0.034	0.52	1.43	0.051	0.036	0.51	1.45	0.121	0.033	0.53

On close inspection of the mass fractions listed in Table 5.5a, the results determined for the PO and UPO are quite consistent throughout the duration of experimental investigation. The mean f_{cv} mass ratio for the PO VSS varies between 1.43 and 1.47, which is fairly consistent. The f_N mass fraction range mostly between 0.08 and 0.095 with only batches 8 and 9 outside of this range. The f_P mass fraction range mostly between 0.03 and 0.034 where again only Sewage Batches 8 and 9 are outside of this range.

The f_{cv} of UPO is uniformly 1.43 for the full extent of the experimental investigation because the UPO component for all the sewage batches was determined from the averaged measurements from the 60 day R_s test of the AD system. The f_N mass fraction for the UPO components range mostly between 0.047 and 0.051, which is acceptable and the f_P mass fraction ranges between 0.031 and 0.036 where only batches 8 and 9 are outside of this range. The f_C (TOC/VSS) for the PO VSS and UPO components were assumed at 0.52 and 0.51 respectively. The f_{cv} of the BPO components varies between 1.44 and 1.52 over the experimental investigation. The f_N mass fractions for the BPO components vary significantly between 0.096 and 0.146 probably a consequence of the calculation method where the N content of the BPO as the difference between the PO and UPO. The f_P mass fraction range between 0.029 and 0.034 where only batches 8 and 9 are outside this range. The significance of these inconsistencies of Sewage Batches 8 and 9 will be discussed below in context of the elemental composition results obtained from these mass ratios.

With four mass fractions known, the remaining unknown mass fractions f_H and f_O were determined using Equations E4.7a to E4.7c described in Section 4.1.2. These results (not listed) were used with the mass fractions in Table 5.5a to determine the carbon (X), oxygen (Z), nitrogen (A) and phosphorus (B) elemental composition for the PO VSS, UPO and BPO components of the NDBEPR WAS. The hydrogen (Y) elemental was set at 7 for all the elemental compositions. The elemental compositions were determined from the application of Equations E4.8a to E4.8f as described in Section 4.1.2 and the results for the elemental compositions of the PO VSS, UPO and BPO for each sewage batch are presented in Table 5.5b.

Table 5.5b: Elemental Composition of NDBEPR WAS

Sewage Batch Number	*$C_XH_YO_ZN_AP_B.\ q_{\o}[MePO_3]$ composition of the WAS Components*		
	VSS	**UPO**	**BPO**
Batch 3	$C_{5.00}H_7O_{2.11}N_{0.76}P_{0.12}.\ 0.29[MePO_3]$	$C_{5.11}H_7O_{2.63}N_{0.44}P_{0.12}$	$C_{4.90}H_7O_{1.61}N_{1.09}P_{0.12}.\ 0.61[MePO_3]$
Batch 4	$C_{5.31}H_7O_{2.35}N_{0.73}P_{0.13}.\ 0.30[MePO_3]$	$C_{5.13}H_7O_{2.63}N_{0.44}P_{0.13}$	$C_{5.58}H_7O_{1.91}N_{1.18}P_{0.13}.\ 0.75[MePO_3]$
Batch 5	$C_{5.21}H_7O_{2.33}N_{0.68}P_{0.13}.\ 0.30[MePO_3]$	$C_{5.13}H_7O_{2.63}N_{0.44}P_{0.13}$	$C_{5.31}H_7O_{1.94}N_{1.00}P_{0.13}.\ 0.69[MePO_3]$
Batch 6	$C_{5.05}H_7O_{2.19}N_{0.72}P_{0.13}.\ 0.33[MePO_3]$	$C_{5.16}H_7O_{2.64}N_{0.44}P_{0.13}$	$C_{4.94}H_7O_{1.74}N_{0.99}P_{0.12}.\ 0.64[MePO_3]$
Batch 7	$C_{5.18}H_7O_{2.32}N_{0.68}P_{0.13}.\ 0.35[MePO_3]$	$C_{5.13}H_7O_{2.63}N_{0.44}P_{0.13}$	$C_{5.24}H_7O_{1.83}N_{1.03}P_{0.12}.\ 0.87[MePO_3]$
Batch 8	$C_{5.30}H_7O_{2.50}N_{0.60}P_{0.11}.\ 0.39[MePO_3]$	$C_{5.02}H_7O_{2.60}N_{0.43}P_{0.11}$	$C_{5.77}H_7O_{2.33}N_{0.88}P_{0.113}.1.05[MePO_3]$
Batch 9	$C_{5.25}H_7O_{229}N_{0.67}P_{0.17}.\ 0.31[MePO_3]$	$C_{5.38}H_7O_{2.70}N_{0.46}P_{0.17}$	$C_{5.10}H_7O_{1.84}N_{0.89}P_{0.16}.\ 0.68[MePO_3]$
Batch 10-18	$C_{5.16}H_7O_{2.25}N_{0.73}P_{0.13}.\ 0.32[MePO_3]$	$C_{5.19}H_7O_{2.68}N_{0.42}P_{0.13}$	$C_{5.13}H_7O_{1.81}N_{1.05}P_{0.12}.\ 0.68[MePO_3]$
Batch 11-60	$C_{5.10}H_7O_{2.18}N_{0.78}P_{0.12}.\ 0.30[MePO_3]$	$C_{5.16}H_7O_{2.66}N_{0.42}P_{0.13}$	$C_{5.02}H_7O_{1.62}N_{1.18}P_{0.11}.\ 0.67[MePO_3]$
Batch 12-40	$C_{5.16}H_7O_{2.30}N_{0.69}P_{0.12}.\ 0.34[MePO_3]$	$C_{5.13}H_7O_{2.67}N_{0.41}P_{0.12}$	$C_{5.18}H_7O_{1.9}N_{1.0}P_{0.11}.\ 0.71[MePO_3]$
Batch 13-25	$C_{5.33}H_7O_{2.34}N_{0.74}P_{0.14}.\ 0.36[MePO_3]$	$C_{5.21}H_7O_{2.65}N_{0.45}P_{0.14}$	$C_{5.46}H_7O_{1.99}N_{1.07}P_{0.13}.\ 0.76[MePO_3]$
Batch 14-10	$C_{5.33}H_7O_{2.34}N_{0.74}P_{0.14}.\ 0.36[MePO_3]$	$C_{5.21}H_7O_{2.65}N_{0.45}P_{0.14}$	$C_{5.46}H_7O_{1.99}N_{1.07}P_{0.13}.\ 0.76[MePO_3]$

The results for the elemental compositions of PO VSS, UPO and BPO determined in this study were compared to studies of ND WAS described in Section 2.2.7, Table 2.4. The reason for this was because no elemental compositions for NDBEPR WAS could be found in the literature. The elemental compositions of NDBEPR WAS are similar to that of ND WAS. This is in part due to assuming the same elemental for the OHOs and PAOs and in part due to this experimental investigation yielding similar results to the previous studies. Furthermore, the experimental UCT MBR AS system was operated at a long sludge age (10 days) that ensured that all the influent biodegradable organics were utilized. Consequently, the NDBEPR WAS consisted only of inert mass and biomass.

The WAS UPO is largely influenced by the influent UPO concentration (S_{upi}) and UPO of the endogenous mass. Based on the assumption state above that OHO and PAO organic elemental compositions are similar, the UPO generated from the biomass should ideally be the same as the biomass. However, the grouping of the UPO and BPO makes the elemental composition of the endogenous UPO and influent UPO the same and different to the BPO. The influent UPO is dependent on the wastewater sources and can vary periodically for a specific WWTP and more so for different WWTPs.

Table 5.5b presents the elemental compositions of PO VSS, UPO and BPO determined for the NDBEPR WAS considered in this study. In comparing the BPO results in Table 5.5b to the biomass compositions summarised in Table 2.4, the results are very similar. If a range for the biomass compositions are established based on the molar composition of the carbon element it contains, it is found that the BPO or biomass compositions range from $C_{4.8}H_7O_2N_{0.77}$ (Dold *et al.*, 1980) to $C_{5.67}H_7O_2N_{0.865}$ (Ekama, 2009). On this basis only the elemental composition of Batch 9 is outside of this range. The organic phosphorus of that reported by Volcke *et al.* (2006), in the composition $C_{5.02}H_7O_{2.04}N_{0.95}P_{0.113}$, is similar to that found for this study.

The UPO determined in this study has lower molar carbon, nitrogen and phosphorus compositions than reported by Volcke *et al.* (2006) as $C_{5.44}H_7O_{2.04}N_{0.75}P_{0.038}$. However, the Volcke *et al.* UPO composition appears to be an assumed one. Nevertheless, the comparison of the results for UPO from the two studies remains reasonably similar as compared to the UPO results from the PS studies described in Section 2.2.7. Finally, the VSS (organic particulate) found for this study are higher in terms of carbon and oxygen molar content but similar in terms of phosphorus to that found by Ekama (2009) from the van Haandel *et al.* (1998) data, reported at $C_{4.96}H_7O_2N_{0.773}$.

The P composition for Sewage Batch 9 is significantly higher than that for the other batches and the N composition of Sewage Batch 8 is smaller than that determined for the other batches. This can directly be linked to the significant variations of these mass ratios presented in Table 5.5a compared to the other sewage batches.

Generally, the PO VSS, UPO and BPO elemental compositions determined for this study are fairly similar to those found in other studies on WAS. This provides confidence in the quality of elemental composition results obtained for the NDBEPR WAS in this study. This elemental composition will be used as input to the stoichiometric part of the steady state AD model developed in Chapter Four of this study. The results from thus part of the model are utilized and discussed in context below.

5.3 Anaerobic Digestion Stoichiometry and Physico-chemical processes

This anaerobic digestion and physico-chemical processes section presents and discusses issues central to the main objective of this study. The steady state model describing the AD of NDBEPR WAS that was developed in Chapter 4 is calibrated and validated in this section. To calibrate the steady state AD model the averages of the measured data for steady state anaerobic digester at 10, 18, 25, 40 and 60 days R_s are used as described in Section 4.2.3 that summarised the AD of NDBEPR WAS part from the Ikumi *et al.* (2009) study. Furthermore, the measured data for R_s 12 and 20 days are afterwards checked in the model calibration.

The steady state AD model is calibrated based on the biodegradable COD utilisation via the hydrolysis kinetics developed by Ikumi *et al.* (2009). Therefore, it is expected that the change in the measured COD concentration should be closely predicted by the steady state model. However, the model predicted results for FSA, Ortho-P, VSS, dissolved counter-ion metal concentrations and the pH and alkalinity measurements are independent of this calibration function and depend mainly on the elemental composition. These results therefore need to be evaluated and compared against the observed measurements at the various steady state sludge ages of the experimental AD system. Although the methane gas (CH_4) has a direct relationship to the COD removed determined from the hydrolysis kinetic part of the model, the methane and carbon dioxide molar fluxes will also be evaluated based on the measured and predicted quantities. In addition, the comparison between the predicted results will also depend on the elemental mass balance over the experimental AD system.

This section starts by reviewing the measured data for the influent (feed) and effluent (waste sludge) characteristics of the anaerobic digester. This is done to evaluate the consistency of the measured data throughout the experimental investigation. Next, the hydrolysis kinetic rates based on COD utilisation of the NDBEPR WAS, as studied by Ikumi *et al.* (2009), are summarized. The kinetic constants determined by Ikumi *et al.* (2009) are used to predict the concentration of BPO utilized from which the stoichiometry predicts the quantities of products generated within the AD process. The gas produced in this AD process is related to the measured COD removal at each steady state sludge age. These results are then compared to the model predicted COD removal. Thereafter, the measured products that do not contribute to precipitant formation within the AD system can be compared directly to the predicted quantities determined with the steady state model. Finally, the measured and predicted quantities of those components that may contribute to precipitant formation are determined and discussed. This is done by calculating the ionic product of the soluble AD products and comparing it with the thermodynamic solubility product (K_{spm}) of a possible precipitant, such as struvite. Issues that relate to the phosphorus release and UPO fraction of the NDBEPR WAS are reviewed and discussed in context for the AS to AD system within this section.

5.3.1 AD Measured Data

The averages of the measured data from the feed (influent) and waste (effluent) of the experimental AD system for the various steady state sludge ages are presented in Table 5.6a. These data sets have been evaluated by performing mass balances over the AD systems for COD, Nitrogen, Phosphorus and the Counter-ion metals at the various test R_s in Section 5.1.2. Here the data are evaluated based on the trends of the different parameters vs. the steady state R_s, such as change in COD, VSS, TKN, FSA, TP, Ortho-P and dissolved counter-ion metal concentrations as well as the inorganic carbon and phosphate alkalinities (H_2CO_3* Alk and H_3PO_4 Alk)[2]*. These measured data trends are not compared to predicted data in this section, but the data sets are inspected for consistency based on their trend with increasing sludge age.

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[2] * In this report the notation of Loewenthal *et al.* (1991) is adopted where H_2CO_3* Alk is the alkalinity of the inorganic carbon <u>and</u> water subsystems and Alk H_3PO_4 the alkalinity of the phosphate subsystem only.

a. AD feed (influent) and waste (effluent) measured concentrations

Table 5.6a presents the average AD influent concentration data from Section 5.2 that are utilized in the calibration and validation of the steady state AD model.

Table 5.6a: Influent (Feed) concentrations of NDBEPR WAS to the Anaerobic Digester

Steady State AD Sludge Age	10 day AS Batch 14	12 day AS Batch 14	18 day AS Batch 10	20 day AS Batch 14	25 day AS Batch 13	40 day AS Batch 12	60 day AS Batch 11
Utilisation	*Model Calibration*	*Model Validation*	*Model Calibration*	*Model Validation*	*Model Calibration*	*Model Calibration*	*Model Calibration*
COD (Total) (mg/l)	9355.4	9355.4	10061.8	9355.4	9589.4	10126.7	10417.9
COD (Soluble) (mg/l)	36.26	36.26	29.39	36.26	37.37	14.65	29.94
TKN (mg/l)	550.5	550.5	598.6	550.5	596.4	576.2	670.1
FSA (mg/l)	1.85	1.85	4.31	1.85	4.90	4.97	5.09
TP (mg/l)	866.57	866.57	914.48	866.57	988.53	837.98	921.90
Ortho P (mg/l)	18.78	18.78	19.59	18.78	24.78	16.41	18.88
TSS (mg/l)	8595.88	8595.88	9175.60	8595.88	9882.00	9494.50	9870.80
VSS (mg/l)	6482.40	6482.40	6921.20	6482.40	6582.80	6990.50	7168.40
ISS (mg/l)	2113.48	2113.48	2254.40	2113.48	3299.20	2504.00	2702.40
H_2CO_3* Alkalinity (mg as $CaCO_3$/l)	230.00	230.00	230.00	230.00	230.00	230.00	230.00
pH	7.60	7.60	7.60	7.60	7.60	7.60	7.60
Mg (Total) (mg/l)	260.83	235.67	290.88	249.83	289.53	313.10	279.32
Mg (Soluble) (mg/l)	89.22	89.22	59.59	89.22	74.07	81.81	93.21
K (Total) (mg/l)	369.53	400.00	494.00	400.00	442.33	447.93	401.80
K (Soluble) (mg/l)	94.97	94.97	80.60	94.97	98.67	75.40	98.06
Ca (Total) (mg/l)	46.50	50.67	54.00	50.67	58.50	52.86	56.38
Ca (Soluble) (mg/l)	12.33	12.33	22.84	12.33	27.20	21.75	21.10
Carbon of WAS (mgC/l)	3372.46	3372.30	3598.40	3373.07	3422.28	3635.48	3723.95
Carbon of Alk. (mgC/l)	55.20	55.20	55.20	55.20	55.20	55.20	55.20

Table 5.6b present the average measured results for the effluent sludge from the AD system fed NDBEPR WAS.

Table 5.6b: Concentrations of the effluent sludge from the Anaerobic Digester

Steady State AD Sludge Age	**10 day AS Batch 14**	**12 day AS Batch 14**	**18 day AS Batch 10**	**20 day AS Batch 14**	**25 day AS Batch 13**	**40 day AS Batch 12**	**60 day AS Batch 11**
Utilisation	*Model Calibration*	*Model Validation*	*Model Calibration*	*Model Validation*	*Model Calibration*	*Model Calibration*	*Model Calibration*
COD (Total) (mg/l)	7519.8	7415.3	7234.6	7127.5	6953.9	6375.5	6080.0
COD (Soluble) (mg/l)	96.9	94.6	122.5	126.1	113.1	91.6	144.4
VFA (mg/l)	24.7	24.3	24.7	26.0	24.7	24.7	20.5
TKN (mg/l)	596.4	593.6	589.1	585.7	596.4	602.0	589.1
FSA (mg/l)	88.9	120.2	141.5	172.9	177.8	210.7	282.9
TP (mg/l)	912.7	906.0	914.6	901.1	855.2	886.2	853.2
Ortho P (mg/l)	492.1	525.4	458.7	561.0	460.4	530.7	422.8
TSS (mg/l)	7209.9	7301.0	7395.0	7250.2	7199.4	6727.0	6566.1
VSS (mg/l)	5042.6	4971.0	4933.0	4892.2	4759.7	4319.7	4182.1
ISS (mg/l)	2167.3	2330.0	2462.0	2358.0	2439.8	2407.3	2273.1
H_2CO_3* Alkalinity (mg as $CaCO_3$/l)	247.3	274.0	317.3	380.3	639.0	749.5	927.4
H_3PO_4 Alkalinity (mg as $CaCO_3$/l)	621.14	675.47	620.22	754.44	592.95	727.70	601.21
CH_4 (mmol/d)	45.09	41.57	37.68	32.24	25.98	21.61	17.99
CO_2 (mmol/d)	24.7	22.8	20.6	17.7	14.2	11.8	9.9
pH	6.75	6.80	6.93	6.92	6.81	6.97	7.06
Mg (Total) (mg/l)	257.1	252.1	296.7	273.2	299.0	251.8	274.3
Mg (Soluble) (mg/l)	24.1	23.8	24.1	22.6	25.0	25.6	24.8
K (Total) (mg/l)	348.5	391.9	394.8	373.3	400.3	376.6	404.8
K (Soluble) (mg/l)	325.7	355.8	362.5	362.5	372.4	369.0	382.3
Ca (Total) (mg/l)	43.9	43.4	43.2	42.8	39.8	26.1	48.6
Ca (Soluble) (mg/l)	41.8	37.4	28.8	34.1	26.8	20.0	45.7
Carbon of CH_4 (mgC/l)	380.11	413.79	536.94	503.08	559.44	735.94	801.06
Carbon of CO_2 (mgC/l)	247.23	264.70	323.04	324.94	316.25	474.94	399.50
Carbon of HCO_3^- (mgC/l)	50.78	60.24	86.51	76.95	112.79	117.95	196.51
Carbon of S_{bpe} (mgC/l)	805.71	744.02	652.38	563.23	496.50	262.36	153.17
Carbon of UPO (mgC/l)	1755.48	1755.48	1839.98	1755.48	1786.66	1883.66	2012.94

The trend of the influent and effluent total COD and VSS concentrations versus the steady state AD sludge age are presented in Figures 5.9a & b. The trend effluent total COD and VSS concentrations of the effluent sludge are shown in Figure 5.9c.

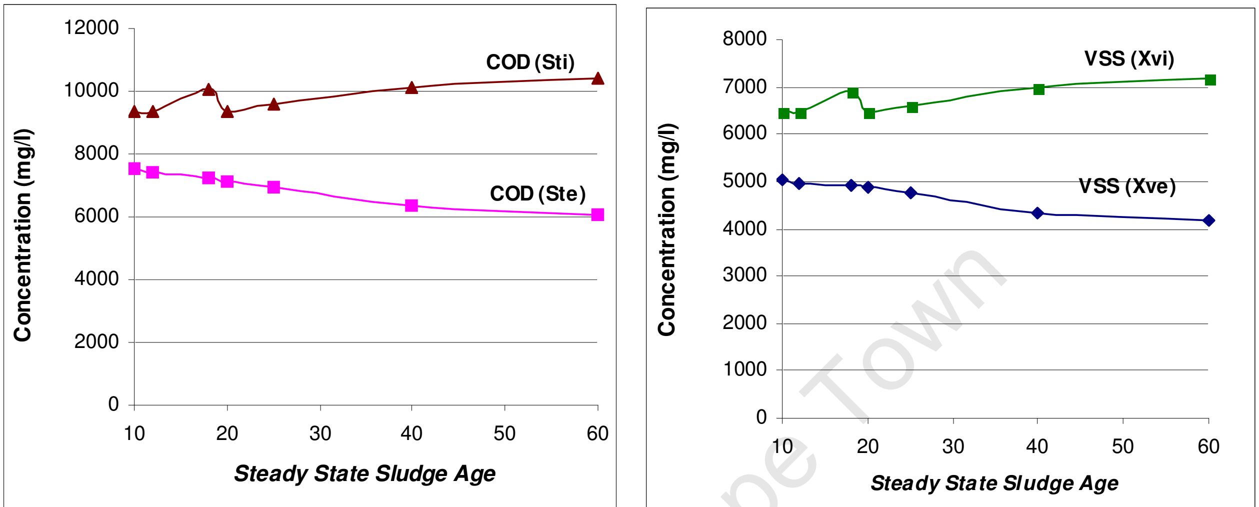

Figure 5.9a:
Comparision Influent & Effluent Sludge COD
(measured)

Figure 5.9b:
Comparision of Influent & WAS Sludge VSS
(measured)

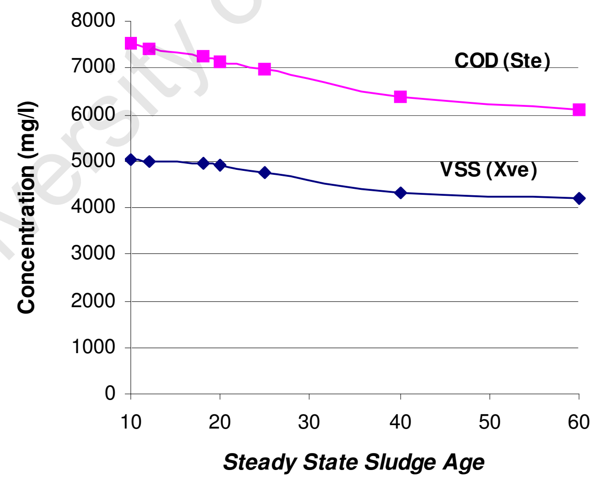

Figure 5.9c:
Effluent Sludge COD and VSS
(measured)

Figure 5.9 a to c: Comparing the COD and VSS conc. of the Influent and Waste Sludge

Figures 5.9a & b show the reduction in the COD and VSS concentrations with increased sludge age. These figures clearly show that the COD and VSS removal within the methanogenic AD process increases with R_s i.e. the longer the sludge age the greater the proportion of BPO hydrolysis and utilization. This COD utilisation is related to the methane (CH_4) production. This methane production measurement can be used to balance the COD concentration over the AD system at the various test R_s. This will be shown later in this chapter.

Furthermore, Figure 5.9c shows the relationship between the COD removal and the change in VSS concentration of the AD system. This clearly indicates that the COD removal is related to the digestion or transformation of the organic particulate component (VSS) in of the anaerobic digester.

Figures 5.9d and e present the measured TKN and FSA and TP and Ortho-P versus sludge age. The measured TKN and TP of the AD influent indicates the maximum nitrogen and phosphorus content of the WAS.

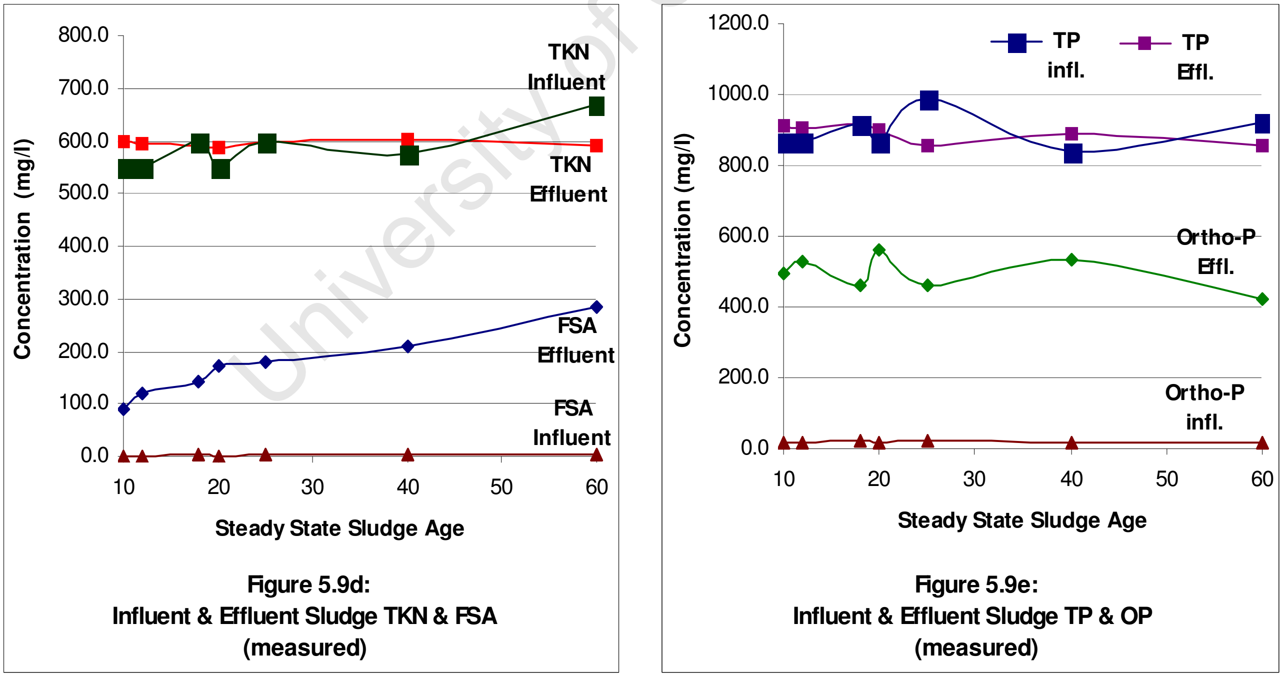

Figure 5.9d:
Influent & Effluent Sludge TKN & FSA
(measured)

Figure 5.9e:
Influent & Effluent Sludge TP & OP
(measured)

Figure 5.9 d to e: Compare TKN vs. FSA (d) and TP vs. OP (e)

Ideally (or at 100% N and P mass balance), the unfiltered TKN and TP concentrations will remain the same from the influent to the effluent of the AD system at each sludge age. This should be true at all the different AD sludge ages throughout the experimental investigation because the TKN and TP characteristics of the feed sludge to the AD system were approximately constant for all sludge ages. However, variations in the wastewater feed and operation conditions of the AS system resulted in some variations in the concentrations of the WAS. Figures 5.9d & e show that the variations in the influent and effluent unfiltered TKN and TP throughout the period of experimentation were minor and good N and P mass balances were achieved at all sludge ages.

Figure 5.9d shows that as R_s increased more of the N content of the PO VSS concentration was released as dissolved FSA. However, if precipitation of struvite (or any other mineral that contains N) occurs, the measured FSA concentration would be less than the predicted FSA because some of the produced FSA will form mineral precipitants like $MgNH_4PO_4$ (struvite).

Figure 5.9e does not indicate any overall increase in the ortho-P concentration with increased R_s. However, the dissolved ortho-P concentration is significantly higher than the influent ortho-P concentration at the shortest sludge age. This is in keeping with that observed by Jardin *et al.* (1994) who state that the stored polyphosphate content of NDBEPR WAS is released in a period less than 7 days as described in Section 2.3.4.

To confirm whether most of the polyphosphate contained by the BPO NDBEPR WAS is released at $R_s < 7$ days, experimental AD batch tests were conducted. These batch tests were setup using two 5 litre aspirator flasks each fitted with fish tank heater to control the temperature of the reactor content at 35^oC. These heaters maintained the temperature of the sludge content within a 1^oC variance from the mean temperature. These reactors were seeded with a 50:50 ratio mixture of NDBEPR WAS to effluent waste sludge from the continuously fed anaerobic digester. The waste sludge from the anaerobic digester treating NDBEPR WAS was used to seed the batch test with AD biomass. Because the unfiltered TP of the AD influent and effluent are the same (see Figure 5.9e) this blending did not dilute the TP concentration. Three sets of 11 day batch tests were conducted using the concentrated AD waste sludge to WAS mixture, batch test no.1 (11-02-08 to 21-02-08), batch test no.2 (01-03-08 to 11-03-08) and batch test no. 3 (08-07-08 to 18-07-08). The results of changes in the TP and ortho-P concentrations with time are shown in Figures 5.9f, g & h (below).

The measured P release for each of test batches reached maximum concentration at around 4 days after which it shows no further increase in P release. However, the maximum OP concentrations observed are far less than expected from the polyphosphate content of the BPO component of the NDBEPR WAS fed to the batch AD system, which should be about 3% less than the TP concentration. This indicates that either all the polyphosphate is not released or some phosphate based precipitant forms in the batch AD system during the test period. If precipitation occurs, a chemical equilibrium will exist between the solid and the aqueous phases. The variations in the concentrations at the maximum ortho-P therefore shown in Figures 5.9 f, g & h are an indication that precipitation is likely to have occurred within these batch AD systems. So, to evaluate the hypothesis of precipitant formation, the measured data will be compared to the results of the steady state AD model developed in Section 4.2, which includes hydrolysis of biomass but does not include precipitation in the AD system. This is done in a subsequent section of this chapter. If the trend of P release over the first 3 days is followed and P precipitation did not take place, then the OP concentration will reach a concentration close to that of the TP concentration at about 5 days. The batch tests confirm that most of the P release takes place within a period less than 7 days of AD operation, which was also found by Jardin *et al.* (1994).

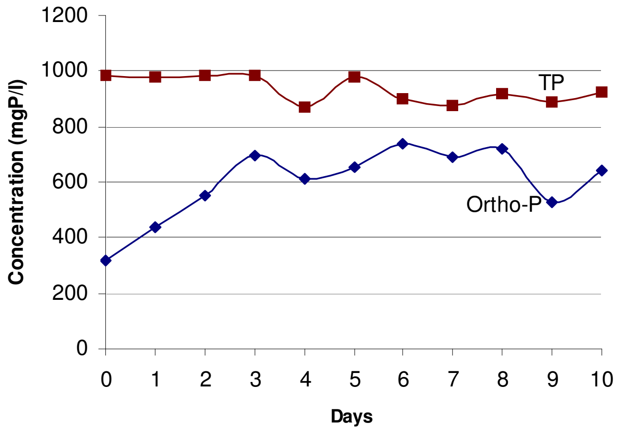

Figure 5.9f:
Batch Test No.1 (50:50) Concentrated
(P release in AD system)

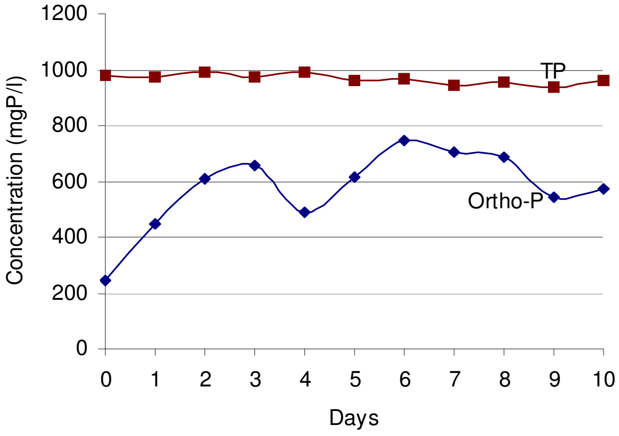

Figure 5.9g:
Batch Test No.2 (50:50) Concentrated
(P release in AD system)

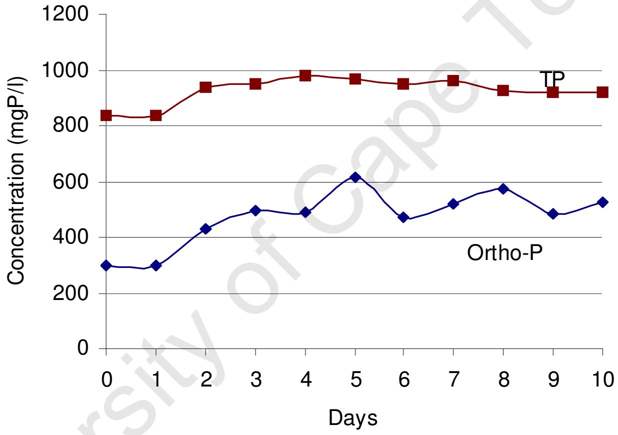

Figure 5.9h:
Batch Test No.3 (50:50) Concentrated
(P release in AD system)

Figure 5.9 f to h: Concentrated Batch Test indicating P release in Period > 10 days (50:50)

In the first of two subsequent batch tests (BT4 and BT5), the concentrated 50:50 WAS-AD effluent mixture was diluted in a 50:50 final mixture tap water (Batch test no. 4). This was done to dilute the concentration of dissolved ortho-P contained by the AD mixed liquor relative to the first mixture to possibly prevent precipitant formation in the diluted batch test.In the second (BT5), the mixture of the NDBEPR WAS to AD effluent sludge was changed to 75:25 and this was diluted as previously (50:50) resulting in the AD effluent seed sludge being diluted 8 times for this BT5. So the seed AD sludge was diluted 4 times before use in batch test no. 4 and 5 (02-08-08 to 12-08-

08) shown in Figures 5.9 I and j, but the unfiltered TP was diluted only half compared with Batch Test 1 to 3.

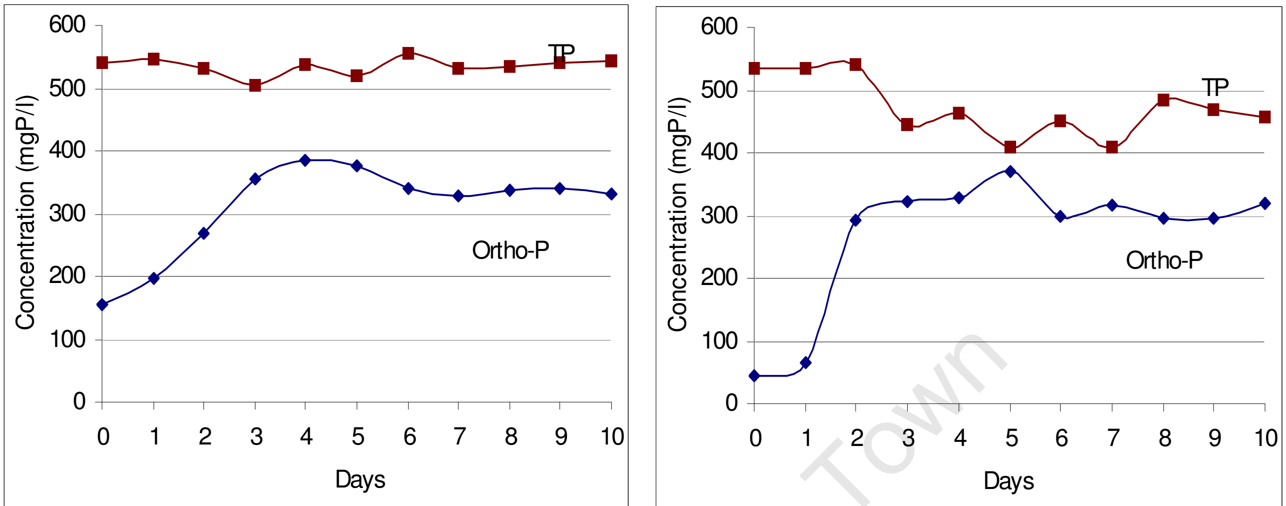

Figure 5.9i:
Batch Test No.4 (50:50) Diluted
(P release in AD system)

Figure 5.9j:
Batch Test No.5 (75:25) Diluted
(P release in AD system)

Figure 5.9i to j: Diluted Batch Test indicating P release in Period > 10 days

Figures 5.9i and j shows more clearly that most of the phosphate is released in less than 5 days from these batch tests. In these test the difference between the TP and OP is only half that in the previous more concentrated batch tests (2 times). This is a clear sign of mineral precipitation which is a concentration driven process. Still, the difference in the TP and ortho-P for the diluted test is more than that expected from the P concentration of the UPO component at a concentration of 360 mgP/l (for BT4) and 250 (for BT5) in the concentrated sludge. However, the phosphate released into the bulk liquid of the AD system are more likely to come from the stored polyphosphate as the biomass P release is related to the release of C and N components also contained by the organic parts BPO during the hydrolysis process. If the counter-ion metals associated with polyphosphate are also found in high concentration in the AD liquor at the short sludge ages of 10 and 12 days the high P concentration in solution is likely to come from the hydrolysis of polyphosphate. This is in line with findings by Jardin *et al.* (1994) and others.

Figures 5.9k & l present comparisons between the AD system influent and effluent total alkalinity and the pH. The total effluent alkalinity is subdivided into the two dominant weak acid/base system alkalinities that control the pH of the anaerobic digester i.e. the inorganic carbon (H_2CO_3*

Alk) and ortho-phosphate (Alk H_3PO_4) systems. These weak acid/base chemistry systems are described in Section 2.4.2.

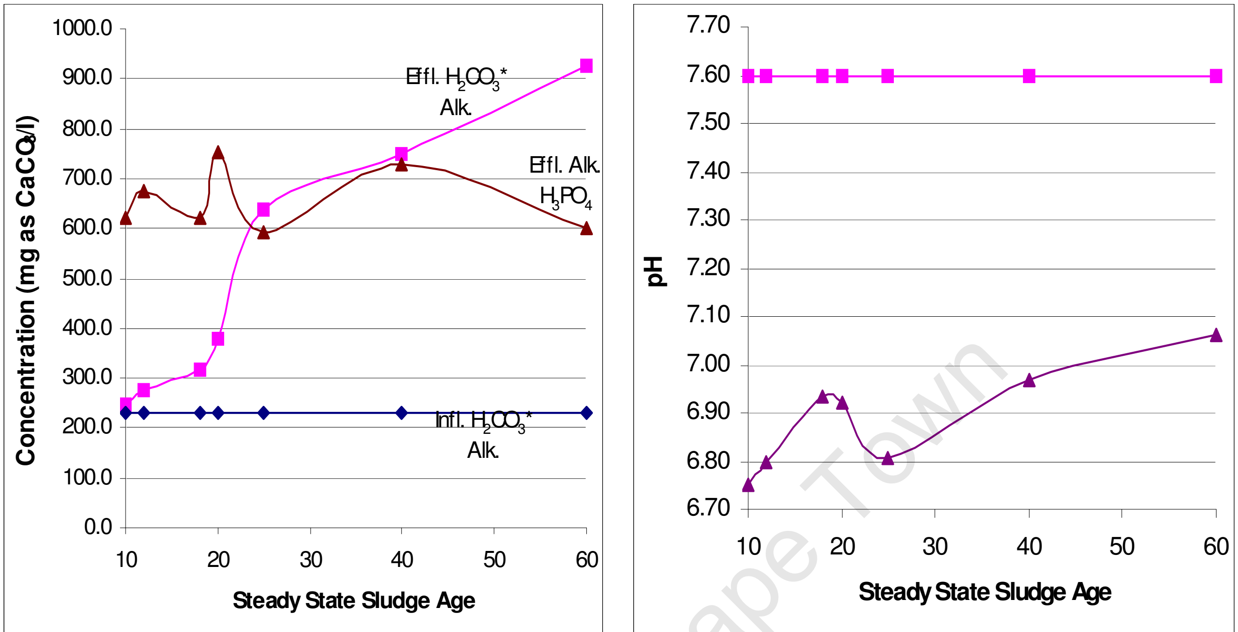

Figure 5.9k:
Change in H_2CO_3* Alkalinity & H_3PO_4 Alkalinity (measured)

Figure 5.9l:
Influent and Effluent Sludge pH (measured)

Figure 5.9k to l: Changes in the influent and effluent measured Alk. (H_2CO_3* and H_3PO_4) and pH

Figure 5.9k shows that the influent H_2CO_3* alkalinity is around 230 mg/l as $CaCO_3$ and there is a clear increase in effluent H_2CO_3* alkalinity with increase in the R_s. Furthermore, Figure 5.9i also indicates the significance of the phosphate subsystem (Alk H_3PO_4) at short steady state sludge ages. Based on the log species pH diagram for the H_3PO_4 system, the pK_{p2} value near 7.2 will have a strong influence on the pH of steady state AD at R_s < 25 days. The H_2CO_3* subsystem starts to dominate the system pH at R_s >25 days. The kinetic rate of $[H_2PO_4^-]$ / $[HPO_4^{2-}]$ release is faster than the HCO_3^- release. The organically bound nitrogen (which generates the $H_2CO_3^*$ Alk., via $NH_3 + H_2O + CO_2 \rightarrow NH_4^+ + HCO_3^-$) is released by the slower hydrolysis of the BPO component while the inorganic stored phosphorus is released in less than the 10 days R_s. However, P release still occurs at R_s >10 days from the hydrolysis of the organic biomass components which contains P. Figures 5.9 f, g, h, i & j indicate that P precipitation likely occurred and, thus, no further increase OP is observed. The detail of precipitation formation will be evaluated and confirmed in a subsequent section of this chapter.

In the study of Sötemann *et al.* (2005) the inorganic carbon species (H_2CO_3*) alkalinity is the only dominant weak acid/base subsystem irrespective of the AD sludge age. Hydrolysis is the only kinetic rate that describes the release of all the weak acid/base species to the aqueous phase that affect pH in the AD system. Since nitrogen dominates the mass content of the PO VSS concentration of PS or ND WAS, the bicarbonate species generated by $NH_3 + H_2O + CO_2 \rightarrow NH_4^+ + HCO_3^-$ has a much higher concentration in solution than the phosphorus species in the AD. Although the N and P content of the OHOs and PAOs in ND and NDBEPR WAS are the same, the dominance of the H_3PO_4 subsystem via the polyphosphate in the PAOs at shorter sludge ages is related to the kinetic rate of P release which is higher than that of the biomass N and P for the AD of NDBEPR WAS.

The higher release rate of the phosphorus species than that of the N species can be seen in Figure 5.9k. The change in the dominance of the weak acid/base subsystem relates to the change in the dominant species concentration as sludge age increases. Figure 5.9l indicates that the pH of the effluent (or digester) is lower than the influent (feed) WAS. However, there is an increase in the digester pH with increase on the sludge age. At the low R_s where Alk H_3PO_4 dominates the system, the pH is lower than at the $R_s > 25$ days where the inorganic carbon system (H_2CO_3* Alk. via HCO_3^-) dominates the pH.

Figures 5.9m and n presents the total influent, dissolved influent and effluent (Sol.) Mg and K counter-ion metal concentrations with increase in the steady state R_s of the AD system. From observation of Figure 5.9m it is evident that nearly all the influent total (unfiltered) K becomes dissolved K which remains constant with increase in sludge age. Due to the relationship between the K and Mg element in the stored polyphosphate, it was expected that the Mg concentration should also follow the trend of the K concentration. However, this is not observed, as shown in Figure 5.9m. The Mg concentration of the feed (influent) sludge is higher than that of the effluent. This observation confirms that Mg is precipitating in the AD system, but not K.

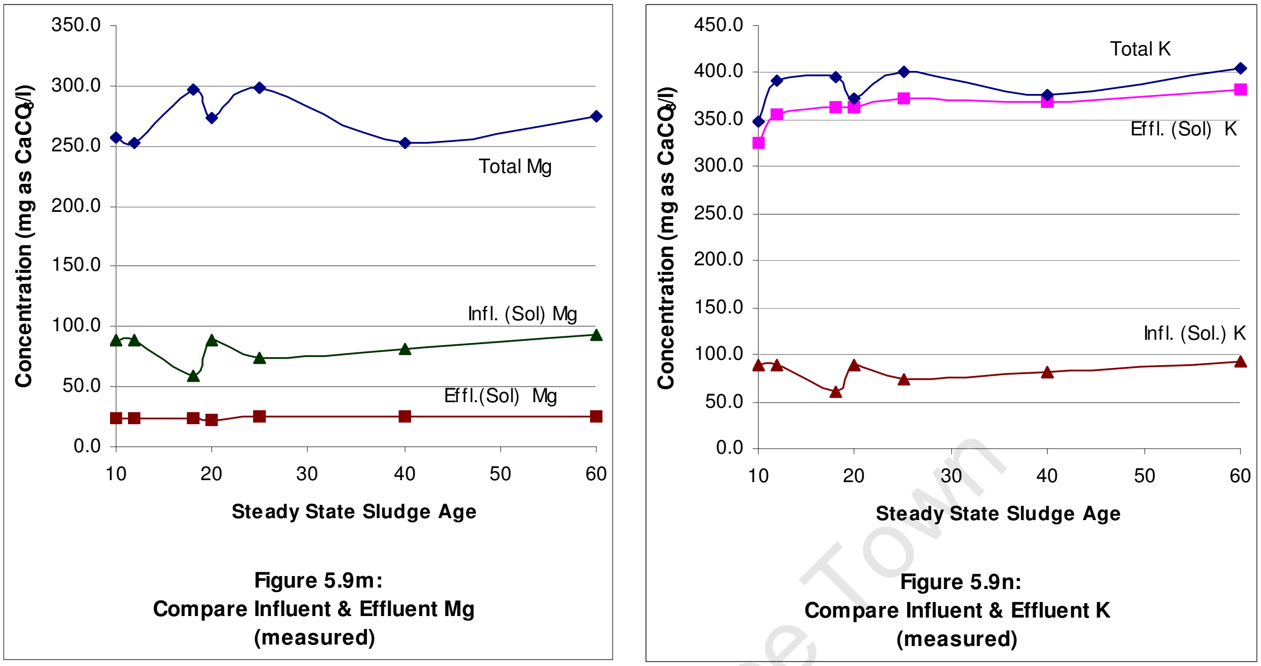

Figure 5.9m:
Compare Influent & Effluent Mg
(measured)

Figure 5.9n:
Compare Influent & Effluent K
(measured)

Figure 5.9m to n: Compare Influent & Effluent Dissolved (Sol) Mg and K Counter-ion metals

From the difference between the Mg and K results, Mg almost certainly took part in a precipitation process, like struvite ($MgNH_4PO_4$) formation, and this will be explored in a subsequent section of this chapter. Thermodynamic solubility products (K_{spm}) of possible mineral precipitants related to the products of AD system are listed in the studies of Mustovo *et al.* (2000) suggest that mineral precipitants containing K are unlikely to occur under these anaerobic digestion conditions (If NH_4^+ is limiting, which it is not the case in the AD, K can replace NH_4^+ in struvite. This is more likely to happen in aerobic digestion of NDBEPR WAS with complete nitrification). The observation that the Mg concentration of the influent and effluent sludge will be used to confirm that Mg precipitant formation occurred within the AD system.

In conclusion, this section presented and discussed important results from the experimental AD system, like the COD, VSS, TKN, FSA, TP, Ortho-P and dissolved counter-ion metal concentrations as well as the carbonate and phosphate alkalinities and AD system pH versus increase in the steady state sludge age. Reasonable explanations were provided to account for and support the trends observed from the measured data obtained at the various test sludge ages of the experimental AD system.

5.3.2 Application of the Kinetic Model to determine S_{bp} residual and utilized.

The purpose of this section is to present and discuss the UPO, determined from the AS and AD systems, and the BPO (S_{bpi}) components of NDBEPR WAS. The UPO components determined from the AS system are compared with those measured and further determined from regression plots for the AD system. This is done to evaluate whether the UPO content of the AS system changes under AD conditions. Furthermore, the results for the residual BPO (S_{bpe}) and utilized BPO [S_{bp} (utilized)] are determined, presented and discussed here. Finally, the total BPO molar flux into (J_{BPO}) and hydrolysed BPO ($J_{BPO(U)}$) molar flux to the AD system used in the stoichiometric part of the steady state AD model are presented and discussed in this section.

A. The Unbiodegradable Particulate Organics (UPO) of NDBEPR WAS

The UPO results, determined from Equation E4.2c for the AS system and determined for the AD system from the 60 day sludge age AD system and additional regression plots to find the hydrolysis rate kinetic and the best UPO fraction are presented, compared and discussed. The comparison of the UPO fractions from the AS system with that of the AD system, is the secondary aim of this study to determine whether the UPO of the AS systems remains unbiodegradable in the AD system. These results are determined as described in Section 4.2.4a and presented in Table 5.7a.

Table 5.7a: Comparison of the UPO fractions (f_{up}) of the AS and AD systems

Sludge Age	10	12	18	20	25	40	60
	Calibration	*Validation*	*Calibration*	*Validation*	*Calibration*	*Calibration*	*Calibration*
Based on Measurements and Calculations on the AS system							
S_{ti}	9355.4	9355.4	10061.8	9355.4	9589.4	10126.7	10417.9
S_{up} (UPO AS)	4998.8	4990.3	5237.5	4990.3	5086.6	5360.0	5739.4
$f_{up\ (AS)}$	0.533	0.533	0.521	0.533	0.530	0.529	0.551
Best UPO determined for regression plot on the AD system							
S_{up} (UPO AD)	5130.4	5065.3	5447.8	5065.3	5192.0	5482.9	5640.6
$f_{up(AD)}$	0.541	0.541	0.541	0.541	0.541	0.541	0.541

To visually compare the UPO determined for the AD system and that determined for the AS system, these results have been plotted and presented in Figures 5.10a & b.

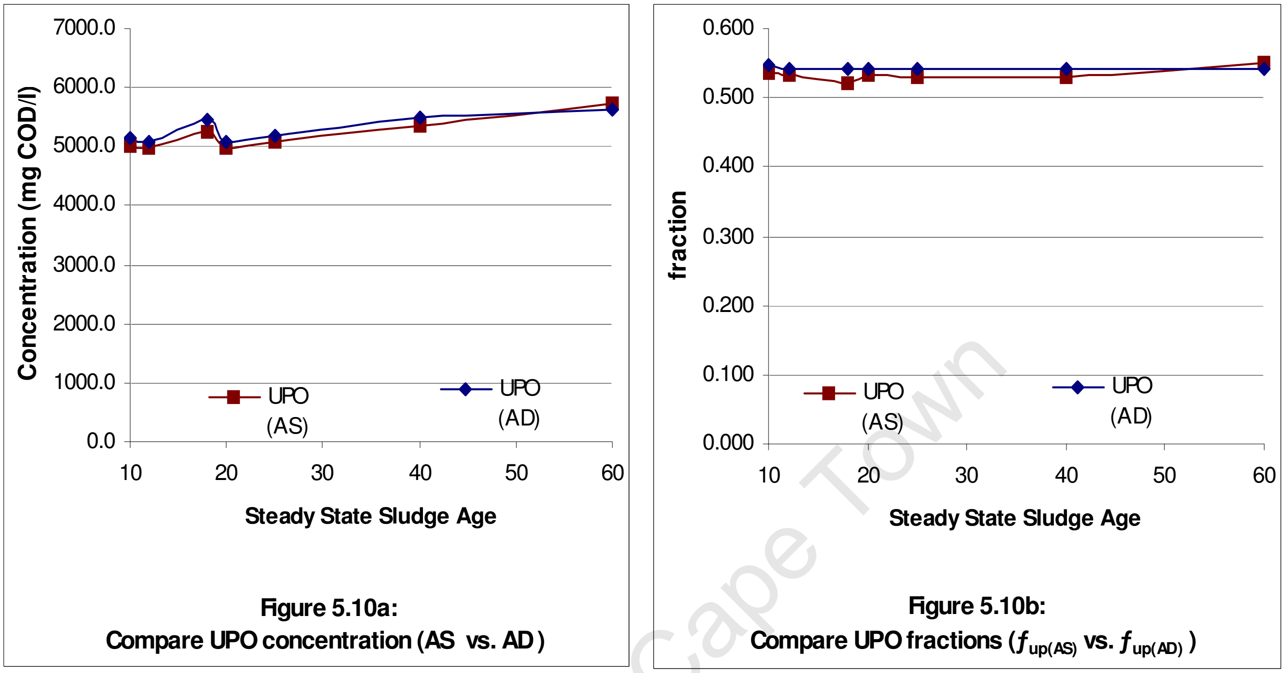

Figure 5.10a:
Compare UPO concentration (AS vs. AD)

Figure 5.10b:
Compare UPO fractions ($f_{up(AS)}$ vs. $f_{up(AD)}$)

Figure 5.10a&b: Compare UPO concentration (mgCOD/l) and fraction (f_{up}) for the AS and AD systems

Ikumi *et al.* (2009) estimated the UPO for the NDBEPR WAS $f_{up(AD)}$ in the AD system by plotting the correlation coefficients (R^2) against a range of $f_{up(AD)}$ estimates between 0.5 and 0.6 over the different AD sludge ages. This is presented in Figure 5.10c below. The $f_{up(AD)}$ value that gives the highest R^2 value is the best $f_{up(AD)}$ value for the experimental AD data set over the range of sludge ages tested and at the same time gives the best kinetic constants for the particular hydrolysis kinetics used in the correlation (Monod, First Order and Saturation).

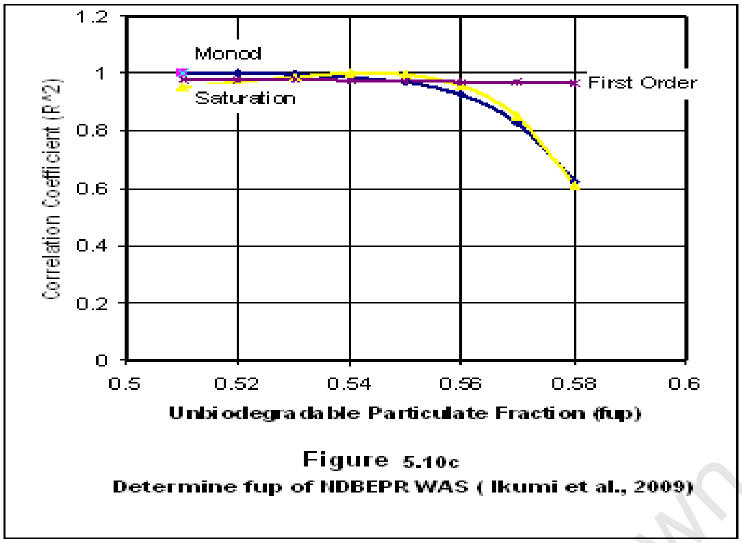

Figure 5.10c: Plot used to determine $f_{up(AD)}$ for the AD system (Ikumi *et al.*, 2009)

Figure 5.10c shows that the best R^2 values for the first order, Monod and saturation kinetics are for $f_{up(AD)}$ fractions between 0.51 and 0.545 yielding R^2 values close to 1. The $f_{up(AD)}$ value determined for the 60 day sludge age NDBEPR WAS assuming all the BPO is utilized is 0.541 which is within the is range. These values are close to the $f_{up(AS)}$ determined for the AS system from the Equation E4.2 at an average of 0.535. Therefore, it can be concluded, at least for this study, that the f_{up} fractions determined for the AS system ($f_{up(AS)}$) with the steady state AS BEPR and for the AD system ($f_{up(AD)}$) with the AD hydrolysis model are essentially the same. This indicates that the unbiodegradable organics as defined by the “aerobic” conditions of the AS system (i.e. the influent UPO, OHO and PAO endogenous mass plus 8% of the active OHO (f_{BH}) and PAO (f_{BG}) biomass) remains unbiodegradable in the AD system.

B. The Total, Residual and Utilized Biodegradable Particulate Organics

With the UPO concentration fed to the AD system known, the influent BPO concentration also is known from the AD hydrolysis model (Equation E4.17b). The UPO fraction $f_{up(AS)}$ is the input to the hydrolysis kinetic model to determine the BPO utilized [S_{bp} (utilized)] during the AD process at the different test sludge ages.

The hydrolysis kinetic models, described in Section 4.2.2.2 are applied as described in Section 4.2.2.3 to determine the residual S_{bpe}. The kinetic constants determined by Ikumi *et al.* (2009), as presented in Table 4.11a & b, are used as input parameters to Equations E4.16a to determine the residual BPO (S_{bpe}). The utilized BPO is determined using Equation E4.17 from the difference between the influent BPO and residual (effluent) BPO concentration. Table 5.7b presents the results of the hydrolysis kinetic model calculated with measurements of the AD influent and effluent COD concentrations.

Table 5.7b: The UPO & BPO (from AS & AD methods)

Sludge Age	**10**	**12**	**18**	**20**	**25**	**40**	**60**
	Calibration	*Validation*	*Calibration*	*Validation*	*Calibration*	*Calibration*	*Calibration*
Based on measurements (Calculated UPO(AS))							
S_{ti} (PO AS)	9355.4	9355.4	10061.8	9355.4	9589.4	10126.7	10417.9
$f_{up(AS)}$	0.534	0.533	0.521	0.533	0.530	0.529	0.551
S_{bpi} (BPO AS)	4225.0	4290.1	4614.0	4290.1	4397.4	4643.8	4777.3
S_{bpe} (Residual)	2139.4	2100.0	1536.8	1812.1	1511.9	642.6	189.4
S_{bp} (Utilized)	1945.7	2090.1	2827.2	2478.0	2885.5	4001.2	4587.9
f_{Sbp} (utilized)	0.46	0.49	0.61	0.58	0.66	0.86	0.96
Based on Application of Hydrolysis Kinetic Model (Calculated UPO(AS))							
S_{bpe} (Residual)	2605.6	2355.8	2131.9	1813.6	1640.3	940.1	160.4
S_{bp} (Utilized)	1891.7	2043.3	2743.6	2585.5	2904.3	3892.6	4698.5
f_{Sbp} (utilized)	0.45	0.48	0.59	0.60	0.66	0.84	0.98

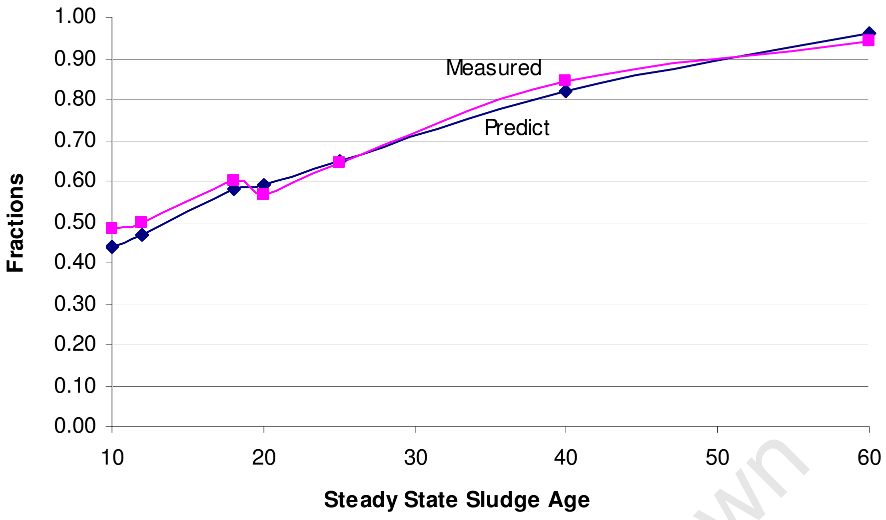

Figure 5.11:
Measrured & Predicted BPO fraction utilised

Figure 5.11: Compare Measured and Predicted BPO fraction utilized

The predicted and measured utilized BPO fractions (S_{bp} utilized as a fraction of the total AS BPO) are presented in Figure 5.11. The close correlation between the measured and predicted fractions of BPO utilized is because the measured influent and effluent COD concentrations from the AD system at the steady state sludge ages of 10, 18, 25, 40 and 60 days were used to calibrate the hydrolysis kinetic part of the AD model. The calibrated hydrolysis kinetics were then evaluated by comparing the model predicted results for 12 and 20 day sludge ages to that observed from the experimental AD system operation at these two sludge ages (Figure 5.11). A single set of hydrolysis kinetic constants was used for all the sludge ages although these constants do not align the measured and predicted results precisely the correlation is very close. The important aspect of this correlation is not the closeness of the fit to the measured results, but that it is obtained for the same unbiodegradable fraction ($f_{up\ (AS)}$) across all sludge ages (0.541).

C. Anaerobic digester feed fluxes with change in Sludge Age

The feed rate of NDBEPR WAS to the experimental AD system was determined from the AD system volume and the required steady state sludge age for the specific AD test. However, the required units for the feed rates used as input variables to the stoichiometric part of the steady state AD model, are molar flux (mmol/day). This is because the stoichiometry is expressed on a molar basis. To calculate the molar flux the elemental composition is required to convert COD concentration (mgCOD/l) to molar flux (mmol/d). This elemental composition was determined in the characterization of the WAS (Table 5.5b above). The molar fluxes of the total BPO (J_{BPO}) and the BPO utilized ($J_{BPO(U)}$) are determined from the method described in Section 4.2.4b (Eq.. 4.18b) and the results are presented in Table 5.7c below.

Table 5.7c: Influent NDBEPR WAS Volumetric and Molar Flux to the Anaerobic Digester

AD Sludge Age	10 day AS Batch 14	12 day AS Batch 14	18 day AS Batch 10	20 day AS Batch 14	25 day AS Batch 13	40 day AS Batch 12	60 day AS Batch 11
Utilisation	*Model Calibration*	*Model Validation*	*Model Calibration*	*Model Validation*	*Model Calibration*	*Model Calibration*	*Model Calibration*
Vol. flux (l/d)	**1.600**	**1.333**	**0.889**	**0.800**	**0.640**	**0.400**	**0.267**
PO Molar flux (mmol/d)	**84.4**	**69.0**	**51.5**	**35.3**	**31.0**	**21.1**	**15.3**
UPO Molar flux (mmol/d)	**45.0**	**36.5**	**26.1**	**22.1**	**18.5**	**12.1**	**8.7**
BPO Molar flux (mmol/d)	**39.4**	**32.5**	**25.4**	**21.2**	**18.8**	**11.1**	**7.6**
BPO (Utilized) Molar flux (mmol/d)	**17.6**	**15.1**	**14.3**	**13.2**	**12.5**	**9.0**	**7.1**

To visually show the reduction in the molar fluxes with change in the AD sludge age, the results from Table 5.7c are plotted in Figure 5.12 below.

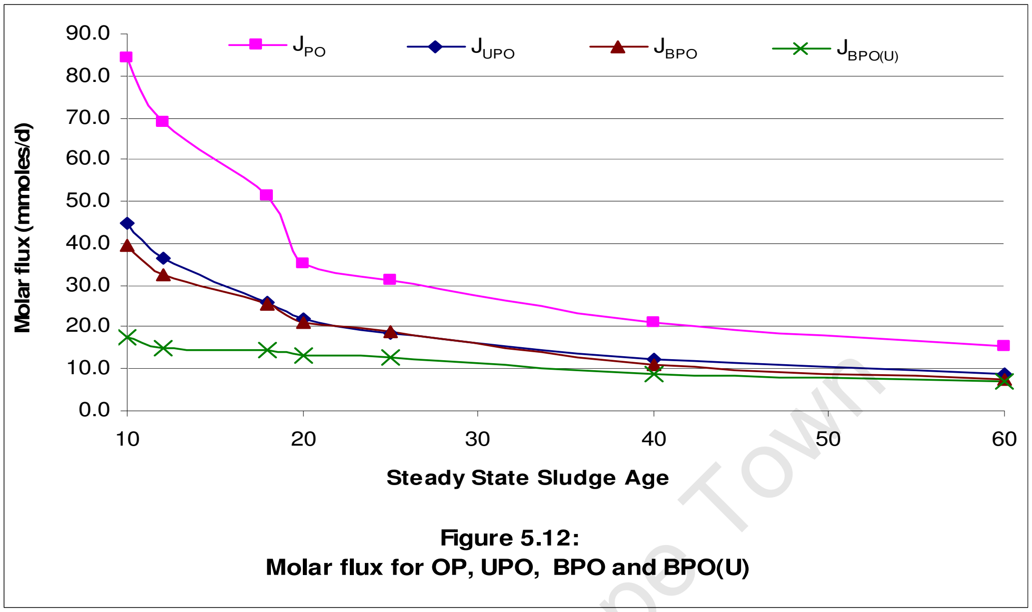

Figure 5.12: Molar flux for OP, UPO, BPO and BPO(U)

Figure 5.12 shows the decreasing trend of the J_{PO}, J_{UPO} J_{BPO} and $J_{BPO(U)}$ fed to the AD system with increase in the operating R_s. The decrease in the J_{PO}, J_{UPO} and J_{BPO} arise from the decreasing feed flow (Qi) as digester sludge age increased for fixed digester volume ($Q_i = V/R_s$ in l/d) and feed COD concentration e.g. J_{BPO} is 39.4 mmol/day at the R_s of 10 days and 10 mmol/day at an R of 60 days. The decrease in $J_{BPO(U)}$ is a combination of the decrease in influent flux and the increase in the BPO utilized because the feed COD concentration was approximately constant. The measured AD products of the experimental AD system in concentration units (mg/l) increase as the utilisation of BPO increases at longer sludge ages up to the highest at 60 days. However, in terms of molar fluxes the steady state AD model predicted results will show a decrease because flux includes the reduction in feed rate (molar fluxes). To keep the changes with sludge ages easy to interpret, the comparison of the predicted results for the AD products with those measured, concentration units will be used.

The only reason these fluxes are introduced is because the polyphosphate is all released for all sludge ages while the organic particulates that contain the polyphosphate is hydrolysed much slower. If the polyphosphate were not linked to the PAO biomass and BPO via the linkage factors (q) but considered as a molar concentration with its own hydrolysis rate and stoichiometry, the incorporation of the fluxes within the stoichiometric part of the AD model would not be required. In hindsight, for this particulate study, this would have been simpler because all the polyphosphate was released at the shortest sludge ages of 10 days, but where this not the case, then the fluxes as developed here would be required.

5.3.3 Application of the stoichiometric part of the steady state AD Model

This section presents, evaluates and describes the predicted results determined from the application of the steady state AD model and compares them with those measured on the influent and effluent of the experimental AD system. Section 4.2.4 described the procedure for determining the predicted results at the different AD test sludge ages.

The hydrolysis kinetic model described in Section 4.2.3 and applied in Section 4.2.4a to c is used to determine the utilized BPO ($J_{BPO(U)}$) and total BPO (J_{BPO}) molar fluxes. These are input variables to E4.18b for the different AD test R_s. The predicted results in mmol/d are converted to mass concentration and compared with the measured results at the different sludge ages. Comparisons of the measured and predicted COD, VSS, TKN & FSA, TP & Ortho-P, total and dissolved Mg and K counter-ion metal concentrations and the CH_4, and CO_2 gas fluxes are presented and discussed in this section. From evaluating the measured results in Section 5.3.1b above the possibility of mineral precipitation became evident. This will be further explored by comparing the measured and predicted results, and if mineral precipitation is confirmed, the effected compounds will be evaluated to determine the specific mineral precipitant.

From preliminary evaluations of the measured data in Table 5.6b and other studies into mineral precipitant formation in the AD liquor, struvite formation seems most likely. Therefore, the precipitation potential for struvite will be determined from the ionic activity products of the aqueous phase Mg^{2+}, NH_4^+ and PO_4^{-3} concentrations and check if this exceeds the thermodynamic solubility product (K_{spm}) for struvite. First, the measured and predicted results that are not affected by precipitant formation are compared and discussed. This is followed by comparing the measured and predicted results of the concentrations that are affected by precipitant formation.

An aspect that is also evaluated in detail is the relationship of the CH_4 gas flux and the COD removal from the AD system. This section shows how the COD removal from the AD system relates to the COD value of the CH_4 gas released from the AD system. The COD value of the CH_4 gas is used to determine the COD mass balance over the AD system.

A. Measured and Predicted

The stoichiometry part of the AD model is applied to determine the theoretically predicted results for the biomass growth ($C_5H_7O_2NP_{0.114}$), bicarbonate (HCO_3^-), ammonium (NH_4^+), phosphates ($H_2PO_4^-$ and HPO_4^{2-}), counter-ion metals (Mg, K and Ca) and gaseous product (CH_4 and CO_2) components. Also, the H_2O requirement of this reaction is determined to complete the H and O mass balances. The full procedure on the application of this steady state AD model is described in Section 4.2.4. The relevant predicted results used in the comparison, evaluation and discussion below are presented in the Table 5.8a. The measured data was presented earlier in Table 5.6b of Section 5.3.1b.

Table 5.8a: Predicted results from the application of the Stoichiometry part of the AD model (AD Products)

Sludge Age	**10**	**12**	**18**	**20**	**25**	**40**	**60**
	Calibration	*Validation*	*Calibration*	*Validation*	*Calibration*	*Calibration*	*Calibration*
Total COD (mgCOD/l)	7701.3	7440.7	7288.8	7056.1	6840.1	6391.7	6044.2
VSS (mgVSS/l)	5203.6	5070.2	5056.6	4784.3	4614.8	4334.8	4053.3
TKN (mgN/l)	556.1	558.6	625.7	583.4	647.2	605.5	694.6
FSA (mgN/l)	172.2	204.1	266.9	248.2	282.1	323.1	420.5
TP (mgP/l)	827.9	812.4	844.7	849.2	772.0	827.1	840.4
OrthoP (mgP/l)	693.9	685.8	716.2	733.1	658.9	726.2	701.3
Mg (Soluble) (mg/l)	159.5	157.1	149.2	178.6	166.6	211.3	221.6
K (Soluble) (mg/l)	226.9	277.7	263.0	287.5	264.7	305.3	327.6
Ca (Soluble) (mg/l)	28.76	35.30	36.59	36.53	42.33	40.95	47.75
H_2CO_3* Alkalinity (mg/l as $CaCO_3$)	211.6	251.0	360.5	320.6	469.9	491.4	818.8
H_3PO_4 Alkalinity (mg/l as $CaCO_3$)	1099.1	1092.5	1133.0	1111.6	1038.5	1053.0	1079.7
CH_4 (mmol/l)	50.7	45.8	39.8	33.5	29.8	24.5	17.8
CH_4 Carbon mass (mgC/l)	380.1	412.5	536.9	503.1	559.4	735.9	801.1
CO_2 (mmol/l)	33.0	29.4	23.9	21.7	16.9	15.8	8.9
CO_2 Carbon mass (mgC/l)	247.2	264.7	323.0	324.9	316.2	474.9	399.5
COD removed (Based on CH_4) (mgCOD/l)	1739.3	1887.0	2561.5	2779.3	3109.7	3718.5	4110.5
pH	7.34	7.36	7.34	7.23	7.33	7.11	7.23

As expected the effluent COD and VSS concentrations decrease as sludge age increase with respect to the feed concentrations. The COD concentration is removed via the CH_4 gas release from the anaerobic digester. Accordingly, the predicted COD concentration removed corresponds to the COD concentration of the CH_4 gas with respect to the influent flow because the theoretical COD balance is 100%. This will be described in more detail in Section 5.3.3b. Also, because not all the P expected from the released of polyphosphate was measured as aqueous ortho-P the results indicated towards the possibility of precipitation formation. The “missing” concentrations all appear to be components of the mineral precipitant, struvite ($MgNH_4PO_4.6H_2O$). This is the reason for determining the precipitation potential of struvite from the measured and predicted results of the relevant products of digestion. If the results from this calculation indicate the likelihood of struvite formation then the variation between the measured and predicted concentration of the relevant component will be ascribed towards its utilisation in the formation of struvite.

B. COD and VSS concentration removal and Gas Production and Composition

This section centres on the comparison of the theoretically predicted and experimentally measured COD and VSS concentrations. COD is removed from the AD system during methanogenic anaerobic digestion through the release of methane gas from this AD unit. The COD balances performed over the AD system, with exclusion of the COD concentration of CH_4, ranges between 58% and 80% for the various AD test steady state sludge ages. To obtain a more accurate COD balance it is important to measure the released gas flow rate and determine the gas composition through analytical methods. The COD of the released CH_4 gas can be quantified and then used in determining the COD mass balance over the anaerobic digester. The total COD concentration leaving the AD system is composed of the COD concentration of the effluent sludge and the COD content of the methane gas (see Section 5.1.2 above).

Figure 5.13a presents the measured and predicted results of the stoichiometric part of the AD model for the effluent COD concentration versus sludge age. These results match closely because they mirror the results of the hydrolyses part of the AD model. However, it does prove that for the same BPO utilized, the hydrolyses kinetic part and stoichiometric part of the AD model give the same COD results which it must theoretically because both are based on 100% COD balance. The predicted results for the 12 and 20 day steady state sludge age conform closely to experimentally measured results as can be observed in Figure 5.13a and so validate the kinetic and stoichiometric part of the AD model. The slight deviation in the trend at the 18 and 20 day R_s are the result of variation in the elemental composition obtained for the BPO as explained in Section 5.2.2d above.

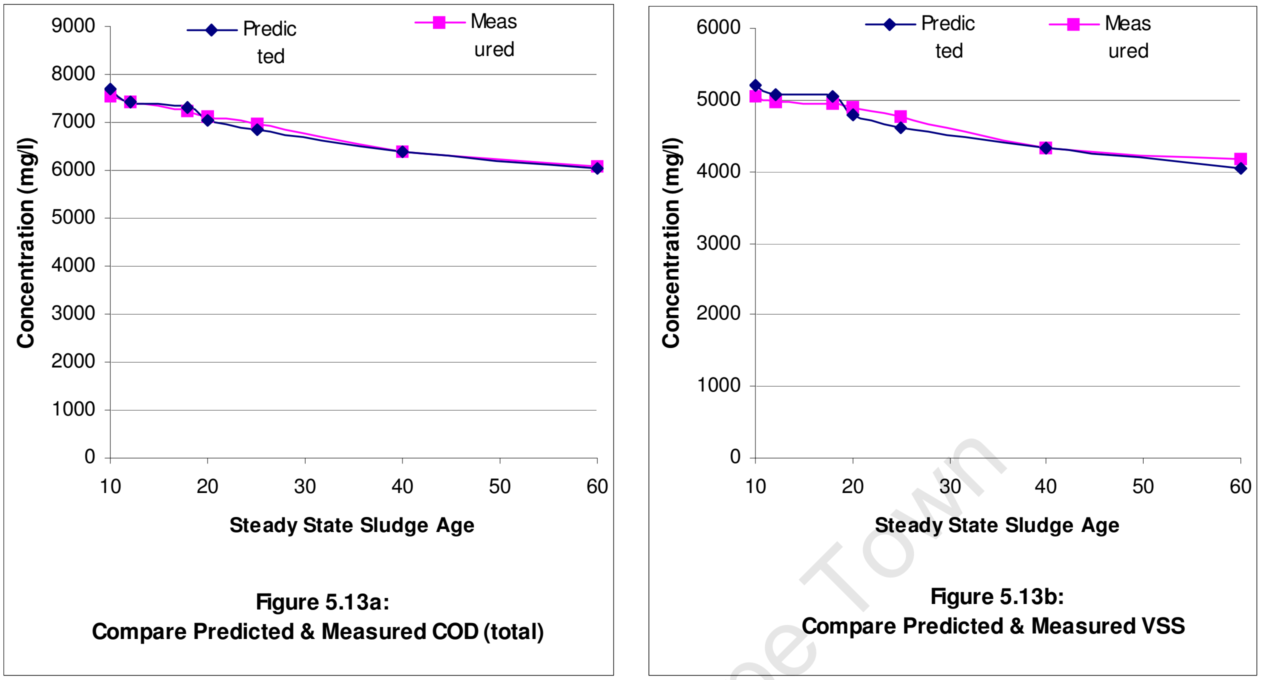

Figure 5.13a:
Compare Predicted & Measured COD (total)

Figure 5.13b:
Compare Predicted & Measured VSS

Figure 5.13a & b: Compare Predicted and Measured COD (S_{te}) and VSS (X_v)

Figure 5.13b presents the predicted and measured results for the effluent VSS concentration. Although this plot shows some variation between the measured and predicted results, this variation is acceptable for this parameter. The predicted VSS concentration deviates less than 5% from the measured results throughout the duration of this experimental investigation.

Because the CH_4 gas production is associated with the COD removal, it can be used to evaluate the COD removal of the AD system at the different sludge ages as mentioned earlier. The comparison of the measured COD removal and the CH_4 gas production, transformed to COD concentration per litre influent, provides a useful method to check the reliability of the CH_4 gas measurement results and the experimental COD balance. The comparison of the predicted and measured CH_4 results is presented in Figure 5.13c, where the predicted methane is based on 100% COD balance. Also from the stoichiometry it can be seen that the CH_4 production depends only on the COD of the organics (γ_s) and the sludge age (via Eq. E4.18b) is independent of the f value (the split between the [$H_2PO_4^-$] and [HPO_4^{2-}] concentrations).

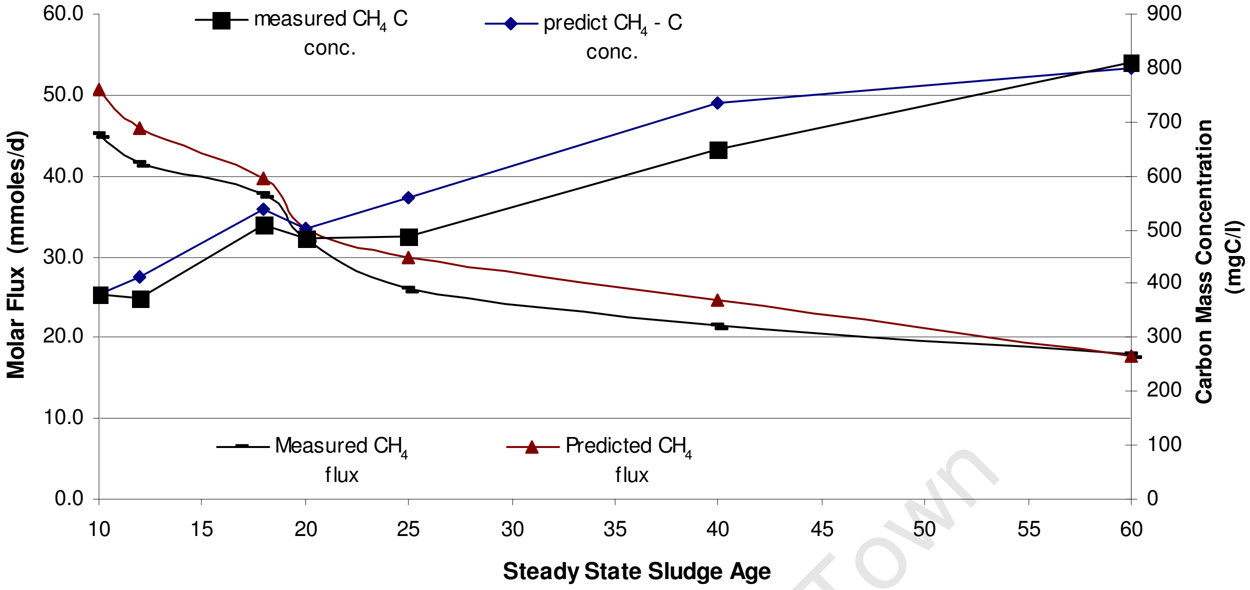

Figure 5.13c:
Compare Predicted & Measured CH_4 flux and Carbon Concentration

Figure 5.13c: Compare Predicted and Measured CH_4 fluxes & Carbon conc.

The predicted CH_4 results change consistently with change in R_s while the measured results show a higher decrease between the 18 and 25 day sludge ages. The 60 day R_s predicted and measured CH_4 fluxes correspond very closely because the predicted and measured UPO fraction ($f_{up(AS)}$) match closely. All the CH_4 gas flux results are predicted within 10% of the measured fluxes except for the 25 day R_s. A reason for this difference is the dissimilarity between the measured and predicted COD concentration at the 25 day sludge age. Although the COD results do not seem so different in Figure 5.13a, the effect is multiplied in case of the CH_4 gas flux measurements. The main reason for the difference between predicted and measured CH_4 is that the measured results do not conform to 100% COD balance and that is all on the CH_4 because the hydrolysis kinetics is matched to the effluent COD.

The measured and predicted carbon concentration (mgC/l) of the CH_4 gas released from the AD system increases with increase in the sludge ages of the system. The increasing trend of the C concentration compared with the reducing trend of the molar fluxes for the CH_4 gas is the result of the conversion of molar flux (mmol/d) to mass concentration (mgC/l) by dividing by the decreasing influent flow sludge age. The predicted and measured C concentrations correspond fairly closely with increased sludge age. The measured and predicted results for the C concentration shows no change between the 18 and 25 day sludge ages, which is the result of the higher decrease of the CH_4 gas fluxes between the 18 and 25 day sludge ages.

The stoichiometry of AD shows that the gaseous CO_2 depends on the phosphate species ($H_2PO_4^-$/ HPO_4^{2-}) in the aqueous phase i.e. the f value ($f = 0$ for 100% HPO_4^{2-} and $f = 1$ for 100% $H_2PO_4^-$). The pH of the AD is fixed by both the phosphate and inorganic carbon systems. The pH of the former is fixed by the pCO_2 and [HCO_3^-] generated which are in time also affected by the f value. The f value for which the pH of the P_t system matches the pH of the inorganic carbon system is the predicted pH for the AD (for infinite solublulity of minerals). But the P precipitation complicates this 2 phase mixed weak acid/base calculation into a 3 phase one. However, the stoichiometry also shows that the sum of the gaseous CO_2 and HCO_3^- concentrations (mmol/l) is independent of the f value and therefore also of pH. Furthermore, the sum of the [HPO_4^{2-}] and [$H_2PO_4^-$] concentrations are independent of the f value. So first the predicted CO_2 generated in both the gaseous CO_2 and dissolved CO_2 ([HCO_3^-], measured via the $H_2CO_3^*$ Alk) will be compared with that measured. Similarly, the predicted OP ([HPO_4^{2-}] + [$H_2PO_4^-$]) will be compared to the measured OP. Figures 5.13d and e shows the comparison of the predicted and measured CO_2 and HCO_3^- carbon contents.

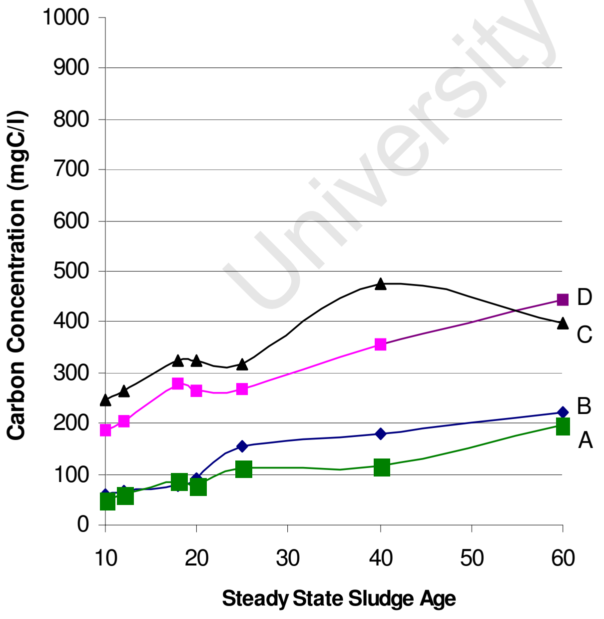

Figure 5.13d:
Predicted and Measured Exiting gas CO_2 C and Dissolved CO_2 C (HCO_3^-) Concentration

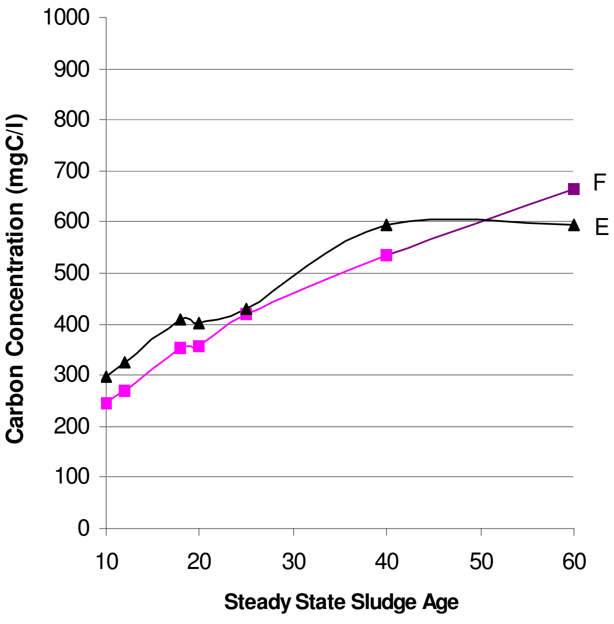

Figure 5.13e:
Predicted and Measured Exiting Total CO_2 C Concentration

Figure 5.13d and e: Compare Predicted and Measured CO_2 and HCO_3^- carbon conc. 25

(where A – Predicted HCO_3^- C, B – Measured HCO_3^-C,C – Pred. CO_2 C, D- Measured CO_2 C, E Total Pred CO_2-C and F –Total Measured CO_2-C)

The pH is calculated as follows. The ƒ value in the stoichiometric part of the AD model is varied in small steps (0.01) from 0 to 1. This changes the HPO_4^{2-} and $H_2PO_4^-$ species formed and with the pK_{p2} (≈ 7)value (H_3PO_4 and PO_4^{3-} are assumed to be negligibly small in the pH range of the normal operation of an AD system) , fixes the pH for the phosphate system. The ƒ value also affects the HCO_3^- and gaseous CO_2 concentrations. The gaseous CO_2 with the CH_4, fixes the partial pressure of CO_2 (pCO_2). The HCO_3^- and pCO_2 fix the pH for the inorganic carbon system. The ƒ value at which the pH for the phosphate and inorganic carbon systems is the same as the predicted pH for the AD system (at infinite solubility of minerals). The ƒ value that yields the predicted pH and the predicted pH are shown in Figure 5.13f versus AD sludge age.

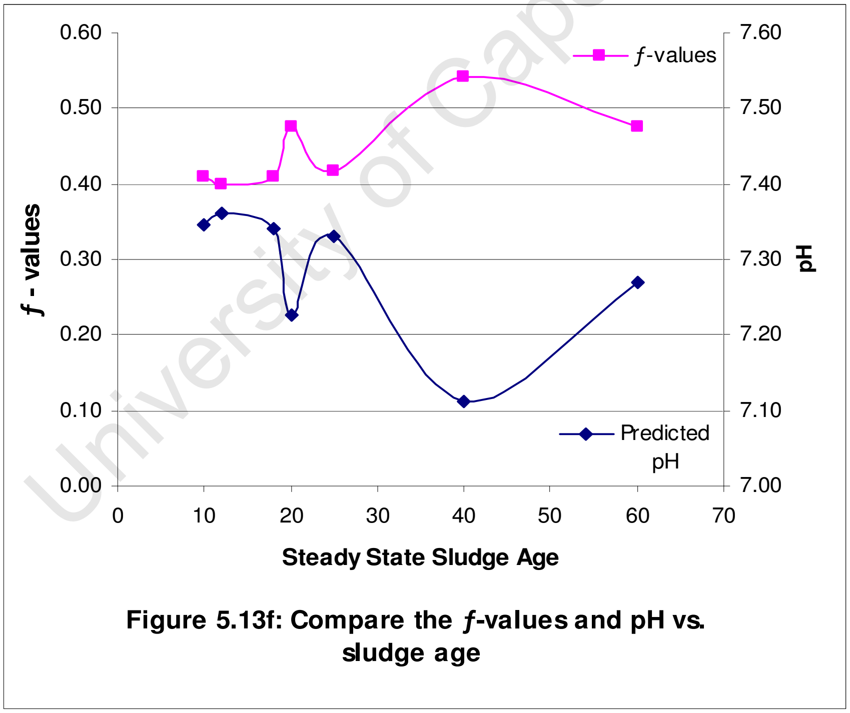

Figure 5.13f: Compare the ƒ-values and pH vs. sludge age

The biogas released does not only consist of CH_4 but also CO_2 gas, but the CO_2 gas cannot be related to the COD removal because CO_2 has no COD value. However, the CO_2 produced does relate to the carbon balance over the AD system (not forgetting that a significant proportion of the influent C exits the AD as HCO_3^-, but this is taken into account in the stoichiometry). The predicted (based on a 100% C mass balance) and measured CO_2 gas results (in flux, mmol/d units on left axis and concentration/l influent flow, mgC/l on right axis) are presented in Figure 5.13g.

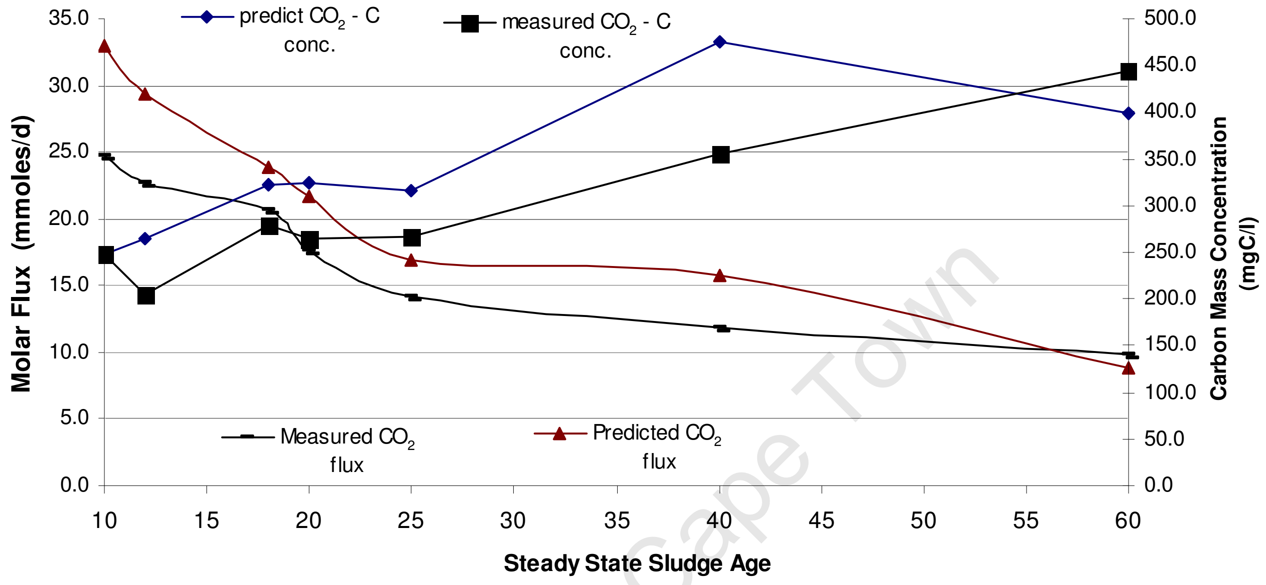

Figure 5.13g:
Compare Predicted & Measured CO_2 flux and Carbon Concentration

Figure 5.13g: Compare Predicted and Measured CH_4 & CO_2 flux (mmol/d)

Figure 5.13g shows that the CO_2 gas fluxes are considerably over predicted for all the steady state sludge ages. The CO_2 gas measurement only records the CO_2 in the gaseous phase and excludes the dissolved CO_2, most in the HCO_3^- (bicarbonate) form. The over prediction of the CO_2 is a consequence of two possible causes (i) either the assumed carbon content (f_C) allocated to the BPO component was too high or (ii) the weak acid/base chemistry of the aqueous phase changes due to the presence of the phosphate and mineral precipitation so less CO_2 exits the AD system in the gaseous phase than if no struvite precipitation occurs. Cause (i) is not very likely because the carbon mass balance obtained for the system over the different sludge ages are acceptably close to a 100% and it was therefore concluded that the calculated f_C value for the BPO component from the difference between the carbon content of the PO (BPO + UPO) and the UPO was acceptable. Cause (ii) was checked above by evaluating the measured and predicted $H_2CO_3^*$ Alkalinity for the AD system because it was noticed that over prediction of the gaseous

CO_2 is accompanied by a under prediction of the dissolved CO_2 (HCO_3^-or equivalently $H_2CO_3^*$ Alk i.e. $HCO_3^- \approx H_2CO_3^*$ Alk concentrations).

The Figure 5.13h(i) presents the measured and predicted $H_2CO_3^*$ alkalinity, where the predicted $H_2CO_3^-$ Alk was taken to be equal to the predicted HCO_3^- concentration which is reasonable at pH ≈ 7. Figure 5.13h(ii) shows the measured and predicted Alk. H_3PO_4.

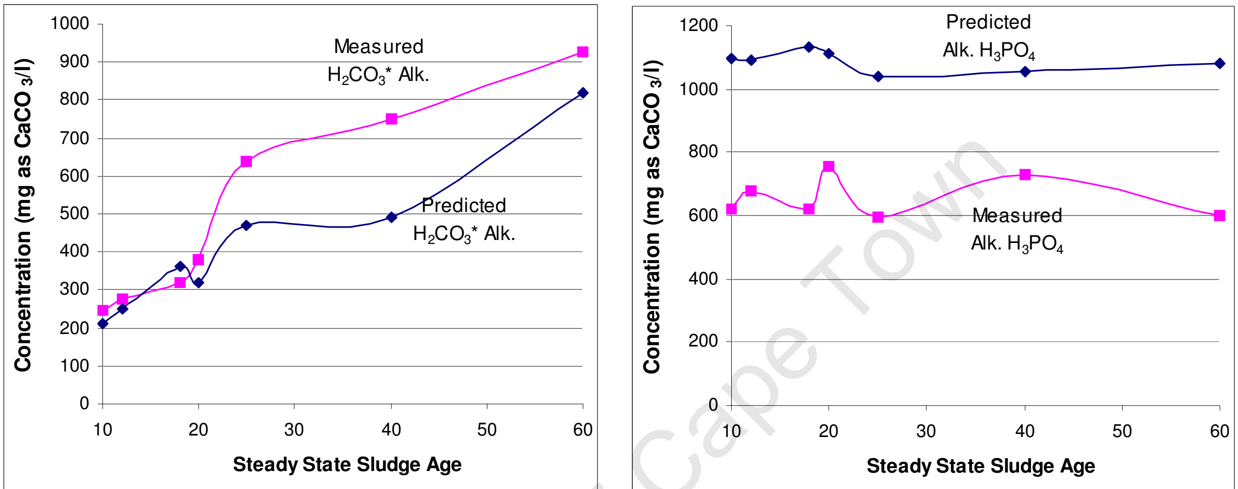

Figure 5.13h(i): Compare Predicted & Measured $H_2CO_3^*$ Alkalinity

Figure 5.13h(ii): Compare Predicted & Measured Alk H_3PO_4

Figure 5.13h(i) and (ii): Compare Predicted and Measured (i) $H_2CO_3^*$ and (ii) H_3PO_4 Alkalinity

From Figure5.13h(i) it can be seen that the $H_2CO_3^*$ alkalinity is mostly under predicted which in turn supports the CO_2 gas production being over predicted. The steady state AD model has over predicted the CO_2 in the gaseous phase and, thus, under predicted the CO_2 in the aqueous phase, as $H_2CO_3^*$ alkalinity (or HCO_3^- concentration). The cumulative CO_2 (aqueous and gaseous) predicted to exit the AD system is fairly close to the measured cumulative CO_2 exiting the AD system (Fig 5.13e) confirming the C balance. The under prediction of the $H_2CO_3^*$ alkalinity is therefore connected to the same cause as the over prediction of the gaseous CO_2 which relates to the phosphate system and precipitation formation in the experimental system compared with the steady state AD model that does not incorporate the effect of precipitation on the predicted AD products. This is confirmed by comparing the measured and predicted pH of the AD system at the different sludge ages. Higher dissolved CO_2 or HCO_3^- concentration can be related to a lower pH in a closed system where the phosphate and ammonia species remains constant. This comparison will be conducted as part of Section 5.3.3e later in this chapter.

Figure 5.13h(ii) shows the predicted and measured Alk H_3PO_4. The difference in the predicted and measured Alk H_3PO_4 indicates towards the presence of a phosphate containing precipitant in the experimental AD system. The total Alkalinity ($H_2CO_3^*$ Alk. + Alk. H_3PO_4) decreases by 3 times, the struvite concentration precipitation (both in mol/l, Loewenthal *et al.,* 1994)

As described earlier, the CH_4 gas flux is related to the BPO COD concentration removed. The Ideal Gas Law is applied to convert the CH_4 gas flux to COD concentration per litre of influent WAS removed as is described in Appendix B4. Table 5.8b and Figure 5.13i presents the results for the COD concentration removed determined from the measured CH_4 flux, the COD concentration removed determined from the predicted CH_4 flux and the measured COD concentration removal for each of the AD test sludge ages.

Table 5.8b: Measured, Predicted (Based on CH_4) & Calculated (Based on CH_4) COD removal

Sludge Age	10	12	18	20	25	40	60
	Calibration	*Validation*	*Calibration*	*Validation*	*Calibration*	*Calibration*	*Calibration*
Measurement Units	*mgCOD/l*	*mgCOD/l*	*mgCOD/l*	*mgCOD/l*	*mgCOD/l*	*mgCOD/l*	*mgCOD/l*
COD removed (measured)	1835.6	1940.1	2587.2	2628	2935.5	3751.2	4337.9
COD rem. (Calc. Ideal Gas)	1803.6	1995.4	2713.2	2578.8	2598.2	3457.5	4317.6
COD rem. (Mod. Predicted)	1739.3	1887.0	2561.5	2779.3	3109.7	3718.5	4110.5

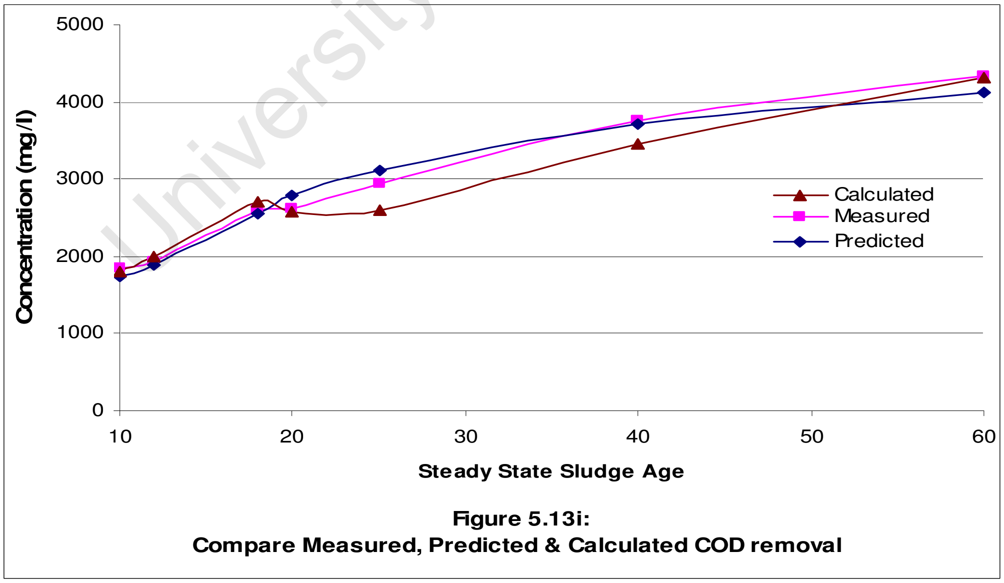

Figure 5.13i: Compare Predicted, Calculated and Measured COD removal

The predicted and calculated COD removal concentrations correspond well with the measured COD removal concentrations. The predicted and calculated COD removal concentrations of the 10, 12, 18, 20, 40 and 60 days sludge ages are within 10% variance from the measured COD removal concentration. This is acceptable in the context of this study and shows that the COD balance on the experimental AD system was close to 100%. However, the calculated COD concentration removal for the 25 days AD sludge age deviates 11% from that measured and 16% from that predicted. This deviation can be related back to the deviation found for the 25 days sludge age AD CH_4 gas flux measurement shown in Figure 5.13c, which was used to determine the calculated COD removal concentration. The reason for this deviation has been discussed earlier and is related to the variation in the COD removal observed in Figure 5.13a.

The measured and predicted carbon concentrations were determined for the each of the components of the influent and effluent that contain carbon. This was done using the f_C (TOC/VSS) values of 0.52 and 0.51 assumed for the influent VSS (PO) and UPO components respectively, as described in Section 4.1.1.2c. The assumed f_C values for the PO and UPO components were made based on the f_C (mgC/mgVSS) reported by Ekama (2009) based on studies by Ekama *et al.* (2006b), Volcke *et al.*(2006) and others, as described in Section 2.2.7. The f_C (TOC/VSS) values for the BPO components were determined by difference between the carbon content of the PO (UPO + BPO) and the C content of the UPO. Table 5.8c shows the predicted and measured carbon concentrations of the feed and products (effluent) of the AD system.

Table 5.8c: Pred. and Meas. C concentrations of the C- base components of the in- and effluent WAS

Sludge Age	**10**	**12**	**18**	**20**	**25**	**40**	**60**
	Calibration	*Validation*	*Calibration*	*Validation*	*Calibration*	*Calibration*	*Calibration*
Predicted Carbon Contents (in mgC/l)							
AD system Influent							
HCO_3^- C	55.2	55.2	55.2	55.2	55.2	55.2	55.2
Influent PO (VSS) C	3372.5	3306.3	3598.4	3373.1	3422.3	3635.5	3724.0
Total C influent	***3427.7***	***3361.5***	***3653.6***	***3428.3***	***3477.5***	***3690.7***	***3779.2***
AD products exiting the system							
CH_4	380.1	413.8	536.9	503.1	559.4	735.9	801.1
CO_2	247.2	264.7	323.0	324.9	316.2	474.9	399.5
HCO_3^-	50.8	60.2	86.5	77.0	112.8	117.9	196.5
residual C	805.7	744.0	652.4	563.2	496.5	262.4	153.2
UPO C	1755.5	1755.5	1840.0	1755.5	1786.7	1883.7	2012.9
Biomass C	128.7	122.2	117.5	101.5	94.9	78.4	60.8
Total C exiting	***3368.0***	***3360.5***	***3556.3***	***3325.2***	***3366.5***	***3553.3***	***3624.0***
Measured Carbon Contents (in mgC/l)							
AD system Influent							
HCO_3^-	55.2	55.2	55.2	55.2	55.2	55.2	55.2
influent C	3372.5	3372.3	3598.4	3373.1	3422.3	3635.5	3724.0
Total C influent	***3427.7***	***3427.5***	***3653.6***	***3428.3***	***3477.5***	***3690.7***	***3779.2***
AD products exiting the system							
CH_4	338.2	374.1	508.7	483.5	487.2	648.3	809.6
CO_2	185.2	204.9	278.6	264.8	266.8	355.0	443.3
HCO_3^-	59.3	65.8	76.1	91.3	153.4	179.9	222.6
residual C	804.0	742.5	662.0	562.0	505.3	265.2	159.3
UPO C	1755.2	1755.2	1842.2	1755.2	1789.1	1885.3	2018.7
Total C effluent	***3141.9***	***3142.5***	***3367.7***	***3156.8***	***3201.7***	***3333.6***	***3653.5***

The results in Table 5.8c is graphically presented in Figures 5.13j, k, l and m below.

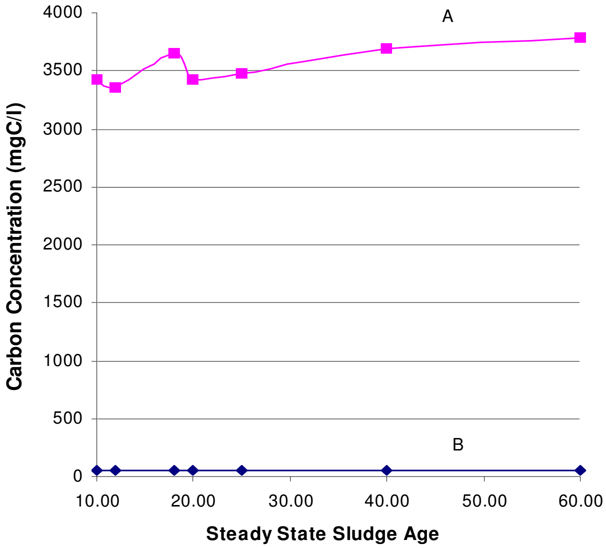

Figure 5.13j:
Predicted Influent Carbon Concentration

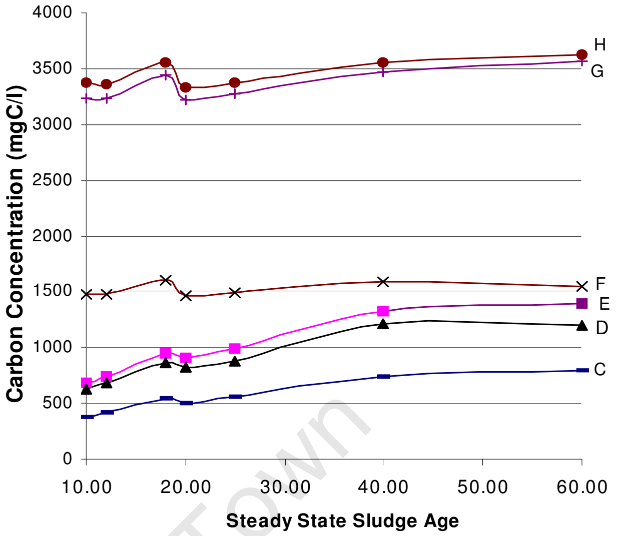

Figure 5.13k:
Predicted Exiting Carbon Concentration

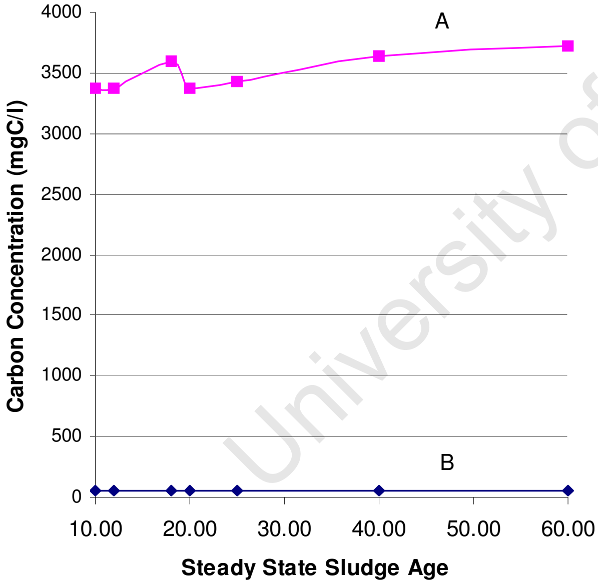

Figure 5.13l:
Measured Influent Carbon Concentration

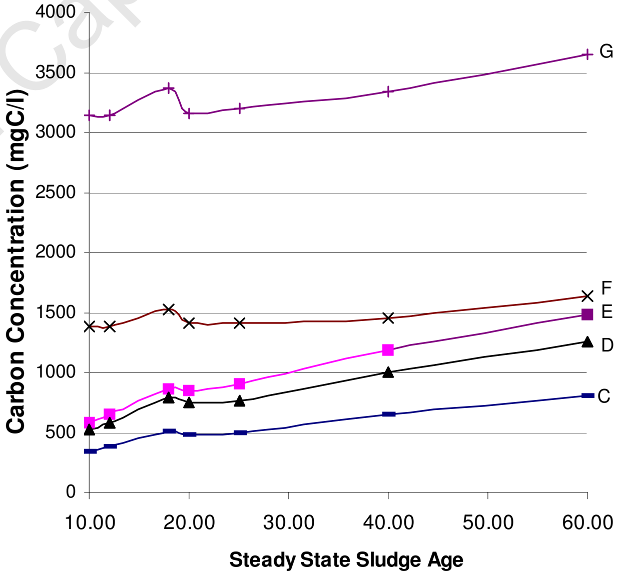

Figure 5.13m:
Measured Exiting Carbon Concentration

Figures 5.13j, k, l & m: Compare the Predicted Influent and Exiting Carbon mass concentrations *(where for both the measured and predicted: A = infl. B + WAS PO C conc.,B = infl. WAS* HCO_3^- *C conc., C = effl.* CH_4 *C conc, D = C +* CO_2 *C conc, E = D + effl.* HCO_3^- *, F= E + Res BPO C conc and G = F + UPO C conc.)*

The carbon content for both predicted and measured influent (feed) WAS (shown in Figures 5.13j and l) consists mostly of the carbon concentration of the PO (VSS) component as the C contribution of the HCO_3^- or $H_2CO_3^*$ alkalinity makes up a very small portion of the influent C concentration. The PO (VSS) component contributes more than 98% of the carbon content of the influent with the less than 2% contained by the $H_2CO_3^*$ alkalinity of the influent WAS. From Figures 5.13k and m it is observed that the C concentration of the UPO contributes the largest portion of the C concentration exiting the AD system. The UPO contributes about 53% of the total influent PO C content of NDBEPR WAS. It can also be observed that the C concentration of the UPO remains unchanged at the different sludge ages as it is not hydrolysed. Both Figures 5.13k and m also shows that the C concentration of the residual BPO (Res C) decreases with increase in sludge age as more BPO is hydrolysed at longer sludge ages and this is accompanied by an increase in the C concentrations of the CH_4 and CO_2 exiting the AD system. The effluent residual BPO accounts for about 24% of the C concentration at the 10 day R_s but is reduced to only about 4% at the 60 day sludge age. In contrast, the C concentrations of the CH_4 and CO_2 exiting the AD system were 11% and 7% respectively at the 10 sludge age but increase to about 22% and 11% respectively at the 60 day sludge age. This shows the transfer of the C content of the utilized BPO to the gaseous phase products, CH_4 and CO_2, within the AD system. The effluent C concentration contributed by the HCO_3^- or $H_2CO_3^*$ alkalinity remained a small portion (like the case of the influent) but shows an increasing trend from about 2% at the 10 day R_s to about 5% in the 60 day R_s of the AD system effluent.

C. The effect of struvite precipitation the measured and predicted results

Section 2.4.4 described the procedure for evaluating the AD system to determine whether the conditions within the aqueous phase of anaerobic digestion environment are favourable for the formation of struvite ($MgNH_4PO_4.6H_2O$). These results are presented in Table 5.8d,

Table 5.8d: Determine Precipitation Potential for Measured and Calculated Data

Sludge Age	**10**	**12**	**18**	**20**	**25**	**40**	**60**
	Calibration	*Validation*	*Calibration*	*Validation*	*Calibration*	*Calibration*	*Calibration*
Precipitation Potential determined from Measured Data (Influent)							
$pK'_{spm}{}^*$	11.78	11.78	11.78	11.78	11.78	11.78	11.78
pK_{is}	14.13	14.13	13.92	14.13	13.66	13.79	13.67
Precipitation Potential determined from Measured Data (Effluent)							
pK_{spm}	11.78	11.78	11.78	11.78	11.78	11.78	11.78
pK_{is}	12.86	13.22	12.98	12.86	13.08	12.66	12.50
Precipitation Potential determined from Predicted Data (Effluent)							
$pK'_{spm}{}^*$	11.78	11.78	11.78	11.78	11.78	11.78	11.78
pK_{is}	10.69	10.64	10.53	10.66	10.50	10.64	10.31

***** *Corrected for ionic strength i.e.* $K'spm = Kspm - \log(f_m f_d f_t)$**

Table 5.8d and Figure 5.13n present the negative logarithmic (-ℓog) results of the Ionic and Solubility products for struvite formation. The solubility product of struvite in the -ℓog form is equal to 12.6 (pK_{spm}) at $25^{o}C$ and the -ℓog of ionic product (pK_{is}) for the compounds that make up struvite (Mg, NH_4^+ and PO_4^{3-}) are determined for each R_s. If the pK_{is} is smaller or equal to pK_{spm} ($K_{is} \geq K_{spm}$) then precipitation is likely to occur. However, if precipitation has occurred in the actual (measured) AD system, then the equilibrium conditions of the aqueous compounds that make up struvite will produce a pK_{is} close to pK_{spm} indicating this solid phase is in equilibrium with the aqueous phase measurements that were taken. Appendix B3 describe the method used to determine the ionoc product (pK_{is}). This can be confirmed by comparing the measured and predicted ionic products of the components that participate in struvite precipitation (Fig. 5.13n).

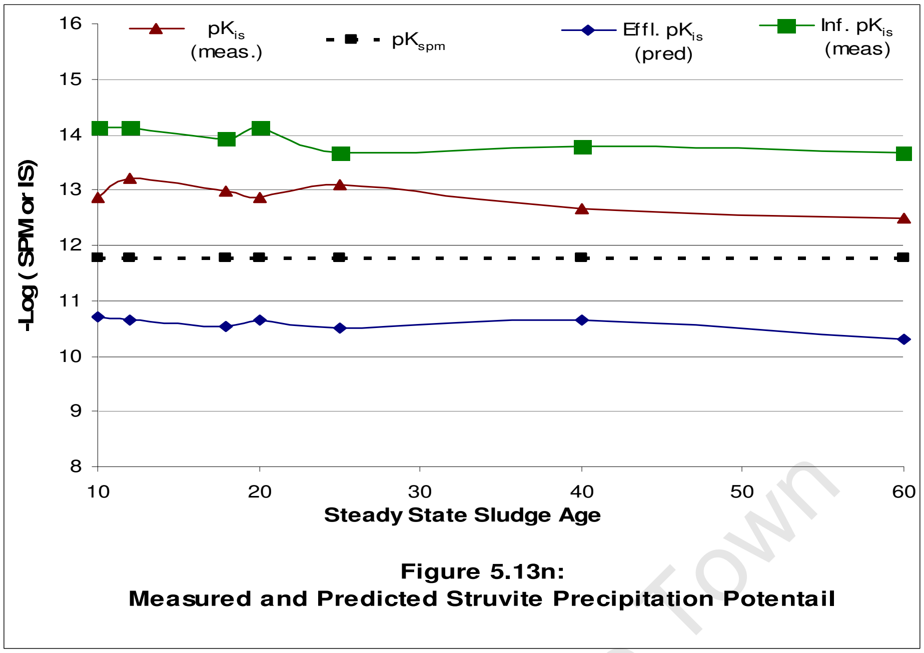

Figure 5.13n: Determine the Precipitation Potential of struvite on the Infl. & Effl.

These precipitation potential calculations are preformed using the measured aqueous concentrations of the compounds that make up struvite contained by the AD influent NDBEPR WAS and likewise for the measured and predicted AD effluent. No precipitation formation is expected to occur the feed and this is confirmed by pK_{is} results (13.9) being greater than 12.6 (pK_{spm}) [3]*. However, the trend line indicating the pK_{is} values for the stoichiometry predicted concentrations of the effluent are below (10.6) the thermodynamic solubility product (K_{spm}) of struvite line (pK_{spm} = 12.6), which indicates that struvite formation most likely occurred in the AD system. In addition, the measured effluent pK_{is} at the aqueous concentration is very close to the thermodynamic solubility product (K_{spm}) of struvite, at an average value of 12.9, indicating aqueous and solid phase equilibrium. It is therefore reasonable to accept that precipitation of struvite occurred within the anaerobic digester at all the sludge ages.

The comparison of the measured and predicted results of the compounds that make up struvite will further confirm struvite formation in the experimental AD system at all of the AD sludge ages.

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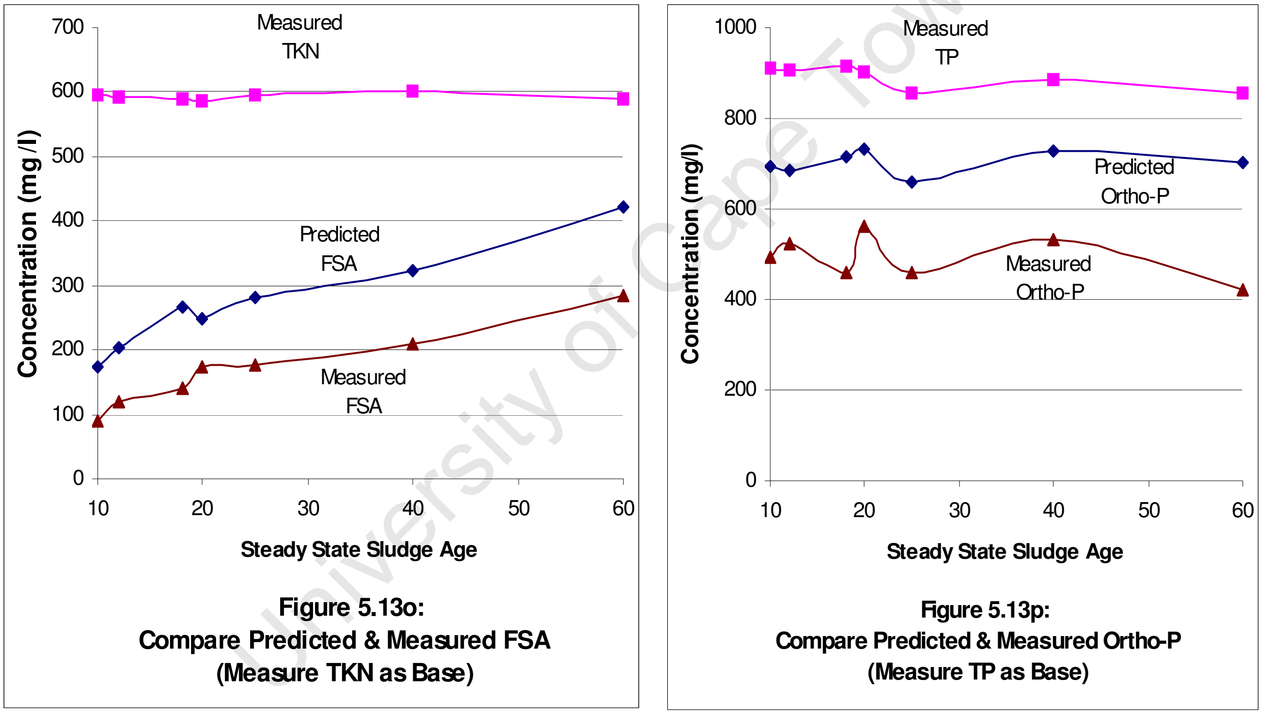
[3] * Because the pK values are the negative log a higher pK value implies a lower real number as 10^{-pK}.

D. Precipitant Forming Components

To confirm struvite precipitation, the predicted and measured results for the compounds that makeup struvite ($MgNH_4PO_4.6H_2O$), are compared. The precipitation of K^+ replacement for NH_4^+ in struvite is unlikely to occur in the AD because NH_4^+ is in excess and therefore K^+ can be used as a marker to indicate that polyphosphate has been hydrolysed and released to the bulk liquid.

Struvite components are NH_4^+ and PO_4^{3-} and the counter-ion metal Mg^{2+}. Figure 5.13o and p present the comparison of measured and predicted FSA and Ortho-P concentration in relation to the measured influent unfiltered TKN and TP.



Figures 5.13o & p: Compare Predicted and Measured FSA (with measured TKN as base)

Figure 5.13o of the measured and predicted FSA shows that the measured FSA concentrations are significantly lower than the predicted concentrations. The NH_4^+ is one of the compounds that make up struvite so a difference between the predicted and measured FSA concentrations is expected. The TKN concentration of the influent solid at the 60 day R_s is determined to evaluate whether the predicted FSA at the 60 day R_s represents all the nitrogen released by the BPO component so that only the N contained by the UPO component remains as particulate TKN

(Organic N). From the characterization of the UPO component, it was determined that the UPO has an average OrgN content of about 200 mgN/l. Figure 5.13o also shows that at the 60 day R_s, where only UPO remains, and the OrgN concentrations (TKN-FSA) is about 200 mgN/l which is close to the expected N content of the UPO component. The differences between the measured and predicted FSA concentration ranges between 60 mgN/l to 120 mgN/l and should be the N content of the struvite precipitated. If this range of N concentration was precipitated in struvite then from the Mg and P content of struvite, between 103 to 206 mgMg/l and 133 to 266 mgP/l should have precipitated also.

Similarly, a difference in the concentrations of the measured and predicted Ortho-P is expected where struvite precipitation occurs. This is shown in Figure 5.13p. In this case, the expected OrgP content of the UPO component is an average 130 mgP/l. The predicted results indicated the P content of the UPO to be about 200 mgP/ l from an f_P ratio of 0.033 mgP/mgVSS. This shows that the P content of the UPO was over estimated resulting in an under estimation of the P content of BPO. The elemental composition should therefore be recalculated but there was no time for this. The differences between the measured and predicted ortho-P ranges between 170 mgP/l to 280 mgP/l. This is the same range as estimated from the N content of the struvite above (133 to 266 mgP/l).

The measured and predicted dissolved Mg and K concentrations and the unfiltered total concentration are shown in Figures 5.13q and r.

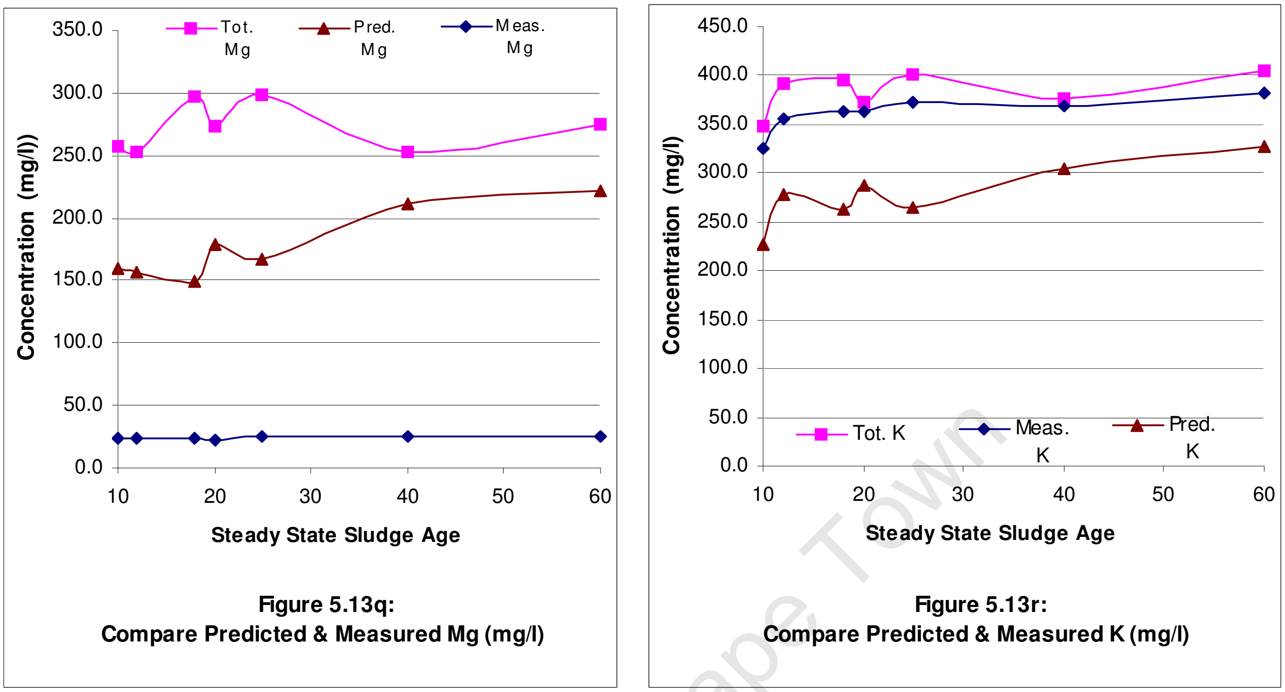


Figure 5.13q:
Compare Predicted & Measured Mg (mg/l)

Figure 5.13r:
Compare Predicted & Measured K (mg/l)

Figures 5.13q & r: Comparison Predicted and Measured Mg and K aqueous and unfiltered total

The measured dissolved Mg concentrations are significantly lower than those expected. The differences between the measured and predicted ortho-P range between 115 mgP/l to 190 mgP/l. This also matches the range of Mg concentration precipitated estimated from the N content above (103 to 206 mgMg/l). The difference between the measured and predicted FSA, Ortho-P and Mg concentrations therefore can be ascribed to these compounds being utilized in struvite ($MgNH_4PO_4.6H_2O$) formation. The differences between the measured and predicted results for the FSA, Ortho-P and Mg compounds are converted to the molar concentration units to evaluate the composition of the mineral precipitant and compare this to the molar requirement for struvite formation, i.e. 1: 1: 1 molar ratio for Mg: NH_4 : PO_4. From the ranges of the N, Mg and P precipitated between 570 and 1140 mg/l of struvite ($MgNH_4PO_4.6H_2O$) precipitated.

To support the struvite formation hypothesis, the K concentration, which does not take part in struvite formation, is compared with the Mg concentration. Both these counter-ion metals are released simultaneously during the hydrolysis of polyphosphate and are expected to be present in the same molar ratios as it exists within PO components. However, Figure 5.13q and r show that the measured K concentrations are higher than the predicted values. This means that more K was released to the aqueous phase than theoretically predicted. This could partly be due to under estimation of the P content of the BPO component and partly due to under estimation of the K component in the P: Mg: K molar ratio of the polyphosphate. In any event, the fact that the measured K concentration is higher than predicted means that at least all the polyphosphate in the PAOs was hydrolysed and released in the AD system at all the sludge ages.

The fact that the measured Mg concentrations are significantly lower than the predicted concentrations confirms that Mg precipitation took place. The measured P: Mg: K molar ratio in the feed WAS is 1: 0.276: 0.3 (without correction) and a similar molar ratio expected to exist in the AD system liquor when polyphosphate Me are released. The measured P: Mg: K molar ratio in the AD effluent is 1: 0.08: 0.71. This major change in the effluent P: Mg: K molar ratio composition is due to the struvite formation that occurs within the AD system. Because significant NH_4^+ and P concentrations remain, it is clear that the Mg limits struvite precipitation in the AD.

The differences between the predicted and measured Mg, FSA and Ortho-P are presented in Table 5.8e in molar units. This is done in an attempt to better estimate the quantity the struvite formed during the operation of the anaerobic digesters at the various AD test sludge ages. Because struvite is composed of a 1:1:1 molar ratio of Mg : NH_4 : PO_4 the compounds in Table 5.8e are presented on molar concentration units. These concentrations are plotted vs. sludge age and presented in Figure 5.13s. If all Mg, FSA and Ortho-P were taken up into struvite, then the molar ratios of each should be the same at each sludge age. This may indicate towards other mineral precipitation occurring.

At the different sludge ages, the molar concentration of struvite formed is limited to the lowest molar quantity available of the components that make up struvite. The possible struvite formation row in Table 5.8e lists these lowest molar concentrations.

Table 5.8e: Differences between measured and predicted concentration (mmol/l)

Sludge Age	10	12	18	20	25	40	60
	Calibration	*Validation*	*Calibration*	*Validation*	*Calibration*	*Calibration*	*Calibration*
Mg (Δ Meas. - Pred.)	5.64	5.55	5.22	6.50	5.90	7.74	8.20
NH_4 (Δ Meas. - Pred.)	5.95	6.00	8.96	5.38	7.45	8.03	9.82
PO_4^{-3} (Δ Meas. - Pred.)	6.51	5.18	8.30	5.55	6.40	6.31	8.98
Possible Struvite formation based on moles of available elements	5.64	5.18	5.22	5.38	5.90	6.31	8.20

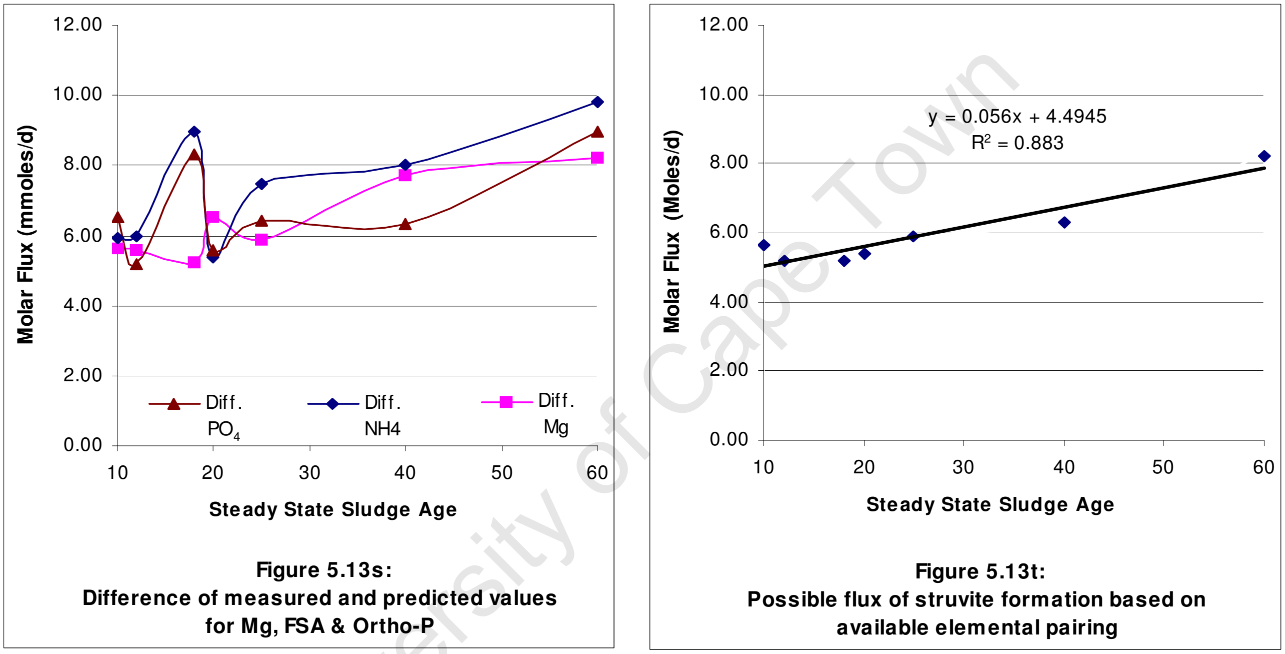


Figure 5.13s:
Difference of measured and predicted values for Mg, FSA & Ortho-P

Figure 5.13t:
Possible flux of struvite formation based on available elemental pairing

Figure 5.13s & t: Difference in struvite components and possible quantity of precipitant

Based on the lowest available concentration, the flux (flow x concentration) of struvite formed at each sludge age are plotted vs. R_s and displayed in Figure 5.13t. A linear trend fits the lowest available concentration results at about 88% and is used to describe the struvite formation trend at the different sludge ages. The Equation for the linear trend is y = 0.056x + 4.495. Where x is sludge age (R_s). Although the polyphosphate is all released at a sludge ages less than 10 days, the increase in the struvite precipitation with sludge age is probably related to the NH_4^+ and cell bound P release as the BPO is hydrolysed with increase in sludge age.

E. System pH evaluation

The predicted and measured results for the AD system pH are presented and discussed in this section. Differences in the measured and predicted pH results exist due to mineral precipitation. The weak acid/base chemistry part of the steady state AD model does not describe this precipitant formation. The pH changes when mineral precipitation occurs. Figure 5.13u shows the measure and predicted pH versus sludge age.

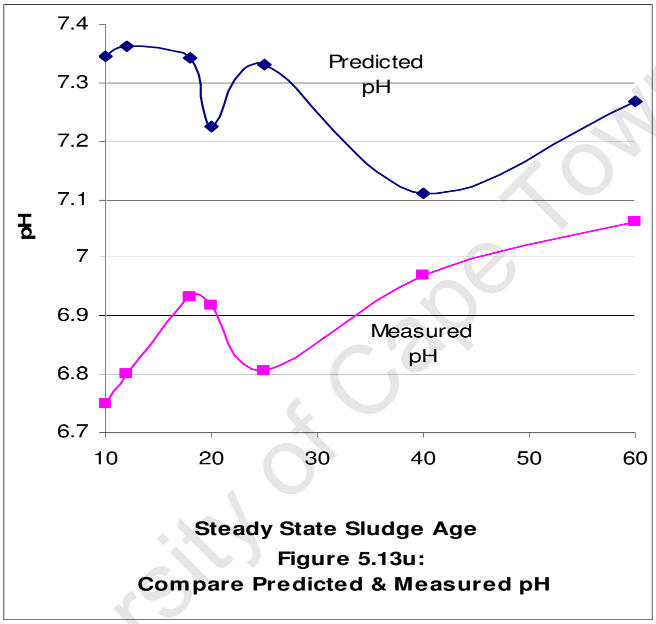


Figure 5.13u: Comparison of the Predicted and Measured pH vs. sludge age

The measured and predicted pHs varies significantly at the short sludge ages. This is due to the dominance of the phosphate species on the pH in the range of 10 to 25 days sludge age because the hydrolysis of BPO and hence the release of CO_2, is lowest. The short sludge ages are therefore where the phosphate system and struvite precipitation has the greatest effect on the pH, all the PO_4^{3-} and Mg^{2+} from the polyphosphate have been released to the AD dissolved phase at short sludge ages. The released rate of the organically bound nitrogen which is the primary generation of alkalinity through the uptake of an H^+ from $H_2CO_3^*$ (dissolved CO_2) to the form HCO_3^- is governed by hydrolysis, which is a much slower process than the hydrolysis of polyphosphate. Therefore as sludge ages increase, the inorganic carbon system begins to dominate the phosphate system making the effect of mineral precipitation on the pH smaller (see Fig 5.9k). This results in an improved AD pH prediction as sludge ages increase.

5.4 Closure

This chapter presented, compared, evaluated and discussed the experimentally measured and associated calculated results with those theoretically predicted. The measured data from the experimental setup described in Chapter Three were evaluated at the start of this chapter, Section 5.1, by means of mass balances over the AS and AD systems. The outcomes of these mass balances were evaluated and found to be acceptable for all of the elements considered viz. COD, N, P, Mg, K and Ca. Based on an assumed C content of the PO (UPO + BPO) and UPO, the carbon content of the BPO was calculated by difference. The resulting C content of the BPO yielded good C mass balances over the AD system at all the sludge ages which validate the assumed C content. In Section 5.2 the results from the application of the WAS characterization procedure described in Section 4.1 were presented and discussed. The elemental compositions of the NDBEPR WAS components (UPO and BPO) determined from the characterization procedure were found to be comparable with those found in other studies on ND WAS with respect to the organic components of the different WAS types. This section also described the calculation of the linkage factor that couples the elemental composition of the organic parts of NDBEPR WAS to the polyphosphate content stored inside the organic part of the PAOs and hence also the BPO which includes the biodegradable part of the PAOs.

In Section 5.3, the results obtained from the application of the stoichiometric part of the steady state AD model describing the digestion of NDBEPR WAS were compared with the results obtained from measurements taken from the experimental AD. This section discussed the removal of COD and how it relates to the VSS removal in the AD system. The COD removal and the COD of the released CH_4 gas were also compared and found to be closely the same. Furthermore, figures showing that most of the phosphate contained by NDBEPR WAS is released at sludge ages > 10 days are presented, which included anaerobic digestion batch test performed to evaluate the release of P during the AD of NDBEPR WAS. The effect of the difference in the kinetic rates of hydrolysis of polyphosphate and BPO were shown resulting in the dominance by the phosphate system on the AD system pH at $R_s \leq 25$ days and the shift of dominance to the inorganic carbon system on the AD system pH at $R_s > 25$ days. The UPO determined from the AS system was compared with the UPO obtained from measurements on the AD system. It was found that the unbiodegradable organics as defined by the (aerobic) activated sludge system remained unbiodegradable under AD conditions. Furthermore, it was confirmed that precipitation of struvite took place in the AD system from the difference between the measured and predicted concentrations of the elements that make up this mineral and from calculations that compared the dissolved species ionic products with the struvite solubility product.

The conclusion from this study will be presented in the next chapter (Chapter Six).

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This study presented the development of the steady state model describing the anaerobic digestion (AD) of nitrification denitrification biological excess P removal (NDBEPR) waste activated sludge (WAS) and the development of a procedure to characterize this WAS to the form required as input to the AD model. Consequently, this steady state AD model can be coupled to NDBEPR AS systems to predict the composition of the AD effluent. Previous studies conducted in the WRG to develop a mass balance based steady state plant-wide model focused on the coupling (1) a PST unit to an anaerobic digester (Sötemann *et al.,* 2005), (2) a BEPR AS system coupled to an aerobic digester (Mebrahtu *et al.,* 2008) and (3) a ND AS system to an anaerobic digester (Sötemann *et al.,* 2005). This study made significant advances to extend the existing mass balance based plant-wide steady state models by coupling the NDBEPR AS system to an anaerobic digester.

The objectives set out for this study as stated in Chapter One were fully achieved. The conclusions set out in this chapter summarize (1) the quality of the measured data collected from the UCT MBR AS system and the AD system (fed NDBEPR WAS) during the experimental investigation of this study; (2) the results of the fractionation and elemental composition determination procedure developed in this study to transform NDBEPR WAS into the required form for the AD model (its CHONP and Me elements composition); (3) the values of the linkage factors to couple the polyphosphate and organic elemental composition parts of the PAO, BPO and PO components; (4) compares the elemental composition results from this study with that of other studies; (5) summarizes the addition of the polyphosphate hydrolysis kinetics and extension of the stoichiometry part of the AD model of Sötemann *et al.* (2005) to include P and (6) describes the mixed weak acid/base chemistry of the inorganic carbon and phosphate components (HPO_4^{2-} and $H_2PO_4^-$) to determine the AD pH and the struvite precipitation potential. The chapter closes with recommendations for further research to incorporate the formation of mineral precipitation in the AD system in the AD model developed in this study.

6.2 Conclusions

The conclusions are presented in the same progression of Chapters 2, 4 and 5 described by Figure 1.1 in Section 1.6. First, the measured data obtained from the experimental AS and AD systems are evaluated. The findings from the development and application of the characterization procedure and steady state AD model are presented next. Finally this chapter presents the conclusions from the comparison of the UPO fractions of the AS and AD systems.

6.2.1 The evaluation of the experimental measured data using mass balances

Measured data collected from the experimental AS and AD systems were evaluated by performing COD, N, P, Mg, K and Ca mass balances over both systems and additionally the C mass balance over the AD system. The experimental UCT MBR AS system was operated at a constant steady state sludge age of 10 days throughout the duration of the experimental investigation and the results were numbered according to the Sewage Batch fed to the AS system. During the periods when the Ads were tested eleven sewage batches which each lasted 15 to 20 days were feed to the UCT AS system and the measured data on 7 to 10 days during each sewage batch were averaged. The mass balances were checked with the sewage batch average results. The experimental AD system was operated at steady state sludge ages of 10, 12, 18, 20, 25, 40 and 60 days. The changes in AD sludge age were aligned with the changes in sewage batch and the mass balances over the AD systems were checked with the average results measured over each AD system sludge age. The results are numbered according to the AD test sludge age. The results were presented and discussed in Section 5.1.

1. The COD mass balances for all the sewage batches of the AS system remained within 10% of the 100% target (average 98.5%) and the AD system remained within 3% of the 100% target (average 99.9%). The accuracy of the measured COD results are important as COD is used to calculate the NDBEPR WAS characteristics and calibrate the steady state AD model developed in this study. The COD mass balances achieved throughout this study were very good (better than in several previous studies) and so the COD results are acceptable for use in this study.

2. The phosphorus (P) balance over the AS and AD systems is important because the P content of the NDBEPR WAS is what differentiates this WAS characterization procedure and steady state AD model from that previously developed by Sötemann *et al.* (2005). The phosphorus mass balance varied within 10% of the 100% target for both the AS and AD systems (average 95.8% and 99.6% respectively) except for the 25 day sludge age AD test at 87%. However, this variation did not affect the results obtained for the 25 day AD when compared with the P results at the other AD sludge ages. Therefore, it was concluded that the P results from both systems were acceptable for use in this study.

3. The nitrogen (N) mass balance for the measured data of both systems varied over a wider range than that of the COD and P results. The variations in the AS system results was ascribed to variations in the measured nitrate concentration particularly in the anoxic reactor. This affects the N removal by the AS system but not the N content of the WAS, which is important for the AD system. Hence, these variations did not influence results of the N content of the WAS significantly.

4. The average C mass balance over the AD system was 92.7% (excluding about 3% for the AD biomass) and deviates less than 5% from the target 100%. These good mass balance results for the C content of the measured data that they are reliable and acceptable for use in the steady state AD model and confirmed the C mass fraction (f_C) assumed for the VSS (0.52) and UPO (0.51) components are acceptable for this study.

5. The polyphosphate counter-ion metals (Mg, K and Ca) were sampled and analysed only when the AD tests were conducted. The sample preparation procedure is similar to that of the TKN analysis, as described in Section 3.3, but much larger dilution was required for these samples. Consequently, variation and error from the preparation procedure resulted in inconsistencies in some measured results for these metals. Also, the proportion of the metals taken up into the WAS was relatively small compared with the mass/d of the influent so variation in the influent metals concentration affect the metals balance. Nevertheless, the mass balances results are all within 20% of the 100% target (average 87.1%, 101.7% and 96.9% for Mg, K and Ca respectively in the AS system and average 100.3%, 89.1% and 85.4% for Mg, K and Ca respectively in the AD system) for most parts that is acceptable for this measurement within this study.

The quality of the data collected from the UCT membrane AS system during the experimental stage of this research was found to be consistent for the COD and TP and acceptable for the N and counter-ion metals. Where relevant, the mass balance results were considered when evaluating the measured data from the AS system.

6.2.2 The WAS VSS Fractionation Procedure

The much greater (5 times) content of phosphorus and metals in NDBEPR WAS as opposed to that of PS or ND WAS introduced the need to extend and amend the WAS fractionation procedure of Sötemann *et al.* (2005) to integrate this element into the BPO and UPO components of NDBEPR WAS. This fractionation procedure consists of two steps. The first step fractionates the NDBEPR WAS particulate organics (PO) VSS into its active (OHO and PAO), endogenous (OHO and PAO) and inert organic masses from the influent and determines the P content of the PAOs. This was achieved by applying the NDBEPR steady state AS models of Wentzel *et al.* (1990) and ISS model by Ekama and Wentzel (2004) and selecting the influent UPO COD fraction (f_{upi}) so that the calculated VSS mass matches that measured and the P content of PAOs (f_{XBGP}) so that the calculated P removal matches that measured.

The VSS fractionation is then used to determine the BPO and UPO components of the WAS. The BPO was assumed to be 92% of the OHO and PAO biomass VSS concentration and the UPO the remainder of the VSS (i.e. the UPO from the influent, the PAO and OHO endogenous mass at 8% of the OHO and PAO biomass).

6. The average influent unbiodegradable fractions (f_{upi}) for Sewage Batches 3 to 14 (fed to the UCT AS system during the experimental investigation) is 0.196 with a maximum f_{upi} of 0.225 and a minimum f_{upi} of 0.167. This is close to the f_{upi} = 0.216 found by Ramphao *et al.* (2004) for the same AS system and wastewater from the same WWTP (Mitchell's Plain WWTP) used in this study.

7. The P content of the PAOs (f_{XBGP}) varied between 0.373 and 0.310 mgP/mgPAOVSS in this study was. This is less than the P content of 0.38 mgP/mgactivePAOVSS observed by Wentzel *et al.* (1989) for > 90% aerobic P uptake BEPR. However, Wentzel *et al.* (1989) study observed this for an enhanced PAO culture where the maximum P content of PAOs is 0.38 mgP/mgactivePAOVSS. The maximum polyphosphate content of the PAOs (f_{XBGPP}) was 0.35

mgP/ mgPAOVSS with the P content of the cell mass (f_{XBGPBM}) being 0.033 mgP/ mgPAOVSS (similar to the assumed value of the biological P of PAOs and OHO in this study). In this study, a mixed culture is present in the NDBEPR WAS and the average stored P as polyphosphate (f_{XBGPP}) was 0.308 mgP/mgPAOVSS. The P content of PAOs has been observed to vary in different BNR system (Ekama and Wentzel, 1999).

8. The UPO fraction ($f_{up(AS)}$) of NDBEPR WAS was found to be significantly larger at 0.535 (on average) than that of PS (0.33 to 0.36 on average). The f_{up} component of the WAS will be discussed in more detail later in this chapter in the comparison of the UPO components of the AS and AD systems.

Once the PO, BPO and UPO VSS concentrations of NDBEPR WAS were known, they were transformed to their elemental compositions in terms of carbon (C), nitrogen (N), hydrogen (H), oxygen (O) and phosphorus (P). This was done using the COD/VSS (f_{cv}), N/VSS (f_N) and P/VSS (f_P) mass ratios measured on the WAS VSS (PO). The TOC/VSS (f_C) mass ratio for the PO and UPO were assumed at 0.52 and 0.51 respectively. The hydrogen (f_H) and oxygen (f_O) mass ratios were solved by mass balance and f_{cv} ratio as described by Equation E4.7c in Section 4.1.2.

9. The measured f_{cv}, f_N and f_P mass fractions of the PO (VSS) ranged between 1.44 and 1.46 (average = 1.45) mgCOD/mgVSS, between 0.08 and 0.093 (average = 0.085) mgN/mgVSS and between 0.03 and 0.034 (average = 0.033) mgP/mgVSS respectively. These results for f_{cv}, f_N and f_P mass fractions of the PO excluded Sewage Batches 8 and 9. The f_{cv}, f_N and f_P mass fraction of the UPO were measured on the 60 day sludge age AD system effluent. The mass fractions for the BPO were determined by difference between the PO and UPO values and the estimated unbiodegradable fraction of the NDBEPR WAS (see 7 above).

10. The f_{cv} of UPO was set at 1.43 for the full extent of the experimental investigation period because the UPO component for all the AD sludge ages were determined on the effluent from the 60 day AD system. The measured f_N and f_P mass fractions for the UPO ranged between 0.047 and 0.051 mgN/mgVSS and between 0.031 and 0.036 mgP/mgVSS respectively. The f_C (TOC/VSS) for the UPO WAS assumed at 0.51 as stated above.

11. The f_{cv} of the BPO components varied between 1.44 and 1.52 over the experimental investigation. The f_N mass fractions for the BPO varied considerably between 0.096 and

0.146. This is the result of variation in the measured f_N mass fraction of the WAS (PO). Although this variation is lower, subtracting an approximately constant mass from it to obtain the N content of the BPO, amplifies the variation of the BPO relative to the PO. The f_P mass fractions range between 0.029 and 0.034 where only the values during Sewage Batches 8 and 9 are outside of this range. The significance of the variations in the results from Sewage Batches 8 and 9 will be discussed in context of the elemental composition obtained below.

The mass ratios of PO, BPO and UPO were used to determine the elemental compositions for each of these components of NDBEPR WAS in the form $C_XH_YO_ZN_AP_B$. The elemental compositions of the inorganic polyphosphate ($MePO_3$) are then added to the PAO, BPO and PO via the linkage factors (q) that is calculated from the polyphosphate content of the PAOs. This yielded the elemental compositions of the PAO, BPO and PO components of NDBEPR WAS in the form $C_XH_YO_ZN_AP_B$. q_Φ [$MePO_3$] where Φ refers to the component of WAS that the linking factor couples.

a. Linking polyphosphate to the organic

The linkage factors (q) relate the PAO polyphosphate fraction to the organic components (PAO, BPO and PO) polyphosphate content, both in terms of mol/l. Because these factors relate to the polyphosphate content to the components stated, they varies with change in the polyphosphate content of the PAOs. From the calculated P content of the PAOs (see 7 above), the q_{PAO} varied between 1.0 and 1.39 for this study due to the variation in polyphosphate content of the PAOs for different Sewage Batches fed to the AS system. Because the PAOs are a part of the BPO, the q_{BPO} is lower within the elemental composition of the BPO because it is diluted by the OHO part of the BPO that does not contain polyphosphate. The q_{BPO} factors ranged between 0.63 and 0.97 for this study.

6.2.3 Elemental Composition Calculation Procedure

The elemental compositions for the overall particulate organic (PO), UPO and BPO components of NDBEPR WAS were determined from the four mass fraction ratios (f_{CV}, f_C, f_N and f_P) to transform these components of the WAS to the required form for the input variables to the steady state AD model (see above in 10). The elemental composition of NDBEPR WAS in the form $C_XH_YO_ZN_AP_B.\boldsymbol{q_\Phi}[MePO_3]$ has not previously been determined (within the Water Research Group at UCT) and no other literature sources for the elemental composition of NDBEPR WAS could be found during this study. So the elemental compositions of the NDBEPR WAS were compared to the elemental composition of the ND WAS. Such a comparison is reasonable since the biomass of ND WAS consists of OHOs only and it is reasonable that the elemental composition of PAOs is similar to that of the OHOs (except for the polyphosphate). Therefore, this study assumed that the organic parts of PAOs are the same as that of OHOs. Hence, the organic parts BPO of the NDBEPR WAS should be comparable to that of ND WAS.

12. The elemental composition for all the components were arranged based on the molar composition of carbon for each. The results for the PO VSS composition of NDBEPR WAS ranges from $C_{5.00}H_7O_{2.11}N_{0.76}P_{0.12}.0.29[MePO_3]$ to $C_{5.33}H_7O_{2.34}N_{0.74}P_{0.14}.0.36[MePO_3]$, which is higher in terms of carbon and oxygen molar content than that found by Ekama *et al.* (2006) from the van Haandel *et al.* (1998) data, reported at $C_{4.96}H_7O_2N_{0.773}$.

13. The results for the BPO composition ranged from $C_{4.90}H_7O_{1.61}N_{1.09}P_{0.12}.0.61[MePO_3]$ to $C_{5.58}H_7O_{1.91}N_{1.18}P_{0.13}$. $0.75[MePO_3]$. The BPO of ND WAS composition ranges from $C_{4.8}H_7O_2N_{0.77}$ (Dold *et al.*, 1980) to $C_{5.67}H_7O_2N_{0.865}$ (Ekama *et al.,* 2006) for the comparative studies. Including the organic phosphorus, Volcke *et al.* (2006), quote a composition of $C_{5.02}H_7O_{2.04}N_{0.95}P_{0.113}$. These are similar to that found in this study. Generally, the elemental compositions of the organic parts of the BPO determined in this study compare well with that found in comparative studies. This provided confidence in the elemental composition determined for the BPO within this study

14. The UPO composition determined for this study ranged from $C_{5.11}H_7O_{2.63}N_{0.44}P_{0.12}$ to $C_{5.21}H_7O_{2.65}N_{0.45}P_{0.14}$. This showed lower carbon, nitrogen and phosphorus content to that reported by Volcke *et al.* (2006) as $C_{5.44}H_7O_{2.04}N_{0.75}P_{0.038}$. However, the C content is different. In both studies, the carbon content for the UPO was assumed (f_{cv} = 0.51 in this study). Nevertheless, the composition for UPO from the two studies remains reasonably similar to the UPO composition results from the AD of PS described in Section 2.2.7. Finally, the PO (VSS) component found for this study has higher carbon and oxygen molar content but is similar in terms of nitrogen to that found by Ekama *et al.* (2006) from the van Haandel *et al.* (1998) data, reported at $C_{4.96}H_7O_2N_{0.773}$.

15. Although the C content of the BPO is based on an assumed C content of the PO (f_C = 0.52) and UPO (f_C = 0.51) and the (indirectly) experimentally determined UPO fraction of the VSS (see above), the C content of the BPO was confirmed from a 97% C balance over the AD system, where the C flux exiting the AD as gaseous CH_4 and CO_2, dissolved CO_2 ($HCO_3^- \approx H_2CO_3$ * Alk.) and C on the AD biomass produced but this is very low, < 3%) was 97% of the BPO C utilized in the AD (see below)

Generally, considering the complexity of its determination the elemental composition determined for this study are generally very similar to that found from other studies on WAS. This provides confidence in the quality of elemental composition results obtained for the NDBEPR WAS in this study. This study concludes that the elemental composition found for the PO, BPO and UPO components conform well to that from studies on ND WAS.

6.2.4 Anaerobic Digestion

The steady state AD model developed by Sötemann *et al.* (2005) has been extended in this study to include organically bound P and PAO polyphosphate with its associated metals for the AD of NDBEPR WAS. This has been achieved with the generalized procedure for deriving bioprocess stoichiometry described by McCarty (1975) (see Section 4.2).

The steady state AD model developed in this study consists of three parts (i) a kinetic part that describes the kinetics of hydrolysis/acidogenesis of BPO in NDBEPR WAS, described by Ikumi *et al.* (2009), and the kinetics of hydrolysis/acidogenesis polyphosphate (see Section 4.2.2.3), (ii) a stoichiometry part that describes the reaction stoichiometry of the NDBEPR WAS BPO to the products of AD, viz, anaerobic biomass ($C_5H_7O_2NP_{0.124}$), NH_4^+, HCO_3^-, HPO_4^{2-} and $H_2PO_4^-$, Me^+ (includes Mg^{2+}, K^+ & Ca^{2+}), CH_4 and CO_2 (gas) and (iii) the mixed weak acid/base chemistry part that describes the composition of the phosphate products, HPO_4^{2-} and $H_2PO_4^-$, and the proportion of the CO_2 generated that exists the AD as gas or dissolved CO_2 (HCO_3^-) from which the AD system pH is calculated. However, due to the high P content of the NDBEPR WAS, struvite precipitation occurred in the AD system. This changes the two phase (liquid-gas) mixed weak acid/base chemistry of the inorganic carbon and phosphate systems to a three phase (liquid-gas-solid) system. This added complexity was not addressed in this study so the struvite precipitant cannot be quantified with this steady state AD model, only the precipitation potential of struvite is determined. From the steady state model describing the anaerobic digestion of NDBEPR WAS it was found that:

16. The hydrolysis/acidogenesis kinetic rate defines the AD of the BPO of NDBEPR WAS. The hydrolysis kinetic rates determined by Ikumi *et al.* (2009) in the parallel project to this were used to determine the BPO concentration utilized for this study. These kinetic rates were determined from the AD measured data relating the change in COD concentrations (influent minus effluent) at the different test steady state sludge ages selected for the experimental AD system operated during this investigation. The predicted effluent COD concentration from the calibrated steady state AD hydrolysis model varied less than 5% of the measured values. The VSS concentration removal was closely related to the COD concentration removal for all the AD system sludge ages investigated in this study.

17. The rate of polyphosphate hydrolysis in AD is much faster than that of the BPO that contains it. Literature and batch test in the investigation indicated that all the PAO polyphosphate was released at a sludge age < 7 days (see 11 above).

18. From 17 above it was accepted that for all AD sludge ages (> 10d), all the polyphosphate was released. To deal with the different rates of polyphosphate and BPO hydrolysis, the influent BPO and utilized BPO concentrations at the different sludge ages are converted to molar fluxes (mol/d). These influent BPO and utilized BPO fluxes in mmol/d were incorporated into the stoichiometry part of the AD model to ensure that the production rates for the different AD products conform to those observed. The volumetric fluxes in litres/day are 1.6, 1.333, 0.889, 0.8, 0.64, 0.4 and 0.267 at the different sludge ages of 10, 12, 18, 20, 25, 40 and 60 days respectively. At these volumetric fluxes the J_{BPO} and $J_{BPO(U)}$ were 39.4, 32.5, 25.4, 21.2, 18.8, 11.1 and 7.6 for the influent BPO components and 17.6, 15.1, 14.3, 13.2, 12.5, 9.0 and 7.1 for the utilized BPO at the above sludge ages respectively. The same (but simpler) result would have been obtained if polyphosphate and BPO were considered separate compounds described by separate hydrolysis rates and stoichiometries. (see 12 above).

19. The COD, C, N, P and counter-ion metal mass balances and continuity basis of the steady state AD model ensures that the reaction stoichiometry relates exactly the quantity of substrate (BPO of NDBEPR WAS) to the quantities of AD products produced. The steady state AD model predicts results for the methane (CH_4) and carbon dioxide (CO_2) gas generated, the ammonium (NH_4^+), bi-carbonate (HCO_3^-), counter-ion metals (Mg^{2+}, K^+ and

Ca^{2+}), the ortho phosphates ($H_2PO_4^-$ and HPO_4^{2-} depending on AD system pH) and anaerobic biomass AD products at the different sludge ages.

20. The predicted results of the AD products were compared with the corresponding measured results. For the concentrations not affected by pH and struvite precipitation i.e. methane (CH_4) and total CO_2 (sum of the gaseous CO_2 and HCO_3^- obtained from the $H_2CO_3^*$ Alk.) the model predicted values compared well with the experimentally measure results. The K concentration was significantly under predicted. These could be due to an underestimate of the K content of the polyphosphate from the UCT AS system results. However, it validated that all the polyphosphate was released at AD sludge ages ≥ 10 days. The results were acceptably close for the CH_4 gas at 50.7 mmol/d (predicted) and 45.1 mmol/d (measured) at the 10 day sludge age and 17.8 mmol/d (predicted) and 17.9 mmol/d (measured) at the 60 day sludge age. The CH_4 gas flux results for all the different sludge ages were predicted within 10% of the measured flux results. The difference between the measured and predicted CO_2 gas and aqueous HCO_3^- results could be explained based on the mixed weak acid/base chemistry that shows the dependency of the CO_2 gas, the $H_2CO_3^*$ Alkalinity and the AD pH on mineral precipitation. The steady state AD model over predicted the CO_2 in the gas phase and under predicted the CO_2 in the aqueous phase because struvite precipitation changed the pH of the experimental ADs.

21. The measured and predicted carbon concentrations were determined for each of the component of the influent and effluent that contain carbon by using the assumed f_C values of 0.52 and 0.51 for the VSS (PO) and UPO components respectively. The assumed f_C value for the BPO components was determined from the assumed f_C for the PO and UPO. Within the feed WAS, the PO (VSS) component carbon content contributed to more than 98% of the total carbon concentration of the influent with the less than 2% of the C concentration contained by the influent $H_2CO_3^*$ alkalinity. The C concentration of the UPO remains unchanged from the influent to the effluent as it is not affected by the AD processes and accounted for about 53% of the C concentration exiting the AD system for both the measured and predicted results. The effluent residual BPO accounts for about 24% of the C concentration at the 10 day R_s but is reduced to only about 4% at the 60 day sludge age. In contrast, the C concentrations of the CH_4 and CO_2 exiting the AD system were 11% and 7% respectively at the 10 sludge age but increased to about 22% and 11% respectively at the 60 day sludge age. This shows the transport of the C content of the utilized BPO to the gaseous phase products, CH_4 and CO_2,

within the AD system. The effluent C concentration contributed by the HCO_3^- or $H_2CO_3^*$ alkalinity remained a small portion (like in the case of the influent) but showed an increasing trend from about 2% at the 10 day R_s to about 5% in the 60 day R_s of the AD system effluent.

22. For those concentrations affected by struvite precipitation, i.e. Mg, OrthoP and NH_4^+, $H_2CO_3^*$ Alk. and pH there were significant differences between the predicted and measured results. This indicated the possibility of struvite formation at all the experimental AD system sludge ages. Struvite precipitation was confirmed from the calculated ionic product of the measured molar concentrations of Mg^{2+}, FSA and PO_4^{-3} (determined from the measured Ortho-P and the equilibrium equations) in solution, which exceeded the thermodynamic solubility product (K_{spm}) of struvite in the aqueous phase. Therefore, it was evident that struvite formation occurred during the normal operation of the experimental AD system. Because the AD model for NDBEPR WAS does not include mineral precipitation, the concentrations affected by struvite precipitation, Mg^{2+}, NH_4^+, PO_4^{-3}, pH and $H_2CO_3^*$ Alk do not correlate well between predicted and measured values. The quantification of the mineral precipitation struvite is beyond the scope of this study.

In conclusion, regarding the stoichiometric part of the AD model results measured, the results of the concentrations that are not affected by struvite formation compare well with the measured results. Furthermore, this AD model determines the expected results for all the concentrations if struvite if precipitation did not occur.

6.2.5 Compare the UPO fractions form the AS and AD systems

In this study the unbiodegradable particulate organic (UPO) fraction ($f_{up(AS)}$) was determined for the NDBEPR AS system based on the AS system behaviour. Also the unbiodegradable fraction of the solids (as COD, $f_{up(AD)}$) fed to the ADs was determined from the measured AD behaviour. The $f_{up(AS)}$ and $f_{up(AD)}$ were compared to assess whether or not the UPO content of WAS from the NDBEPR AS system remains unbiodegradable in an anaerobic digester.

23. The UPO content of the WAS from the AS system comprises (1) the enmeshed UPO from the influent (X_{inert}), (2) the PAO and OHO endogenous mass (X_{EG} and X_{EH}) produced in the AS system and (3) the unbiodegradable particulate content of the PAO and OHO biomass which was accepted at a fraction of 0.08 of the PAO and OHO VSS concentration. The $f_{up(AS)}$ (UPO

of the AS system) were determined for the WAS harvested from the NDBEPR system and found to be 0.533, 0.533, 0.521, 0.533, 0.53, 0.529 and 0.551 when the AD sludge age was 10, 12, 18, 20, 25, 40 and 60 day respectively. This resulted in a mean WAS $f_{up(AS)}$ of 0.533 during the period of AD tests.

24. Ikumi *et al.* (2009) used the correlation coefficients (R^2) to determine the $f_{up(AD)}$ from the measured AD performance data with sludge age. The UPO ($f_{up(AD)}$) of the feed WAS was determined by selecting an unbiodegradable particulate COD fraction ($f_{up(AD)}$) and statistical curve fittings of measured influent and effluent COD concentrations for three hydrolysis rate equations (first order, Monod and saturation kinetics). The $f_{up(AD)}$ that maximizes the correlation coefficient (R^2) was the best estimate. The $f_{up(AD)}$ was determined to be 0.54 for the NDBEPR WAS fed to the AD system during the experimental investigation. This value is very close to the UPO fraction calculated from the influent and effluent measurements of the 60 day sludge age AD system at 0.55. The unbiodegradable COD fraction of the WAS determined from the AS system data ($f_{up(AS)}$) and Ad performance data ($f_{up(AD)}$) are therefore nearly the same.

25. From 24 it was concluded that the UPO content of the NDBEPR WAS as defined by the AS system remains unbiodegradable in the AD system. This is a remarkable result considering that it was assumed that the unbiodegradable fraction of the OHOs and the PAOs in the AS system when generating endogenous residue is f_{EH} = 0.2 and f_{EG} = 0.25, but of the OHO and PAO biomass when anaerobically digested is 0.08 for both. If the endogenous respiration model values are used for the OHO and PAO biomass to determine the UPO fraction of the NDBEPR WAS, then a much higher UPO fraction is obtained and the AD performance data would then suggest that some of the OHO and PAO unbiodegradable fraction is biodegradable in the AD. This is an interesting plant-wide modelling issue to investigate more closely.

26. This is the third investigation in which it has been found that the unbiodegradable organics as defined by the AS system, remain unbiodegradable in the AD system, (1) for PS (Sötemann et al., 2005; Ekama *et al.*, 2006a), for WAS from ND AS systems (Ekama *et al.*, 2006b) and now for NDBEPR WAS in this investigation. This razes the question whether the mechanical, thermal or chemical sludge pre-treatment to achieve greater COD and/or VSS redaction in the AD, (i) increase the hydrolysis rate of the BPO, resulting in lower effluent solids concentration and greater methane production at the same sludge age or (ii) transforms unbiodegradable organics to biodegradable organics. The results from these investigations cited above point to the former

(i). Actually, mechanical, thermal and chemical sludge minimization methods are very energy intensive. It seems the best way to reduce sludge production and reduce energy consumption is to treat wastewater anaerobically as in the SANI process (Lu *et al.,* 2009)

6.3 Recommendations

The steady state model of Sötemann *et al.* (2005) describing the AD of PS and ND WAS has been extended in this study to describe the AD of NDBEPR WAS. The mass balance based plant-wide steady state models of Ekama (2009) can therefore be extended by adding this steady state AD model to include the coupling of a BEPR AS system to an AD system. However, the stoichiometric part of the AD model developed in this study requires some further research to eliminate it limitation of not including mineral precipitation.

30. It was observed in this investigation that mineral precipitation occurred in the AD of concentrated (~10gCOD/l) NDBEPR WAS. The results determined from the application of this steady state AD model can be used as input variables to the Loewenthal *et al.* (1994) software (Struvite.exe), Mustovo *et al.* (2000) 3 phase mineral precipitation model or the Stasoft 4 software (Morrison *et al.,* 2000) to determine the quantities of mineral precipitant for each different AD test sludge ages. However, amended versions of these models or an extended mixed weak acid/base chemistry part of the AD model can be developed to include mineral precipitation and be incorporated into the existing steady state model describing the NDBEPR WAS anaerobic digestion that will allow the mineral precipitant to be quantified.

31. The carbon ratio (f_C = TOC/VSS) of the PO and UPO components were assumed to be the same for this study as those found by Ekama *et al.* (2006b) at 0.52 and 0.51 respectively. This was done because the total organic carbon measurement is not a common wastewater and WAS measurement and the TOC results obtained from external laboratory analyses in this investigation were found to be too inconsistent and too variable to use reliably. For this reason, these WAS TOC results from this study were excluded. So the C content of the PO and UPO (f_C) was based on values taken from Ekama *et al.*(2006a) i.e. 0.52 and 0.51 mgC/mgVSS respectively. From these values and the calculated unbiodegradable COD fraction of the NDBEPR WAS ($f_{up(AS)}$), the C content of the BPO was calculated by difference between the PO and UPO. This approach was validated because the measured C produced in the CH_4 gas, CO_2 gas and aqueous CO_2 (HCO_3^-) closely matched (95 to 102%) the carbon released from the

utilized BPO. Nevertheless, it is recommended that further research be conducted to measure the TOC content of the NDBEPR WAS PO, UPO and BPO and compare this with values found in this study.

6.4 Closure

A mass balance based plant-wide model that describes the coupling of the NDBEPR AS system and an AD system has been developed in this study by adding P and extending the steady state model of Sötemann *et al.* (2005) that describes the AD of PS and ND WAS.

In Chapter One the nature and scope of the problem to develop a steady state AD model describing the anaerobic digestion of NDBEPR WAS was introduced and the background literature, such as that of Sötemann *et al.* (2005), who recommended this research, was reviewed. This chapter also gave some insight into the research approach and the method of investigation which included laboratory based experimental work and theoretical modelling work to extend the steady state AD model to evaluate the predicted results against those experimentally measured. Chapter Two reviewed the literature that supported the development of the NDBEPR WAS characterization procedure that transforms COD based WAS characteristics into elemental compositions for input into the stoichiometric part of the steady state model describing the AD of NDBEPR WAS. Chapter Three (Materials and Methods) focused on the experimental setup, analytical methods and procedures used during the experimental investigation phase of this study.

The development of the characterization procedure and stoichiometric part of the AD model were described in Chapter Four and proceeded through the various steps of this development. Chapter Five presented, evaluated, compared and discussed the model predicted results with the measured data obtained from the experimental AS and AD systems and confirmed that struvite precipitation took place in experimental AD system at all sludge ages (10-60d). Furthermore, the WAS UPO fractions determined for the AS system ($f_{up(AS)}$) were found to be nearly the same as the UPO (AD) fractions ($f_{up(AD)}$) determined from the AD system. Chapter Six reported the main conclusions reached from this research and also recommend further research required to address some difficulties and uncertainty encountered in this study.

There are two important outcomes from this study, (1) the development and validation of an AD model for NDBEPR WAS digestion and (2) further evidence that the unbiodegradable organics of NDBEPR WAS as defined by the AS system remain unbiodegradable in the AD. The mixed weak acid/base chemistry part of the AD model needs to be extended to include struvite precipitation.

All the objectives set out in Chapter One of the study has been addressed within this research project and concluded in this chapter.

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APPENDICES

Appendix A: Experimental Results/Measurements Tables

TABLE A1 : Batch No., Experimental Period, Operational Unit, Number of Samples and Measured Data Sets

Sewage	AD SS	Date		Number of Sample		Measured Data Reported	
Batch No.	**Sludge age**	**Start**	**Complete**	**AS**	**AD**	**AS**	**AD**
Batch 3	**None**	17-Jul-07	25-Jul-07	5	None	Appendix A.1.1	None
Batch 4	**None**	31-Jul-07	8-Aug-07	5	None	Appendix A.1.2	None
Batch 5	**None**	11-Sep-07	21-Sep-07	6	None	Appendix A.1.3	None
Batch 6	**None**	23-Sep-07	14-Oct-07	6	None	Appendix A.1.4	None
Batch 7	**None**	25-Oct-07	13-Nov-07	6	None	Appendix A.1.5	None
Batch 8	**None**	20-Nov-07	29-Nov-07	5	None	Appendix A.1.6	None
Batch 9	**None**	20-Dec-07	31-Dec-07	6	None	Appendix A.1.7	None
Batch 10	**18 Day**	31-Mar-08	8-Apr-08	5	10	Appendix A.1.8	Appendix A.2.3
Batch 11	**60 Day**	2-Jun-08	12-Jun-08	6	10	Appendix A.1.9	Appendix A.2.7
Batch 12	**40 Day**	25-Jun-08	4-Jul-08	5	10	Appendix A.1.10	Appendix A.2.6
Batch 13	**25 Day**	18-Aug-08	28-Aug-08	5	10	Appendix A.1.11	Appendix A.2.5
Batch 14	**10 Day**	26-Oct-08	2-Nov-08	5	10	Appendix A.1.12	Appendix A.2.1
Batch 14	**12 Day**	26-Oct-08	2-Nov-08		6		Appendix A.2.2
Batch 14	**20 Day**	26-Oct-08	2-Nov-08		6		Appendix A.2.4

A1 Table of Measurements for the ND BEPR AS system

A.1.1. Sewage Batch no. 3

UCT Membrane AS system (NDBEPR)

Sewage Batch 3

Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			17-Jul-07	**19-Jul-07**	**21-Jul-07**	**23-Jul-07**	**25-Jul-07**	
Chemical Oxygen Demand (COD)	***Measurement***	Influent	0.90	4.90	3.10	3.10	3.50	
		Filt. Influent	16.00	17.90	15.70	15.70	15.50	
		Mixed liquor	13.90	7.60	11.00	11.30	11.40	
		Effluent	23.50	22.90	22.10	22.40	23.70	
		Blank	24.20	23.40	23.40	23.40	24.20	
		FAS Norm.	0.051	0.0512	0.0512	0.0512	0.0512	
	Dilution	Influent	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	
	Calculation	Influent	950.6	757.8	831.5	831.5	847.9	***843.8***
		Filt. Influent	334.6	225.3	315.4	315.4	356.4	***309.4***
		Mixed liquor	8404.8	12943.4	10158.1	9912.3	10485.8	***10380.9***
		Effluent	28.6	20.5	53.2	41.0	20.5	***32.7***
Total Kjeldahl Nitrogen (TKN)	**Measurement**	Influent	45.4	47.0	46.1	44.2	46.5	
		Filt. Influent	41.8	47.1	45.0	40.3	42.0	
		Mixed liquor	19.8	20.5	21.2	19.2	18.7	
		Effluent	2	2.5	2.0	2.2	1.8	
	Dilution	Influent	2	2	2	2	2	
		Mixed liquor	5	5	5	5	5	
	Calculation	Influent	63.56	65.80	64.54	61.88	130.20	***77.20***
		Filt. Influent	58.52	65.94	63.00	56.42	58.80	***60.54***
		Mixed liquor	554.40	574.00	593.60	537.60	1047.20	***661.36***
		Effluent	2.80	3.50	2.80	3.08	2.52	***2.94***
Free and Saline Ammonia (FSA)	**Measure**	Influent	41.6	35.2	38.4	38.4	37.5	
		Effluent	1.3	1.5	1.5	1.1	1.0	
	Dilution	Influent	1	1	1	1	1	
		Effluent	5	5	5	5	5	
	Calc.	Influent	58.24	49.28	53.76	53.76	52.5	***53.51***
		Effluent	1.82	2.1	2.1	1.54	1.4	***1.79***

Character	Function	Sample Point	*Measurements*					*Average*
			Date					
			17-Jul-07	**19-Jul-07**	**21-Jul-07**	**23-Jul-07**	**25-Jul-07**	
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	25.5665	25.5295	25.5355	25.5415	25.5607	
		Weight B	25.7417	25.6755	25.6881	25.7066	25.7247	
		Weight C	25.6004	25.5606	25.5669	25.5764	25.5915	
	Sample size (ml)		50	50	50	50	50	
	Anaerobic Tank (Calc.)	TSS	3504.0	2920.0	3052.0	3302.0	3280.0	***3211.6***
		VSS	2826.0	2298.0	2424.0	2604.0	2664.0	***2563.2***
		ISS	678.0	622.0	628.0	698.0	616.0	***648.4***
	Anoxic Tank (Measured)	Weight A	43.1510	59.3711	59.3884	59.3829	43.1535	
		Weight B	43.4681	59.6989	59.6530	59.6528	43.5585	
		Weight C	43.2246	59.4788	59.4504	59.4410	43.2448	
	Sample size (ml)		50	50	50	50	50	
	Anoxic Tank (Calc.)	TSS	6342.0	6556.0	5292.0	5398.0	8100.0	***6337.6***
		VSS	4870.0	4402.0	4052.0	4236.0	6274.0	***4766.8***
		ISS	1472.0	2154.0	1240.0	1162.0	1826.0	***1570.8***
	Re-aeration Tank (Measured)	Weight A	54.7209	48.7850	48.4172	48.8118	54.7132	
		Weight B	55.0504	49.0723	48.6920	49.1231	55.0243	
		Weight C	54.7975	48.8873	48.4924	48.9019	54.7886	
	Sample size (ml)		50	50	50	50	50	
	Re-aeration Tank (Calc.)	TSS	6590.0	5746.0	5496.0	6226.0	6222.0	***6056.0***
		VSS	5058.0	3700.0	3992.0	4424.0	4714.0	***4377.6***
		ISS	1532.0	2046.0	1504.0	1802.0	1508.0	***1678.4***
	Aerobic Tank (Measured)	Weight A	54.4771	48.4027	48.8057	48.4223	54.4671	
		Weight B	54.9545	48.9171	49.3194	48.9038	54.9108	
		Weight C	54.5817	48.5628	48.9593	48.5598	54.5753	
	Sample size (ml)		50	50	50	50	50	
	Aerobic Tank (Calc.)	TSS	9548.0	10288.0	10274.0	9630.0	8874.0	***9722.8***
		VSS	7456.0	7086.0	7202.0	6880.0	6710.0	***7066.8***
		ISS	2092.0	3202.0	3072.0	2750.0	2164.0	***2656.0***
Nitrates& Nitrites	***Nitrate + nitrite Height (cm)***	Anaerobic	0.00	1.10	0.00	1.30	0.00	
		Anoxic	13.45	11.50	6.50	7.00	8.50	
		Filt. Effluent	7.20	7.70	9.40	7.50	7.50	
	Nitrite Height (cm)	Anaerobic	1.00	1.10	0.80	0.90	0.50	
		Anoxic	6.00	6.60	6.50	5.50	2.00	
		Filt. Effluent	0.00	0.00	0.00	0.00	0.00	
	Slope	m	0.1166	0.1166	0.1166	0.1166	0.1166	
	Intercept	c	0.1867	0.1867	0.1867	0.1867	0.1867	
	Slope	m	0.0704	0.0704	0.0704	0.0704	0.0704	
	Intercept	c	0.0448	0.0448	0.0448	0.0448	0.0448	
		Anaerobic	1	1	1	1	1	
	Dilution	Anoxic	2	2	2	2	2	
		Filt. Effluent	20	20	20	20	20	
	Nitrate Conc. (mgN/l)	Anaerobic	0.000	0.000	0.000	0.000	0.000	***0.00***
		Anoxic	2.76	2.31	1.14	1.26	1.61	***1.82***
		Filt. Effluent	13.06	14.22	18.19	13.76	13.76	***14.60***
	Nitrite Conc. (mgN/l)	Anaerobic	0.026	0.033	0.012	0.019	0.000	***0.02***
		Anoxic	0.755	0.840	0.826	0.000	0.000	***0.48***
		Filt. Effluent	0.000	0.000	0.000	0.000	0.000	***0.00***

Sewage Batch 3								
Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			17-Jul-07	**19-Jul-07**	**21-Jul-07**	**23-Jul-07**	**25-Jul-07**	
Phosphates	**Total Phosphates Measurement**	Influent	0.174	0.178	0.176	0.17	0.174	
		Filt. Influent	0.127	0.143	0.137	0.1354	0.144	
		Anaerobic	0.172	0.183	0.176	0.152	0.167	
		Anoxic	0.148	0.178	0.142	0.144	0.14	
		Aerobic	0.106	0.102	0.118	0.106	0.104	
		Mixed liquor	0.14	0.136	0.125	0.124	0.141	
		Filt. Effluent	0.126	0.11	0.088	0.102	0.09	
	Ortho-Phosphates Reading	Influent	0.492	0.498	0.490			
		Anaerobic	0.331	0.300	0.295	0.316	0.272	
		Aerobic						
		Filt. Effluent	0.353	0.320	0.249	0.293	0.251	
	Line Functions TP	Slope	147.43	147.43	147.43	147.43	147.43	
		Intercept	0	0	0	0	0	
	Line Functions OP	Slope	96.335	96.335	96.335	96.335	96.335	
		Intercept	0.8568	0.8568	0.8568	0.8568	0.8568	
	Dilution TP	Influent	2.5	2.5	2.5	2.5	2.5	
		Filt. Influent	2.5	2.5	2.5	2.5	2.5	
		Anaerobic	5	5	5	5	5	
		Anoxic	2	2	2	2	2	
		Aerobic (filt)	2	2	2	2	2	
		Mixed liquor	40	40	40	40	40	
		Filt. Effluent	2	2	2	2	2	
	Dilution OP	Influent	1	1	1	1	1	
		Anaerobic	1	1	1	1	1	
		Aerobic						
		Filt. Effluent	1	1	1	1	1	
	Total Phosphates Conc. (mgP/l)	Influent	60.94	62.42	61.68	59.47	60.94	***61.09***
		Filt. Influent	43.62	49.52	47.30	46.72	49.88	***47.41***
		Anaerobic	120.41	128.52	123.36	105.67	116.72	***118.94***
		Anoxic	41.09	49.93	39.32	39.91	38.73	***41.79***
		Aerobic (filt)	28.70	27.52	32.24	28.70	28.11	***29.06***
		Mixed liquor	774.57	750.98	686.11	680.21	780.47	***734.47***
		Filt. Effluent	34.60	29.88	23.40	27.52	23.99	***27.88***
	Ortho-Phosphates Conc. (mgP/l)	Influent	46.54	47.12	46.35			***46.67***
		Aerobic						
		Filt. Effluent	33.15	29.97	23.13	27.37	23.32	***27.39***
OUR	Aerobic Tank	(mgO/l)	61.41	61.18	59.82	56.38	56.00	***58.96***
DSVI	Aerobic Tank	ml/gTSS						

Sewage Batch 3								
Character	*Function*	*Sample Point*	*Measurements*					*Average*
			Date					
			17-Jul-07	**19-Jul-07**	**21-Jul-07**	**23-Jul-07**	**25-Jul-07**	
Mg	**mg/l**	Influent	98.7375	101.75	96.7	98.816667		***99.00***
		Aerobic (filt)	77.0125	71.9625	75.75	71.9625		***74.17***
		Aerobic (unfilt)	256	289.1125	275.225	299.84375		***280.05***
		Effluent	72.2375	68.525	71.225	79.1625		***72.79***
K		Influent	99.25	104.825	103.4875	92.766667		***100.08***
		Aerobic (filt)	84.4	89.875	83.45	71.9		***82.41***
		Aerobic (unfilt)	406	413	398	385		***400.50***
		Effluent	89.35	92.325	92	81.966667		***88.91***
Ca		Influent	22.325	21.5	21.9475	23.066667		***22.21***
		Aerobic (filt)	22.625	23.45	24.1	24.55		***23.68***
		Aerobic (unfilt)	51.325	58.3875	54.0125	52.2		***53.98***
		Effluent	16.3525	16.8625	16.39	17.5		***16.78***
VFA		Aerobic	0					***0***
Alk		Aerobic	230					***230***
pH		Aerobic	7.6					***7.6***
System Parameters	**Volumes (litres)**	Anaerobic Vol.	19	19	19	19	19	***19***
		Anoxic Vol.	21	21	21	21	21	***21***
		Re-aeration Vol.	3	3	3	3	3	***3***
		Fully Aerated	32	32	32	32	32	***32***
		Total Aerobic	35	35	35	35	35	***35***
		Total Vol.	75	75	75	75	75	***75***
	Temp.(ºC)		20	20	20	20	20	***20***
	Sludge Recycle (ratios)	a-recycle	3.4	3.4	3.4	3.4	3.4	***3.4***
		r-recycle	1.15	1.15	1.15	1.15	1.15	***1.15***
		n-recycle	2.8	2.8	2.8	2.8	2.8	***2.8***
	Flow Rates (litres/day)	Influent (Qi)	150	150	150	150	150	***150***
		Waste (Qw)	5.7	5.7	5.7	5.7	5.7	***5.7***
		Effluent (Qe)	144.3	144.3	144.3	144.3	144.3	***144.3***

A.1.2. Sewage Batch no. 4

UCT Membrane AS system (NDBEPR)

Sewage Batch 4

Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			31-Jul-07	**2-Aug-07**	**4-Aug-07**	**6-Aug-07**	**8-Aug-07**	
Chemical Oxygen Demand (COD)	***Measurement***	Influent	5.79	5.80	7.00	2.90		
		Filt. Influent	18.50	18.00	18.80	18.20		
		Mixed liquor	11.90	12.88	12.45	12.98		
		Effluent	23.20	23.50	24.00	23.50		
		Blank	24.80	24.80	24.80	24.80		
		FAS Norm.	0.051	0.0512	0.0512	0.0512		
	Dilution	Influent	1	1	1	1		
		Mixed liquor	20	20	20	20		
	Calculation	Influent	775.6	778.2	729.1	897.0		***795.0***
		Filt. Influent	257.0	278.5	245.8	270.3		***262.9***
		Mixed liquor	10526.4	9764.9	10117.1	9682.9		***10022.8***
		Effluent	65.3	53.2	32.8	53.2		***51.1***
Total Kjeldahl Nitrogen (TKN)	**Measurement**	Influent	108	101.0	104.0	114.0	59.1	
		Filt. Influent	33.3	40.0	45.0	40.0	37.5	
		Mixed liquor	40.5	41.5	45.2	44.0	18.8	
		Effluent	2	2.5	2.0	2.2	1.8	
	Dilution	Influent	1	1	1	1	1	
		Mixed liquor	10	10	10	10	10	
	Calculation	Influent	75.60	70.70	72.80	79.80	82.74	***76.33***
		Filt. Influent	46.62	56.00	63.00	56.00	52.50	***54.82***
		Mixed liquor	567.00	581.00	632.80	616.00	526.40	***584.64***
		Effluent	2.80	3.50	2.80	3.08	2.52	***2.94***
Free and Saline Ammonia (FSA)	**Measure**	Influent	36.5	37.6	40.5	38.4	35.2	
		Effluent	1.4	1.2	2.2	1.1	1.0	
	Dilution	Influent	1	1	1	1	1	
		Effluent	10	10	10	10	10	
	Calc.	Influent	51.1	52.64	56.7	53.76	49.28	***52.70***
		Effluent	1.96	1.68	3.08	1.54	1.4	***1.93***

Sewage Batch 4								
Character	*Function*	*Sample Point*	*Measurements*					*Average*
			Date					
			31-Jul-07	2-Aug-07	4-Aug-07	6-Aug-07	8-Aug-07	
MLSS and ISS (mg/l)	*Anaerobic Tank (Measured)*	Weight A	25.5665	25.5295	25.5355	25.5415	25.5607	
		Weight B	25.7417	25.6755	25.6881	25.7066	25.7247	
		Weight C	25.6004	25.5606	25.5669	25.5764	25.5915	
	Sample size (ml)		50	50	50	50	50	
	Anaerobic Tank (Calc.)	TSS	3504.0	2920.0	3052.0	3302.0	3280.0	***3211.6***
		VSS	2826.0	2298.0	2424.0	2604.0	2664.0	***2563.2***
		ISS	678.0	622.0	628.0	698.0	616.0	***648.4***
	Anoxic Tank (Measured)	Weight A	43.1510	59.3711	59.3884	59.3829	43.1535	
		Weight B	43.4681	59.6989	59.6530	59.6528	43.5585	
		Weight C	43.2246	59.4788	59.4504	59.4410	43.2448	
	Sample size (ml)		50	50	50	50	50	
	Anoxic Tank (Calc.)	TSS	6342.0	6556.0	5292.0	5398.0	8100.0	***6337.6***
		VSS	4870.0	4402.0	4052.0	4236.0	6274.0	***4766.8***
		ISS	1472.0	2154.0	1240.0	1162.0	1826.0	***1570.8***
	Re-aeration Tank (Measured)	Weight A	54.7209	48.7850	48.4172	48.8118	54.7132	
		Weight B	55.0504	49.0723	48.6920	49.1231	55.0243	
		Weight C	54.7975	48.8873	48.4924	48.9019	54.7886	
	Sample size (ml)		50	50	50	50	50	
	Re-aeration Tank (Calc.)	TSS	6590.0	5746.0	5496.0	6226.0	6222.0	***6056.0***
		VSS	5058.0	3700.0	3992.0	4424.0	4714.0	***4377.6***
		ISS	1532.0	2046.0	1504.0	1802.0	1508.0	***1678.4***
	Aerobic Tank (Measured)	Weight A	54.4771	48.4027	48.8057	48.4223	54.4671	
		Weight B	54.9345	48.9071	49.3094	48.9138	54.9108	
		Weight C	54.5817	48.5628	48.9593	48.5598	54.5753	
	Sample size (ml)		50	50	50	50	50	
	Aerobic Tank (Calc.)	TSS	9148.0	10088.0	10074.0	9830.0	8874.0	***9602.8***
		VSS	7056.0	6886.0	7002.0	7080.0	6710.0	***6946.8***
		ISS	2092.0	3202.0	3072.0	2750.0	2164.0	***2656.0***
Nitrates& Nitrites	*Nitrate + nitrite Height (cm)*	Anaerobic	0.00	1.10	0.00	1.30	0.00	
		Anoxic	15.20	12.50	4.00	7.50	6.50	
		Filt. Effluent	8.50	7.80	9.20	8.50	7.30	
	Nitrite Height (cm)	Anaerobic	0.50	1.10	0.40	1.80	0.30	
		Anoxic	6.60	6.50	8.00	9.10	1.00	
		Filt. Effluent	0.00	0.00	0.00	0.00	0.00	
	Slope	m	0.1166	0.1166	0.1166	0.1166	0.1166	
	Intercept	c	0.1867	0.1867	0.1867	0.1867	0.1867	
	Slope	m	0.0704	0.0704	0.0704	0.0704	0.0704	
	Intercept	c	0.0448	0.0448	0.0448	0.0448	0.0448	
	Dilution	Anaerobic	1	1	1	1	1	
		Anoxic	2	2	2	2	2	

		Filt. Effluent	20	20	20	20	20	
	Nitrate Conc. (mgN/l)	Anaerobic	0.000	0.000	0.000	0.000	0.000	***0.00***
		Anoxic	3.17	2.54	0.56	1.38	1.14	***1.76***
		Filt. Effluent	16.09	14.46	17.72	16.09	13.29	***15.53***
	Nitrite Conc. (mgN/l)	Anaerobic	0.000	0.033	0.000	0.082	0.000	***0.02***
		Anoxic	0.840	0.826	1.037	0.000	0.000	***0.54***
		Filt. Effluent	0.000	0.000	0.000	0.000	0.000	***0.00***

Sewage Batch 4								
Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			31-Jul-07	**2-Aug-07**	**4-Aug-07**	**6-Aug-07**	**8-Aug-07**	
Phosphates	**Total Phosphates Measurement**	Influent	0.082	0.08	0.075	0.077	0.076	
		Filt. Influent	0.062	0.066	0.067	0.067	0.064	
		Anaerobic	0.159	0.155	0.158	0.179	0.17	
		Anoxic	0.215	0.203	0.242	0.253	0.228	
		Aerobic	0.067	0.069	0.079	0.113	0.054	
		Mixed liquor	0.13	0.14	0.1355	0.15	0.138	
		Filt. Effluent	0.085	0.072	0.1	0.063	0.07	
	Ortho-Phosphates Reading	Influent	0.102	0.108	0.112	0.113	0.106	
		Anaerobic	0.256	0.216	0.244	0.330	0.153	
		Aerobic	0.245	0.211	0.262	0.177	0.156	
		Filt. Effluent						
	Line Functions TP	Slope	147.43	147.43	147.43	147.43	147.43	
		Intercept	1.276	1.276	1.276	1.276	1.276	
	Line Functions OP	Slope	96.335	96.335	96.335	96.335	96.335	
		Intercept	0.8568	0.8568	0.8568	0.8568	0.8568	
	Dilution TP	Influent	5	5	5	5	5	
		Filt. Influent	5	5	5	5	5	
		Anaerobic	5	5	5	5	5	
		Anoxic	2	2	2	2	2	
		Aerobic (filt)	2	2	2	2	2	
		Mixed liquor	40	40	40	40	40	
		Filt. Effluent	2	2	2	2	2	
	Dilution OP	Influent	5	5	5	5	5	
		Anaerobic	1	1	1	1	1	
		Aerobic	1	1	1	1	1	
		Filt. Effluent						
	Total Phosphates Conc. (mgP/l)	Influent	54.07	52.59	48.91	50.38	49.64	***51.12***
		Filt. Influent	39.32	42.27	43.01	43.01	40.80	***41.68***
		Anaerobic	110.83	107.88	110.09	125.57	118.94	***114.66***
		Anoxic	60.84	57.30	68.80	72.05	64.68	***64.74***
		Aerobic (filt)	17.20	17.79	20.74	30.77	13.37	***19.98***
		Mixed liquor	715.60	774.57	748.03	833.54	762.77	***766.90***
		Filt. Effluent	22.51	18.68	26.93	16.02	18.09	***20.45***
	Ortho-Phosphates	Influent	44.85	47.74	49.66			***47.42***
		Aerobic	22.75	19.47	24.38	16.19	14.17	***19.39***

	Conc. (mgP/l)	Filt. Effluent	0.00	0.00	0.00	0.00	0.00	***0.00***
OUR	Aerobic Tank	(mgO/l)	60.23	61.42	58.25	59.05	56.00	***58.99***
DSVI	Aerobic Tank	ml/gTSS						

Sewage Batch 4

Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			31-Jul-07	**2-Aug-07**	**4-Aug-07**	**6-Aug-07**	**8-Aug-07**	
Mg	**mg/l**	Influent	98.7375	101.75	96.7	98.816667		***99.00***
		Aerobic (filt)	77.0125	71.9625	75.75	71.9625		***74.17***
		Aerobic (unfilt)	256	289.1125	275.225	299.84375		***280.05***
		Effluent	72.2375	68.525	71.225	79.1625		***72.79***
K		Influent	99.25	104.825	103.4875	92.766667		***100.08***
		Aerobic (filt)	84.4	89.875	83.45	71.9		***82.41***
		Aerobic (unfilt)	406	413	398	385		***400.50***
		Effluent	89.35	92.325	92	81.966667		***88.91***
Ca		Influent	22.325	21.5	21.9475	23.066667		***22.21***
		Aerobic (filt)	22.625	23.45	24.1	24.55		***23.68***
		Aerobic (unfilt)	51.325	58.3875	54.0125	52.2		***53.98***
		Effluent	16.3525	16.8625	16.39	17.5		***16.78***
VFA		Aerobic	0					***0***
Alk		Aerobic	230					***230***
pH		Aerobic	7.6					***7.6***
System Parameters	**Volumes (litres)**	Anaerobic Vol.	19	19	19	19	19	***19***
		Anoxic Vol.	21	21	21	21	21	***21***
		Re-aeration Vol.	3	3	3	3	3	***3***
		Fully Aerated	32	32	32	32	32	***32***
		Total Aerobic	35	35	35	35	35	***35***
		Total Vol.	75	75	75	75	75	***75***
	Temp.(ºC)		20	20	20	20	20	***20***
	Sludge Recycle (ratios)	a-recycle	3.4	3.4	3.4	3.4	3.4	***3.4***
		r-recycle	1.15	1.15	1.15	1.15	1.15	***1.15***
		n-recycle	2.8	2.8	2.8	2.8	2.8	***2.8***
	Flow Rates (litres/day)	Influent (Qi)	150	150	150	150	150	***150***
		Waste (Qw)	5.7	5.7	5.7	5.7	5.7	***5.7***
		Effluent (Qe)	144.3	144.3	144.3	144.3	144.3	***144.3***

A.1.3.Sewage Batch no. 5

UCT Membrane AS system (NDBEPR)									
Sewage Batch 5									
Character	***Function***	***Sample Point***	***Measurements***						***Average***
			Date						
			11-Sep-07	**13-Sep-07**	**15-Sep-07**	**17-Sep-07**	**19-Sep-07**	**21-Sep-07**	
Chemical Oxygen Demand (COD)	***Measurement***	Influent	3.00	7.60	6.00	2.00	5.40	5.00	
		Filt. Influent	21.00	17.50	18.50	16.90	16.90	16.50	
		Mixed liquor	11.50	11.20	12.80	11.70	11.50	10.20	
		Effluent	24.00	24.10	24.90	23.90	23.80	23.00	
		Blank	24.30	24.30	25.20	24.20	24.20	23.20	
		FAS Norm.	0.0512	0.0512	0.0512	0.0508	0.0508	0.051	
	Dilution	Influent	1	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	20	
	Calculation	Influent	872.4	684.0	786.4	902.2	764.0	742.6	***792.0***
		Filt. Influent	270.3	278.5	274.4	296.7	296.7	273.4	***281.7***
		Mixed liquor	10485.8	10731.5	10158.1	10160.0	10322.6	10608.0	***10411.0***
		Effluent	12.3	8.2	12.3	12.2	16.3	8.2	***11.6***
Total Kjeldahl Nitrogen (TKN)	**Measurement**	Influent	54.8	55.2	46.0	53.0	56.5	54.0	
		Filt. Influent	36.8	31.4	32.1	48.4	41.2	40.0	
		Mixed liquor	20.3	20.0	20.7	20.8	20.5	21.0	
		Effluent	2	2.5	2.0	2.2	1.8	1.7	
	Dilution	Influent	1	1	1	1	1	1	
		Mixed liquor	5	5	5	5	5	5	
	Calculation	Influent	76.72	77.28	64.40	74.20	79.10	75.60	***74.55***
		Filt. Influent	51.52	43.96	44.94	67.76	57.68	56.00	***53.64***
		Mixed liquor	568.40	560.00	579.60	582.40	574.00	588.00	***575.40***
		Effluent	2.80	3.50	2.80	3.08	2.52	2.38	***2.85***
Free and Saline Ammonia (FSA)	**Measure**	Influent	36.6	37.8	38.2	38.0	37.5	37.9	
		Effluent	1.4	1.2	2.2	1.1	1.0	1.0	
	Dilution	Influent	1	1	1	1	1	1	
		Effluent	5	5	5	5	5	5	
	Calc.	Influent	51.24	52.92	53.48	53.2	52.5	53.06	***52.73***
		Effluent	1.96	1.68	3.08	1.54	1.4	1.4	***1.84***

Sewage Batch 5									
Character	Function	Sample Point	Measurements						Average
			Date						
			11-Sep-07	13-Sep-07	15-Sep-07	17-Sep-07	19-Sep-07	21-Sep-07	
MLSS and ISS (mg/l)	*Anaerobic Tank (Measured)*	Weight A	46.0000	46.2967	46.2779	49.1471	48.7936		
		Weight B	46.2178	46.5220	46.4968	49.3627	49.0005		
		Weight C	46.0489	46.3515	46.3326	49.2013	48.8490		
	Sample size (ml)		50	50	50	50	50		
	Anaerobic Tank (Calc.)	TSS	4356.0	4506.0	4378.0	4312.0	4138.0		*4338.0*
		VSS	3378.0	3410.0	3284.0	3228.0	3030.0		*3266.0*
		ISS	978.0	1096.0	1094.0	1084.0	1108.0		*1072.0*
	Anoxic Tank (Measured)	Weight A	46.2832	50.2043	46.0014	48.7829	43.1385		
		Weight B	46.6567	50.6111	46.3912	49.1651	43.5189		
		Weight C	46.3900	50.3344	46.1257	48.8987	43.2590		
	Sample size (ml)		50	50	50	50	50		
	Anoxic Tank (Calc.)	TSS	7470.0	8136.0	7796.0	7644.0	7608.0		*7730.8*
		VSS	5334.0	5534.0	5310.0	5328.0	5198.0		*5340.8*
		ISS	2136.0	2602.0	2486.0	2316.0	2410.0		*2390.0*
	Re-aeration Tank (Measured)	Weight A	50.1916	46.0137	50.2091	43.1241	48.4234		
		Weight B	50.5879	46.4143	50.6060	43.4920	48.8015		
		Weight C	50.3073	46.1300	50.3330	43.2404	48.5500		
	Sample size (ml)		50	50	50	50	50		
	Re-aeration Tank (Calc.)	TSS	7926.0	8012.0	7938.0	7358.0	7562.0		*7759.2*
		VSS	5612.0	5686.0	5460.0	5032.0	5030.0		*5364.0*
		ISS	2314.0	2326.0	2478.0	2326.0	2532.0		*2395.2*
	Aerobic Tank (Measured)	Weight A	47.7323	47.7389	48.8057	48.4068	49.1578		
		Weight B	48.2814	48.3015	49.3194	48.9007	49.6670		
		Weight C	47.8942	47.9274	48.9593	48.5638	49.3294		
	Sample size (ml)		50	50	50	50	50		
	Aerobic Tank (Calc.)	TSS	10982.0	11252.0	10274.0	9878.0	10184.0		*10514.0*
		VSS	7744.0	7482.0	7202.0	6738.0	6752.0		*7183.6*
		ISS	3238.0	3770.0	3072.0	3140.0	3432.0		*3330.4*
Nitrates& Nitrites	*Nitrate + nitrite Height (cm)*	Anaerobic	0.80	0.20	0.00	0.00	0.40	0.00	
		Anoxic	2.60	2.20	2.40	3.50	2.60	2.60	
		Filt. Effluent	5.50	6.50	6.00	6.50	7.00	8.20	
	Nitrite Height (cm)	Anaerobic	0.50	1.10	0.40	1.80	0.30	0.30	
		Anoxic	6.60	6.50	8.00	9.10	1.00	1.00	
		Filt. Effluent	0.70	0.60	0.60	1.20	0.60	0.60	
	Slope	m	0.115	0.115	0.115	0.115	0.115	0.115	
	Intercept	c	0.0966	0.0966	0.0966	0.0966	0.0966	0.0966	
	Slope	m	0.0396	0.0396	0.0396	0.0396	0.0396	0.0396	
	Intercept	c	-0.0465	-0.0465	-0.0465	-0.0465	-0.0465	-0.0465	
		Anaerobic	1	1	1	1	1	1	
	Dilution	Anoxic	2	2	2	2	2	2	
		Filt. Effluent	20	20	20	20	20	20	

	Nitrate Conc. (mgN/l)	Anaerobic	0.000	0.000	0.000	0.000	0.000	0.000	***0.000***
		Anoxic	0.40	0.31	0.36	0.61	0.40	0.40	***0.416***
		Filt. Effluent	10.72	13.02	11.87	13.02	14.17	16.93	***13.286***
	Nitrite Conc. (mgN/l)	Anaerobic	0.066	0.090	0.062	0.118	0.058	0.058	***0.076***
		Anoxic	0.616	0.608	0.727	0.000	0.000	0.000	***0.325***
		Filt. Effluent	0.000	0.000	0.000	0.000	0.000	0.000	***0.000***

Sewage Batch 5

Character	***Function***	***Sample Point***	***Measurements***						***Average***
			Date						
			11-Sep-07	**13-Sep-07**	**15-Sep-07**	**17-Sep-07**	**19-Sep-07**	**21-Sep-07**	
Phosphates	**Total Phosphates Measurement**	Influent	0.099	0.095	0.089	0.093	0.096	0.08	
		Filt. Influent	0.09	0.095	0.076	0.09	0.085	0.078	
		Anaerobic	0.193	0.198	0.185	0.194	0.173	0.187	
		Anoxic	0.307	0.339	0.258	0.32	0.29	0.31	
		Aerobic	0.09	0.07	0.067	0.069	0.06	0.068	
		Mixed liquor	0.15	0.149	0.147	0.155	0.157	0.118	
		Filt. Effluent	0.065	0.079	0.064	0.077	0.064	0.068	
	Ortho-Phosphates Reading	Influent	0.099	0.095	0.089	0.093	0.096	0.080	
		Anaerobic	0.090	0.070	0.067	0.069	0.060	0.068	
		Aerobic	0.065	0.079	0.064	0.077	0.064	0.068	
		Filt. Effluent							
	Line Functions TP	Slope	147.43	147.43	147.43	147.43	147.43	147.43	
		Intercept	1.276	1.276	1.276	1.276	1.276	1.276	
	Line Functions OP	Slope	96.335	96.335	96.335	96.335	96.335	96.335	
		Intercept	0.8568	0.8568	0.8568	0.8568	0.8568	0.8568	
	Dilution TP	Influent	4	4	4	4	4	4	
		Filt. Influent	4	4	4	4	4	4	
		Anaerobic	4	4	4	4	4	4	
		Anoxic	2	2	2	2	2	2	
		Aerobic (filt)	2	2	2	2	2	2	
		Mixed liquor	40	40	40	40	40	40	
		Filt. Effluent	2	2	2	2	2	2	
	Dilution OP	Influent	4	4	4	4	4	4	
		Anaerobic	1	1	1	1	1	1	
		Aerobic	1	1	1	1	1	1	
		Filt. Effluent							
	Total Phosphates Conc. (mgP/l)	Influent	53.28	50.92	47.38	49.74	51.51		***50.57***
		Filt. Influent	47.97	50.92	39.71	47.97	45.02		***46.32***
		Anaerobic	108.71	111.66	103.99	109.30	96.92		***106.12***
		Anoxic	87.97	97.41	73.52	91.80	82.96		***86.73***
		Aerobic (filt)	23.99	18.09	17.20	17.79	15.14		***18.44***
		Mixed liquor	833.54	827.64	815.85	863.03	874.82		***842.98***
		Filt. Effluent	16.61	20.74	16.32	20.15	16.32		***18.03***
	Ortho-	Influent	34.72	33.18	30.87				***32.92***

	Phosphates Conc. (mgP/l)	Aerobic							
		Filt. Effluent	5.40	6.75	5.31	6.56	5.31		***5.87***
OUR	Aerobic Tank	(mgO/l)	65.00	66.50	64.50	66.80	64.90	63.50	***65.20***

Sewage Batch 5

Character	***Function***	***Sample Point***	***Measurements***						***Average***
			Date						
			11-Sep-07	**13-Sep-07**	**15-Sep-07**	**17-Sep-07**	**19-Sep-07**	**21-Sep-07**	
Mg	**mg/l**	Influent	98.74	101.75	96.70	98.82			***99.00***
		Aerobic (filt)	77.01	71.96	75.75	71.96			***74.17***
		Aerobic (unfilt)	256.00	289.11	275.23	299.84			***280.05***
		Effluent	72.24	68.53	71.23	79.16			***72.79***
K		Influent	99.25	104.83	103.49	92.77			***100.08***
		Aerobic (filt)	84.40	89.88	83.45	71.90			***82.41***
		Aerobic (unfilt)	406.00	413.00	398.00	385.00			***400.50***
		Effluent	89.35	92.33	92.00	81.97			***88.91***
Ca		Influent	22.33	21.50	21.95	23.07			***22.21***
		Aerobic (filt)	22.63	23.45	24.10	24.55			***23.68***
		Aerobic (unfilt)	51.33	58.39	54.01	52.20			***53.98***
		Effluent	16.35	16.86	16.39	17.50			***16.78***
VFA		Aerobic	0.00						***0.00***
Alk		Aerobic	230						***230***
pH		Aerobic	7.6						***7.6***
System Parameters	**Volumes (litres)**	Anaerobic Vol.	19	19	19	19	19	19	***19***
		Anoxic Vol.	21	21	21	21	21	21	***21***
		Re-aeration Vol.	3	3	3	3	3	3	***3***
		Fully Aerated	32	32	32	32	32	32	***32***
		Total Aerobic	35	35	35	35	35	35	***35***
		Total Vol.	75	75	75	75	75	75	***75***
	Temp.(ºC)		20	20	20	20	20	20	***20***
	Sludge Recycle (ratios)	a-recycle	3.4	3.4	3.4	3.4	3.4	3.4	***3.4***
		r-recycle	1.15	1.15	1.15	1.15	1.15	1.15	***1.15***
		n-recycle	2.8	2.8	2.8	2.8	2.8	2.8	***2.8***
	Flow Rates (litres/day)	Influent (Qi)	150	150	150	150	150	150	***150***
		Waste (Qw)	5.7	5.7	5.7	5.7	5.7	5.7	***5.7***
		Effluent (Qe)	144.3	144.3	144.3	144.3	144.3	144.3	***144.3***

A.1.4.Sewage Batch no. 6

UCT Membrane AS system (NDBEPR)									
Sewage Batch 6									
Character	*Function*	*Sample Point*	*Measurements*						*Average*
			Date						
			23-Sep-07	25-Sep-07	27-Sep-07	29-Sep-07	12-Oct-07	14-Oct-07	
Chemical Oxygen Demand (COD)	*Measurement*	Influent	3.00	5.60	2.00	14.30	14.30	14.70	
		Filt. Influent	17.40	20.40	16.90	18.00	17.90	17.10	
		Mixed liquor	11.80	11.20	11.70	12.00	13.45	11.90	
		Effluent	24.00	23.90	23.60	23.50	24.40	24.20	
		Blank	24.30	24.30	24.20	24.30	25.00	25.00	
		FAS Norm.	0.0512	0.0512	0.0508	0.0522	0.0502	0.0502	
	Dilution	Influent	1	1	1	2	2	2	
		Mixed liquor	20	20	20	20	20	20	
	Calculation	Influent	872.4	766.0	902.2	835.2	859.4	827.3	***843.8***
		Filt. Influent	282.6	159.7	296.7	263.1	285.1	317.3	***267.4***
		Mixed liquor	10240.0	10731.5	10160.0	10273.0	9277.0	10521.9	***10200.6***
		Effluent	12.3	16.4	24.4	33.4	24.1	32.1	***23.8***
Total Kjeldahl Nitrogen (TKN)	Measurement	Influent	41.7	44.0	41.7	39.3	40.5	42.1	
		Filt. Influent	36.3	37.4	35.9	38.2	37.5	34.0	
		Mixed liquor	20.5	22.0	22.0	21.1	21.8	21.4	
		Effluent	3.2	2.5	4.2	2.0	3.1	2.2	
	Dilution	Influent	1	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	20	
	Calculation	Influent	58.38	61.60	58.38	55.02	56.70	58.94	***58.17***
		Filt. Influent	50.82	52.36	50.26	53.48	52.50	47.60	***51.17***
		Mixed liquor	574.00	616.00	616.00	590.80	610.40	599.20	***601.07***
		Effluent	4.48	3.50	5.88	2.80	2.17	1.54	***3.40***
Free and Saline Ammonia (FSA)	Measure	Influent	33.1	36.1	35.6	35.9	31.4	32.5	
		Effluent	1.2	1.4	3.7	1.2	1.1	1.4	
	Dilution	Influent	1	1	1	1	1	1	
		Effluent	20	20	20	20	20	20	
	Calc.	Influent	46.34	50.54	49.84	50.26	43.96	45.5	***47.74***
		Effluent	1.68	1.96	5.18	1.68	1.54	1.96	***2.33***

Sewage Batch 6									
Character	*Function*	*Sample Point*	*Measurements*						*Average*
			Date						
			23-Sep-07	**25-Sep-07**	**27-Sep-07**	**29-Sep-07**	**12-Oct-07**	**14-Oct-07**	
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	48.7936	59.2796	43.1614	43.1602	27.2510	27.2648	
		Weight B	49.0005	59.4694	43.3189	43.3399	27.5007	27.5019	
		Weight C	48.8490	59.3255	43.1935	43.2054	27.3217	27.3320	
	Sample size (ml)		50.00	50.00	50.00	50.00	50.00	50.00	
	Anaerobic Tank (Calc.)	TSS	4138.0	3796.0	3150.0	3594.0	4994.0	4742.0	***4069.00***
		VSS	3030.0	2878.0	2508.0	2690.0	3580.0	3398.0	***3014.00***
		ISS	1108.0	918.0	642.0	904.0	1414.0	1344.0	***1055.00***
	Anoxic Tank (Measured)	Weight A	43.1385	46.0014	48.7829	48.0990	61.0852	59.2387	
		Weight B	43.5189	46.3912	49.1651	48.4345	61.5112	59.6435	
		Weight C	43.2590	46.1257	48.8987	48.2054	61.2240	59.3657	
	Sample size (ml)		50.00	50.00	50.00	50.00	50.00	50.00	
	Anoxic Tank (Calc.)	TSS	7608.0	7796.0	7644.0	6710.0	8520.0	8096.0	***7729.00***
		VSS	5198.0	5310.0	5328.0	4582.0	5744.0	5556.0	***5286.33***
		ISS	2410.0	2486.0	2316.0	2128.0	2776.0	2540.0	***2442.67***
	Re-aeration Tank (Measured)	Weight A	48.4234	50.2091	43.1241	53.1568	59.2275	61.1228	
		Weight B	48.8015	50.6060	43.4920	53.5032	59.6501	61.5445	
		Weight C	48.5500	50.3330	43.2404	53.2706	59.3632	61.2598	
	Sample size (ml)		50.00	50.00	50.00	50.00	50.00	50.00	
	Re-aeration Tank (Calc.)	TSS	7562.0	7938.0	7358.0	6928.0	8452.0	8434.0	***7778.67***
		VSS	5030.0	5460.0	5032.0	4652.0	5738.0	5694.0	***5267.67***
		ISS	2532.0	2478.0	2326.0	2276.0	2714.0	2740.0	***2511.00***
	Aerobic Tank (Measured)	Weight A	49.1578	48.8057	48.4068	61.0698	54.0408	54.0668	
		Weight B	49.6370	49.2894	48.8907	61.5300	54.6313	54.5320	
		Weight C	49.2894	48.9293	48.5338	61.1909	54.2363	54.1963	
	Sample size (ml)		50.00	50.00	50.00	50.00	50.00	50.00	
	Aerobic Tank (Calc.)	TSS	9584.0	9674.0	9678.0	9204.0		9304.0	***9488.80***
		VSS	6952.0	7202.0	7138.0	6782.0		6714.0	***6957.60***
		ISS	2632.0	2472.0	2540.0	2422.0		2590.0	***2531.20***
Nitrates& Nitrites	***Nitrate + nitrite Height (cm)***	Anaerobic	0.00	0.00	0.00	0.00	0.00	0.00	
		Anoxic	3.00	1.00	4.00	0.30	0.40	1.40	
		Filt. Effluent	5.90	4.50	5.50	4.30	4.30	4.50	
	Nitrite Height (cm)	Anaerobic	0.00	0.00	0.00	0.00	0.00	0.00	
		Anoxic	0.00	0.00	0.50	1.20	1.30	3.50	
		Filt. Effluent	0.00	0.00	0.40	0.90	0.70	1.00	
	Slope	m	0.12	0.10	0.08	0.16	0.16	0.16	
	Intercept	c	0.00	0.00	0.00	0.08	0.08	0.08	
	Slope	m	0.04	0.04	0.03	0.04	0.04	0.04	
	Intercept	c	0.00	0.00	0.00	0.09	0.00	0.09	
	Dilution	Anaerobic	1.00	1.00	1.00	1.00	1.00	1.00	
		Anoxic	1.00	1.00	1.00	1.00	1.00	1.00	
		Filt. Effluent	20.00	20.00	20.00	20.00	20.00	20.00	

	Nitrate Conc. (mgN/l)	Anaerobic	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
		Anoxic	0.35	0.10	0.33	0.00	0.00	0.15	***0.15***
		Filt. Effluent	13.57	8.69	8.97	12.35	12.35	12.99	***11.49***
	Nitrite Conc. (mgN/l)	Anaerobic	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
		Anoxic	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
		Filt. Effluent	0.00	0.00	0.26	0.00	0.63	0.00	***0.15***

Sewage Batch 6									
Character	***Function***	***Sample Point***	***Measurements***						***Average***
			Date						
			23-Sep-07	**25-Sep-07**	**27-Sep-07**	**29-Sep-07**	**12-Oct-07**	**14-Oct-07**	
Phosphates	**Total Phosphates Measurement**	Influent	0.039	0.095	0.162	0.095	0.101	0.098	
		Filt. Influent	0.068	0.137	0.135	0.084	0.093	0.087	
		Anaerobic	0.155	0.342	0.076	0.184	0.221	0.197	
		Anoxic	0.154	0.098	0.051	0.242	0.208	0.233	
		Aerobic	0.03	0.032	0.026	0.042	0.04	0.038	
		Mixed liquor	0.46	0.243	0.225	0.135	0.133	0.134	
		Filt. Effluent	0.034	0.094	0.065	0.075	0.089	0.078	
	Ortho-Phosphates Reading	Influent	0.032	0.321	0.432	0.115	0.117	0.114	
		Anaerobic	0.019			0.123	0.116	0.118	
		Aerobic	0.039	0.187	0.159	0.187	0.186	0.199	
		Filt. Effluent							
	Line Functions TP	Slope	172.66	171.2	177.12	161.96	161.96	161.96	
		Intercept	0	2.05	0	1.7138	1.7138	1.7138	
	Line Functions OP	Slope	117.83	106.99	112.87	116.61	116.61	116.61	
		Intercept	0	0	0	4.68	4.68	4.68	
	Dilution TP	Influent	8	4	2	4	4	4	
		Filt. Influent	4	2	2	4	4	4	
		Anaerobic	5	2	10	4	4	4	
		Anoxic	4	5	10	2	2	2	
		Aerobic (filt)	5	5	5	5	5	5	
		Mixed liquor	10	20	20	40	40	40	
		Filt. Effluent	4	2	2	2	2	2	
	Dilution OP	Influent	10	1	1	5	5	5	
		Anaerobic	5	5	5	5	5	5	
		Aerobic	4	1	1	1	1	1	
		Filt. Effluent							
	Total Phosphates Conc. (mgP/l)	Influent	53.87	56.86	57.39	54.69	58.58	56.63	***56.34***
		Filt. Influent	46.96	42.81	47.82	47.56	53.39	49.51	***48.01***
		Anaerobic	133.81	113.00	134.61	112.35	136.32	120.77	***125.14***
		Anoxic	106.36	73.64	90.33	74.96	63.95	72.05	***80.21***
		Aerobic (filt)	25.90	17.14	23.03	25.44	23.82	22.20	***22.92***
		Mixed liquor	794.24	791.03	797.04	806.03	793.08	799.55	***796.83***
		Filt. Effluent	23.48	28.09	23.03	20.87	25.40	21.84	***23.78***
	Ortho-	Influent	37.71	34.34	48.76				***40.27***

	Phosphates Conc. (mgP/l)	Aerobic	18.38	20.01	17.95	17.13	17.01	18.53	***18.17***
		Filt. Effluent	0.00	0.00	0.00	0.00	0.00	0.00	***0.00***
OUR	Aerobic Tank	(mgO/l)	63.49	68.50	66.00	65.00	64.50	67.40	***65.82***

Sewage Batch 6

Character	***Function***	***Sample Point***	***Measurements***						***Average***
			Date						
			23-Sep-07	**25-Sep-07**	**27-Sep-07**	**29-Sep-07**	**12-Oct-07**	**14-Oct-07**	
Mg	**mg/l**	Influent	98.74	101.75	96.70	98.82			***99.00***
		Aerobic (filt)	77.01	71.96	75.75	71.96			***74.17***
		Aerobic (unfilt)	256.00	289.11	275.23	299.84			***280.05***
		Effluent	72.24	68.53	71.23	79.16			***72.79***
K		Influent	99.25	104.83	103.49	92.77			***100.08***
		Aerobic (filt)	84.40	89.88	83.45	71.90			***82.41***
		Aerobic (unfilt)	406.00	413.00	398.00	385.00			***400.50***
		Effluent	89.35	92.33	92.00	81.97			***88.91***
Ca		Influent	22.33	21.50	21.95	23.07			***22.21***
		Aerobic (filt)	22.63	23.45	24.10	24.55			***23.68***
		Aerobic (unfilt)	51.33	58.39	54.01	52.20			***53.98***
		Effluent	16.35	16.86	16.39	17.50			***16.78***
VFA		Aerobic	0						***0***
Alk		Aerobic	230						***230***
pH		Aerobic	7.6						***7.6***
System Parameters	**Volumes (litres)**	Anaerobic Vol.	19	19	19	19	19	19	***19***
		Anoxic Vol.	21	21	21	21	21	21	***21***
		Re-aeration Vol.	3	3	3	3	3	3	***3***
		Fully Aerated	32	32	32	32	32	32	***32***
		Total Aerobic	35	35	35	35	35	35	***35***
		Total Vol.	75	75	75	75	75	75	***75***
	Temp.(ºC)		20	20	20	20	20	20	***20***
	Sludge Recycle (ratios)	a-recycle	3.4	3.4	3.4	3.4	3.4	3.4	***3.4***
		r-recycle	1.15	1.15	1.15	1.15	1.15	1.15	***1.15***
		n-recycle	2.8	2.8	2.8	2.8	2.8	2.8	***2.8***
	Flow Rates (litres/day)	Influent (Qi)	150	150	150	150	150	150	***150***
		Waste (Qw)	5.7	5.7	5.7	5.7	5.7	5.7	***5.7***
		Effluent (Qe)	144.3	144.3	144.3	144.3	144.3	144.3	***144.3***

A.1.5. Sewage Batch no. 7

UCT Membrane AS system (NDBEPR)

Sewage Batch 7

Character	***Function***	***Sample Point***	***Measurements***						***Average***
			Date						
			25-Oct-07	**28-Oct-07**	**30-Oct-07**	**2-Nov-07**	**7-Nov-07**	**13-Nov-07**	
Chemical Oxygen Demand (COD)	***Measurement***	Influent	7.20	9.00	5.89	7.89	7.00	6.50	
		Filt. Influent	21.80	20.00	20.50	22.60	22.70	19.50	
		Mixed liquor	12.00	11.70	11.45	12.80	12.10	12.50	
		Effluent	23.70	23.70	23.60	23.50	24.40	23.50	
		Blank	24.30	24.30	24.30	25.10	25.10	25.10	
		FAS Norm.	0.051	0.051	0.051	0.0506	0.0506	0.0506	
	Dilution	Influent	1	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	20	
	Calculation	Influent	697.7	624.2	751.1	696.7	732.7	752.9	***709.2***
		Filt. Influent	102.0	175.4	155.0	101.2	97.2	226.7	***142.9***
		Mixed liquor	10036.8	10281.6	10485.6	9958.1	10524.8	10201.0	***10248.0***
		Effluent	24.5	24.5	28.6	64.8	28.3	64.8	***39.2***
Total Kjeldahl Nitrogen (TKN)	**Measurement**	Influent	31.5	30.4	35.5	26.0	30.5	35.0	
		Filt. Influent	30.8	25.4	33.0	22.0	21.0	31.0	
		Mixed liquor	21.58	19.5	18.9	18.0	20.5	21.4	
		Effluent	3.2	2.5	4.2	2.0	3.1	4.2	
	Dilution	Influent	1	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	20	
	Calculation	Influent	44.10	42.56	49.70	36.40	42.70	49.00	***44.08***
		Filt. Influent	43.12	35.56	46.20	30.80	29.40	43.40	***38.08***
		Mixed liquor	604.24	544.60	529.20	504.00	574.00	599.20	***559.21***
		Effluent	2.24	1.75	2.94	1.40	2.17	2.94	***2.24***
Free and Saline Ammonia (FSA)	**Measure**	Influent	28.1	23.1	31.6	22.2	19.8	28.5	
		Effluent	1.2	1.4	1.7	1.2	1.1	1.4	
	Dilution	Influent	1	1	1	1	1	1	
		Effluent	20	20	20	20	20	20	
	Calc.	Influent	39.34	32.34	44.24	31.08	27.72	39.9	***35.77***
		Effluent	1.68	1.96	2.38	1.68	1.54	1.96	***1.87***

Sewage Batch 7

Character	***Function***	***Sample Point***	***Measurements***						***Average***
			Date						
			25-Oct-07	**28-Oct-07**	**30-Oct-07**	**2-Nov-07**	**7-Nov-07**	**13-Nov-07**	
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	19.2762	19.2421	27.8768	48.4357	19.2543	19.2597	
		Weight B	19.4693	19.4554	28.0985	48.6435	19.4743	19.4957	
		Weight C	19.3380	19.3012	27.9322	48.4840	19.3146	19.3295	
	Sample size (ml)		50	50	50	50	50	50	
	Anaerobic Tank (Calc.)	TSS	3862.0	4266.0	4434.0	4156.0	4400.0	4720.0	***4306.3***
		VSS	2626.0	3084.0	3326.0	3190.0	3194.0	3324.0	***3124.0***
		ISS	1236.0	1182.0	1108.0	966.0	1206.0	1396.0	***1182.3***
	Anoxic Tank (Measured)	Weight A	39.3350	62.0914	19.2424	48.1320	27.3112	41.6233	
		Weight B	39.6869	62.4914	19.6516	48.5388	27.7339	42.0281	
		Weight C	39.4461	62.2200	19.3732	48.2518	27.4452	41.7517	
	Sample size (ml)		50	50	50	50	50	50	
	Anoxic Tank (Calc.)	TSS	7038.0	8000.0	8184.0	8136.0	8454.0	8096.0	***7984.7***
		VSS	4816.0	5428.0	5568.0	5740.0	5774.0	5528.0	***5475.7***
		ISS	2222.0	2572.0	2616.0	2396.0	2680.0	2568.0	***2509.0***
	Re-aeration Tank (Measured)	Weight A	32.0881	50.2064	49.8157	55.4546	57.6576	32.0768	
		Weight B	32.4477	50.6376	50.2307	55.8826	58.1015	32.5024	
		Weight C	32.2091	50.3553	49.9538	55.5887	57.8000	32.2182	
	Sample size (ml)		50	50	50	50	50	50	
	Re-aeration Tank (Calc.)	TSS	7192.0	8624.0	8300.0	8560.0	8878.0	8512.0	***8344.3***
		VSS	4772.0	5646.0	5538.0	5878.0	6030.0	5684.0	***5591.3***
		ISS	2420.0	2978.0	2762.0	2682.0	2848.0	2828.0	***2753.0***
	Aerobic Tank (Measured)	Weight A	41.6402	60.1473	27.2772	53.1413	43.1440	39.3171	
		Weight B	42.1669	60.6620	27.8212	53.6749	43.6761	39.8326	
		Weight C	41.7976	60.3270	27.4571	53.3162	43.3327	39.4923	
	Sample size (ml)		50	50	50	50	50	50	
	Aerobic Tank (Calc.)	TSS	10534.0	10294.0	10880.0	10672.0	10642.0	10310.0	***10555.3***
		VSS	7386.0	6700.0	7282.0	7174.0	6868.0	6806.0	***7036.0***
		ISS	3148.0	3594.0	3598.0	3498.0	3774.0	3504.0	***3519.3***
Nitrates& Nitrites	***Nitrate + nitrite Height (cm)***	Anaerobic	4.50	0.00	0.40	0.00	2.50	0.00	
		Anoxic	2.60	0.00	0.00	0.00	2.00	0.80	
		Filt. Effluent	4.40	4.50	4.60	4.80	4.50	4.20	
	Nitrite Height (cm)	Anaerobic	0.00	11.00	0.00	0.50	0.00	0.00	
		Anoxic	0.00	5.50	0.00	0.00	0.00	0.00	
		Filt. Effluent	0.00	0.00	0.00	0.00	0.00	0.00	
	Slope	m	0.0941	0.0941	0.0941	0.0941	0.0941	0.0941	
	Intercept	c	0.1486	0.1486	0.1486	0.1486	0.1486	0.1486	
	Slope	m	0.0636	0.0636	0.0636	0.0636	0.0636	0.0636	
	Intercept	c	0.0611	0.0611	0.0611	0.0611	0.0611	0.0611	
		Anaerobic	1	1	1	1	1	1	
	Dilution	Anoxic	1	1	1	1	1	1	
		Filt. Effluent	20	20	20	20	20	20	
	Nitrate Conc.	Anaerobic	0.275	0.000	0.000	0.000	0.087	0.000	***0.060***
		Anoxic	0.10	0.00	0.00	0.00	0.04	0.00	***0.023***

	(mgN/l)	Filt. Effluent	5.31	5.50	5.69	6.06	5.50	4.93	***5.497***
	Nitrite Conc. (mgN/l)	Anaerobic	0.000	0.639	0.000	0.000	0.000	0.000	***0.106***
		Anoxic	0.000	0.289	0.000	0.000	0.000	0.000	***0.028***
		Filt. Effluent	0.000	0.000	0.000	0.000	0.000	0.000	***0.000***

Sewage Batch 7									
Character	***Function***	***Sample Point***	***Measurements***						***Average***
			Date						
			25-Oct-07	**28-Oct-07**	**30-Oct-07**	**2-Nov-07**	**7-Nov-07**	**13-Nov-07**	
Phosphates	**Total Phosphates Measurement**	Influent	0.089	0.085	0.095	0.096	0.093	0.088	
		Filt. Influent	0.087	0.082	0.084	0.075	0.078	0.087	
		Anaerobic	0.155	0.164	0.145	0.168	0.175	0.15	
		Anoxic	0.086	0.086	0.081	0.085	0.086	0.085	
		Aerobic	0.03	0.032	0.029	0.026	0.032	0.031	
		Mixed liquor	0.18	0.17	0.194	0.175	0.169	0.185	
		Filt. Effluent	0.075	0.027	0.028	0.025	0.026	0.036	
	Ortho-Phosphates Reading	Influent	0.234	0.225	0.300	0.231	0.239	0.240	
		Anaerobic	0.055	0.061	0.052	0.040	0.039	0.055	
		Aerobic							
		Filt. Effluent	0.025	0.044	0.049	0.040	0.042	0.056	
	Line Functions TP	Slope	168.89	168.89	168.89	168.89	168.89	168.89	
		Intercept	0.1324	0.1324	0.1324	0.1324	0.1324	0.1324	
	Line Functions OP	Slope	110.04	110.04	110.04	110.04	110.04	110.04	
		Intercept	0.0092	0.0092	0.0092	0.0092	0.0092	0.0092	
	Dilution TP	Influent	4	4	4	4	4	4	
		Filt. Influent	4	4	4	4	4	4	
		Anaerobic	5	5	5	5	5	5	
		Anoxic	4	4	4	4	4	4	
		Aerobic (filt)	2	2	2	2	2	2	
		Mixed liquor	30	30	30	30	30	30	
		Filt. Effluent	2	5	5	5	5	5	
	Dilution OP	Influent	2	2	2	2	2	2	
		Anaerobic	2	2	2	2	2	2	
		Aerobic							
		Filt. Effluent	2	2	2	2	2	2	
	Total Phosphates Conc. (mgP/l)	Influent	59.60	56.89	63.65	64.32	62.30	58.92	***60.95***
		Filt. Influent	58.24	54.87	56.22	50.14	52.16	58.24	***54.98***
		Anaerobic	130.23	137.83	121.78	141.21	147.12	126.01	***134.03***
		Anoxic	57.57	57.57	54.19	56.89	57.57	56.89	***56.78***
		Aerobic (filt)	9.87	10.54	9.53	8.52	10.54	10.21	***9.87***
		Mixed liquor	908.03	857.37	978.97	882.70	852.30	933.37	***902.12***
		Filt. Effluent	25.07	22.14	22.98	20.45	21.29	29.74	***23.61***
	Ortho-	Influent	51.48	49.50	66.01	50.82	52.58	52.80	***53.86***

	Phosphates Conc. (mgP/l)								
		Aerobic							
		Filt. Effluent	5.48	9.67	10.77	8.78	9.22	12.31	***9.37***
OUR	Aerobic Tank	(mgO/l)	45.00	44.58		54.32	50.54	48.76	***48.64***

Sewage Batch 7

Character	***Function***	***Sample Point***	***Measurements***						***Average***
			Date						
			25-Oct-07	**28-Oct-07**	**30-Oct-07**	**2-Nov-07**	**7-Nov-07**	**13-Nov-07**	
Mg	**mg/l**	Influent	98.74	101.75	96.70	98.82			***99.00***
		Aerobic (filt)	77.01	71.96	75.75	71.96			***74.17***
		Aerobic (unfilt)	256.00	289.11	275.23	299.84			***280.05***
		Effluent	72.24	68.53	71.23	79.16			***72.79***
K		Influent	99.25	104.83	103.49	92.77			***100.08***
		Aerobic (filt)	84.40	89.88	83.45	71.90			***82.41***
		Aerobic (unfilt)	406.00	413.00	398.00	385.00			***400.50***
		Effluent	89.35	92.33	92.00	81.97			***88.91***
Ca		Influent	22.33	21.50	21.95	23.07			***22.21***
		Aerobic (filt)	22.63	23.45	24.10	24.55			***23.68***
		Aerobic (unfilt)	51.33	58.39	54.01	52.20			***53.98***
		Effluent	16.35	16.86	16.39	17.50			***16.78***
VFA		Aerobic	0						***0***
Alk		Aerobic	230						***230***
pH		Aerobic	7.6						***7.6***
System Parameters	**Volumes (litres)**	Anaerobic Vol.	19	19	19	19	19	19	***19***
		Anoxic Vol.	21	21	21	21	21	21	***21***
		Re-aeration Vol.	3	3	3	3	3	3	***3***
		Fully Aerated	32	32	32	32	32	32	***32***
		Total Aerobic	35	35	35	35	35	35	***35***
		Total Vol.	75	75	75	75	75	75	***75***
	Temp.(ºC)		20	20	20	20	20	20	***20***
	Sludge Recycle (ratios)	a-recycle	3.4	3.4	3.4	3.4	3.4	3.4	***3.4***
		r-recycle	1.15	1.15	1.15	1.15	1.15	1.15	***1.15***
		n-recycle	2.8	2.8	2.8	2.8	2.8	2.8	***2.8***
	Flow Rates (litres/day)	Influent (Qi)	150	150	150	150	150	150	***150***
		Waste (Qw)	5.7	5.7	5.7	5.7	5.7	5.7	***5.7***
		Effluent (Qe)	144.3	144.3	144.3	144.3	144.3	144.3	***144.3***

A.1.6. Sewage Batch no. 8

UCT Membrane AS system (NDBEPR)

Sewage Batch 8

Character	Function	Sample Point	Measurements					Average
			Date					
			20-Nov-07	23-Nov-07	25-Nov-07	27-Nov-07	29-Nov-07	
Chemical Oxygen Demand (COD)	*Measurement*	Influent	7.90	8.70	8.60	8.60	8.70	
		Filt. Influent	19.00	17.60	18.80	20.10	17.10	
		Mixed liquor	14.10	14.20	14.40	14.10	13.80	
		Effluent	23.90	23.40	23.80	25.20	25.10	
		Blank	24.70	24.70	24.70	26.00	26.00	
		FAS Norm.	0.0523	0.0523	0.0523	0.0523	0.0523	
	Dilution	Influent	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	
	Calculation	Influent	702.9	669.4	673.6	728.0	723.8	***699.6***
		Filt. Influent	238.5	297.1	246.9	246.9	372.4	***280.3***
		Mixed liquor	8870.1	8786.4	8619.0	9957.9	10209.0	***9288.5***
		Effluent	33.5	54.4	37.7	33.5	37.7	***39.3***
Total Kjeldahl Nitrogen (TKN)	Measurement	Influent	48	46.3	50.2	47.0	44.0	
		Filt. Influent	40.2	41.7	37.1	35.0	42.0	
		Mixed liquor	16.1	16.6	16.5	17.0	16.5	
		Effluent	3.2	2.5	4.2	2.0	3.1	
	Dilution	Influent	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	
	Calculation	Influent	67.20	64.82	70.28	65.80	61.60	***65.94***
		Filt. Influent	56.28	58.38	51.94	49.00	58.80	***54.88***
		Mixed liquor	450.80	464.80	462.00	476.00	462.00	***463.12***
		Effluent	2.24	1.75	2.94	1.40	2.17	***2.10***
Free and Saline Ammonia (FSA)	Measure	Influent	36.8	37.5	36.2	33.0	39.1	
		Effluent	1.2	1.4	1.7	1.2	1.1	
	Dilution	Influent	1	1	1	1	1	
		Effluent	20	20	20	20	20	
	Calc.	Influent	51.52	52.5	50.68	46.2	54.74	***51.13***
		Effluent	1.68	1.96	2.38	1.68	1.54	***1.85***

Sewage Batch 8

Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			20-Nov-07	**23-Nov-07**	**25-Nov-07**	**27-Nov-07**	**29-Nov-07**	
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	19.2762	19.2847	19.2994	19.3158	19.3132	
		Weight B	19.4693	19.4833	19.4893	19.4902	19.5043	
		Weight C	19.3380	19.3492	19.3598	19.3629	19.3681	
	Sample size (ml)		50	50	50	50	50	
	Anaerobic Tank (Calc.)	TSS	3862.0	3972.0	3798.0	3488.0	3822.0	***3788.4***
		VSS	2626.0	2682.0	2590.0	2546.0	2724.0	***2633.6***
		ISS	1236.0	1290.0	1208.0	942.0	1098.0	***1154.8***
	Anoxic Tank (Measured)	Weight A	39.3350	39.3409	41.6601	41.6688	32.1669	
		Weight B	39.6869	39.6960	42.0018	41.9960	32.5139	
		Weight C	39.4461	39.4675	41.7809	41.7788	32.2852	
	Sample size (ml)		50	50	50	50	50	
	Anoxic Tank (Calc.)	TSS	7038.0	7102.0	6834.0	6544.0	6940.0	***6891.6***
		VSS	4816.0	4570.0	4418.0	4344.0	4574.0	***4544.4***
		ISS	2222.0	2532.0	2416.0	2200.0	2366.0	***2347.2***
	Re-aeration Tank (Measured)	Weight A	32.0881	32.1034	32.1220	32.1520	41.6775	
		Weight B	32.4477	32.4482	32.4721	32.4686	42.0268	
		Weight C	32.2091	32.2340	32.2330	32.2662	41.8064	
	Sample size (ml)		50	50	50	50	50	
	Re-aeration Tank (Calc.)	TSS	7192.0	6896.0	7002.0	6332.0	6986.0	***6881.6***
		VSS	4772.0	4284.0	4782.0	4048.0	4408.0	***4458.8***
		ISS	2420.0	2612.0	2220.0	2284.0	2578.0	***2422.8***
	Aerobic Tank (Measured)	Weight A	41.6402	41.6485	39.3483	39.3637	39.3710	
		Weight B	42.1469	42.1231	39.8363	39.8094	39.8550	
		Weight C	41.7976	41.8226	39.5171	39.5186	39.5442	
	Sample size (ml)		50	50	50	50	50	
	Aerobic Tank (Calc.)	TSS	10134.0	9492.0	9759.4	8914.0	9680.0	***9595.9***
		VSS	6986.0	6010.0	6384.0	5816.0	6216.0	***6282.4***
		ISS	3148.0	3482.0	3375.4	3098.0	3464.0	***3313.5***
Nitrates& Nitrites	***Nitrate + nitrite Height (cm)***	Anaerobic	0.00	0.00	0.00	0.00	0.00	
		Anoxic	15.00	15.00	13.50	13.00	11.00	
		Filt. Effluent	7.50	8.70	9.40	9.30	9.00	
	Nitrite Height (cm)	Anaerobic	0.00	0.00	0.00	0.00	0.00	
		Anoxic	18.50	18.00	19.00	16.50	17.00	
		Filt. Effluent	0.00	0.00	0.00	0.00	0.00	
	Slope	m	0.1093	0.1093	0.1093	0.1093	0.1093	
	Intercept	c	0.2193	0.2193	0.2193	0.2193	0.2193	
	Slope	m	0.043	0.043	0.043	0.043	0.043	
	Intercept	c	0.0139	0.0139	0.0139	0.0139	0.0139	
		Anaerobic	1	1	1	1	1	
	Dilution	Anoxic	2	2	2	2	2	
		Filt. Effluent	20	20	20	20	20	

	Nitrate Conc. (mgN/l)	Anaerobic	0.000	0.000	0.000	0.000	0.000	***0.00***
		Anoxic	2.84	2.84	2.51	2.40	1.97	***2.51***
		Filt. Effluent	12.01	14.63	16.16	15.94	15.29	***14.81***
	Nitrite Conc. (mgN/l)	Anaerobic	0.000	0.000	0.000	0.000	0.000	***0.00***
		Anoxic	1.563	1.520	1.606	0.000	0.000	***0.94***
		Filt. Effluent	0.000	0.000	0.000	0.000	0.000	***0.00***

Sewage Batch 8

Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			20-Nov-07	**23-Nov-07**	**25-Nov-07**	**27-Nov-07**	**29-Nov-07**	
Phosphates	**Total Phosphates Measurement**	Influent	0.096	0.077	0.078	0.08	0.084	
		Filt. Influent	0.07	0.073	0.074	0.069	0.075	
		Anaerobic	0.106	0.111	0.124	0.115	0.136	
		Anoxic	0.066	0.075	0.073	0.074	0.088	
		Aerobic	0.055	0.039	0.06	0.09	0.038	
		Mixed liquor	0.152	0.133	0.11	0.13	0.135	
		Filt. Effluent	0.063	0.049	0.058	0.091	0.042	
	Ortho-Phosphates Reading	Influent	0.180	0.172	0.158	0.139	0.179	
		Anaerobic	0.211	0.182	0.215	0.170	0.140	
		Aerobic	0.202	0.156	0.178	0.172	0.129	
		Filt. Effluent						
	Line Functions TP	Slope	160.97	160.97	160.97	160.97	160.97	
		Intercept	-0.4162	-0.4162	-0.4162	-0.4162	-0.4162	
	Line Functions OP	Slope	106.25	106.25	106.25	106.25	106.25	
		Intercept	0.031	0.031	0.031	0.031	0.031	
	Dilution TP	Influent	4	4	4	4	4	
		Filt. Influent	4	4	4	4	4	
		Anaerobic	5	5	5	5	5	
		Anoxic	4	4	4	4	4	
		Aerobic (filt)	2	2	2	2	2	
		Mixed liquor	40	40	40	40	40	
		Filt. Effluent	2	2	2	2	2	
	Dilution OP	Influent	4	4	4	4	4	
		Anaerobic	1	1	1	1	1	
		Aerobic	1	1	1	1	1	
		Filt. Effluent						
	Total Phosphates Conc. (mgP/l)	Influent	63.48	51.24	51.89	53.18	55.75	***55.11***
		Filt. Influent	46.74	48.67	49.31	46.09	49.96	***48.15***
		Anaerobic	87.40	91.42	101.88	94.64	111.54	***97.38***
		Anoxic	44.16	49.96	48.67	49.31	58.33	***50.08***

		Aerobic (filt)	18.54	13.39	20.15	29.81	13.07	***18.99***
		Mixed liquor	995.35	873.01	724.92	853.69	885.89	***866.57***
		Filt. Effluent	21.11	16.61	19.50	30.13	14.35	***20.34***
	Ortho-Phosphates Conc. (mgP/l)	Influent	76.38	72.98	67.03	58.95	75.95	***70.26***
		Aerobic						
		Filt. Effluent	21.43	16.54	18.88	18.24	13.68	***17.76***
OUR	Aerobic Tank	(mgO/l)	48.00	48.31	47.50	45.00	45.31	***46.82***
DSVI	Aerobic Tank	ml/gTSS	177.61989	193.84745	174.19104	197.44223	183.8843	***185.40***

Sewage Batch 8

Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			20-Nov-07	**23-Nov-07**	**25-Nov-07**	**27-Nov-07**	**29-Nov-07**	
Mg	**mg/l**	Influent	98.74	101.75	96.70	98.82		***99.00***
		Aerobic (filt)	77.01	71.96	75.75	71.96		***74.17***
		Aerobic (unfilt)	256.00	289.11	275.23	299.84		***280.05***
		Effluent	72.24	68.53	71.23	79.16		***72.79***
K		Influent	99.25	104.83	103.49	92.77		***100.08***
		Aerobic (filt)	84.40	89.88	83.45	71.90		***82.41***
		Aerobic (unfilt)	406.00	413.00	398.00	385.00		***400.50***
		Effluent	89.35	92.33	92.00	81.97		***88.91***
Ca		Influent	22.33	21.50	21.95	23.07		***22.21***
		Aerobic (filt)	22.63	23.45	24.10	24.55		***23.68***
		Aerobic (unfilt)	51.33	58.39	54.01	52.20		***53.98***
		Effluent	16.35	16.86	16.39	17.50		***16.78***
VFA		Aerobic	0					***0***
Alk		Aerobic	230					***230***
pH		Aerobic	7.6					***7.6***
System Parameters	**Volumes (litres)**	Anaerobic Vol.	19					***19***
		Anoxic Vol.	21					***21***
		Re-aeration Vol.	3					***3***
		Fully Aerated	32					***32***
		Total Aerobic	35					***35***
		Total Vol.	75					***75***
	Temp.(ºC)		20					***20***
	Sludge Recycle (ratios)	a-recycle	3.4					***3.4***
		r-recycle	1.15					***1.15***
		n-recycle	2.8					***2.8***
	Flow Rates (litres/day)	Influent (Qi)	150					***150***
		Waste (Qw)	5.7					***5.7***
		Effluent (Qe)	144.3					***144.3***

A.1.7. Sewage Batch no. 9

UCT Membrane AS system (NDBEPR)

Sewage Batch 9

Character	*Function*	*Sample Point*	*Measurements*						*Average*
			Date						
			20-Dec-07	**22-Dec-07**	**24-Dec-07**	**26-Dec-07**	**28-Dec-07**	**31-Dec-07**	
Chemical Oxygen Demand (COD)	***Measurement***	Influent	7.00	6.70	6.80	6.40	7.10	5.00	
		Filt. Influent	18.10	19.40	18.20	16.10	18.10	16.50	
		Mixed liquor	13.50	13.50	13.20	13.50	13.10	13.40	
		Effluent	24.80	24.90	24.00	24.20	24.20	24.20	
		Blank	25.50	25.30	24.70	24.90	25.00	24.90	
		FAS Norm.	0.0502	0.0502	0.0512	0.0512	0.0512	0.0512	
	Dilution	Influent	1	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	20	
	Calculation	Influent	743.0	747.0	733.2	757.8	733.2	815.1	***754.9***
		Filt. Influent	297.2	236.9	266.2	360.4	282.6	344.1	***297.9***
		Mixed liquor	9638.4	9477.8	9420.8	9338.9	9748.5	9420.8	***9507.5***
		Effluent	28.1	16.1	28.7	28.7	32.8	28.7	***27.2***
Total Kjeldahl Nitrogen (TKN)	**Measurement**	Influent	42	25.0	24.8	51.0	26.5		
		Filt. Influent	28	28.0	29.0	30.0	29.0		
		Mixed liquor	19.5	18.5	17.5	18.9	19.5		
		Effluent	1	1.5	1.5	2.0	1.5		
	Dilution	Influent	1	2	2	2	1		
		Mixed liquor	20	20	20	20	20		
	Calculation	Influent	58.80	70.00	69.44	71.40	74.20		***68.77***
		Filt. Influent	39.20	39.20	40.60	42.00	40.60		***40.32***
		Mixed liquor	546.00	518.00	490.00	529.20	546.00		***525.84***
		Effluent	1.50	2.10	1.80	1.40	2.00		***1.76***
Free and Saline Ammonia (FSA)	**Measure**	Influent	27.0	26.0	28.5	28.5	24.5		
		Effluent	0.5	1.0	1.8	0.5	1.0		
	Dilution	Influent	1	2	2	2	1		
		Effluent	20	20	20	20	20		
	Calc.	Influent	37.8	36.4	39.9	39.9	34.3		***37.66***
		Effluent	0.7	1.4	2.52	0.7	1.4		***1.34***

Sewage Batch 9

Character	*Function*	*Sample Point*	*Measurements*						*Average*
			Date						
			20-Dec-07	22-Dec-07	24-Dec-07	26-Dec-07	28-Dec-07	31-Dec-07	
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	19.3546	19.3649	19.3698	19.3678	19.3611	19.3633	
		Weight B	19.5438	19.5329	19.5427	19.5421	19.5429	19.5656	
		Weight C	19.4067	19.3976	19.4072	19.4033	19.4010	19.4079	
	Sample size (ml)		50	50	50	50	50	50	
	Anaerobic Tank (Calc.)	TSS	3784.0	3360.0	3458.0	3486.0	3636.0	4046.0	***3628.3***
		VSS	2742.0	2706.0	2710.0	2776.0	2838.0	3154.0	***2821.0***
		ISS	1042.0	654.0	748.0	710.0	798.0	892.0	***807.3***
	Anoxic Tank (Measured)	Weight A	30.7575	30.7664	30.7763	30.7802	41.7827	30.7961	
		Weight B	31.1118	31.0953	31.0777	31.1229	42.1156	31.1453	
		Weight C	30.8678	30.8624	30.8526	30.8657	41.8704	30.8898	
	Sample size (ml)		50	50	50	50	50	50	
	Anoxic Tank (Calc.)	TSS	7086.0	6578.0	6028.0	6854.0	6658.0	6984.0	***6698.0***
		VSS	4880.0	4658.0	4502.0	5144.0	4904.0	5110.0	***4866.3***
		ISS	2206.0	1920.0	1526.0	1710.0	1754.0	1874.0	***1831.7***
	Re-aeration Tank (Measured)	Weight A	41.7116	41.7337	41.7512	41.7721	32.3088	39.4216	
		Weight B	42.0478	42.0340	42.0548	42.0664	32.6439	39.7770	
		Weight C	41.8291	41.8301	41.8378	41.8566	32.4090	39.5267	
	Sample size (ml)		50	50	50	50	50	50	
	Re-aeration Tank (Calc.)	TSS	6724.0	6006.0	6072.0	5886.0	6702.0	7108.0	***6416.3***
		VSS	4374.0	4078.0	4340.0	4196.0	4698.0	5006.0	***4448.7***
		ISS	2350.0	1928.0	1732.0	1690.0	2004.0	2102.0	***1967.7***
	Aerobic Tank (Measured)	Weight A	41.6402	32.2623	32.2781	32.2918	30.7775	41.7840	
		Weight B	42.1169	32.6837	32.6770	32.7186	31.2291	42.2674	
		Weight C	41.7976	32.3698	32.3835	32.4039	30.9040	41.9257	
	Sample size (ml)		50	50	50	50	50	50	
	Aerobic Tank (Calc.)	TSS	9534.0	8428.0	7978.0	8536.0	9032.0	9668.0	***8862.7***
		VSS	6386.0	6278.0	5870.0	6294.0	6502.0	6834.0	***6360.7***
		ISS	3148.0	2150.0	2108.0	2242.0	2530.0	2834.0	***2502.0***
Nitrates& Nitrites	***Nitrate + nitrite Height (cm)***	Anaerobic	0.00	0.00	1.50	0.00	0.00	0.00	
		Anoxic	13.00	13.50	10.20	13.50	14.00	5.00	
		Filt. Effluent	7.70	8.40	8.10	7.30	8.00	7.70	
	Nitrite Height (cm)	Anaerobic	0.00	0.00	0.00	0.00	0.00	0.00	
		Anoxic	2.30	20.00	23.00	0.00	8.50	5.00	
		Filt. Effluent	0.00	0.00	0.00	0.00	0.00	0.00	
	Slope	m	0.1114	0.1074	0.1001	0.1001	0.1143	0.1114	
	Intercept	c	0.2522	0.2583	0.1597	0.1597	0.2758	0.2522	
	Slope	m	0.0406	0.0437	0.0435	0.0435	0.043	0.043	
	Intercept	c	0.0615	0.0068	0.0065	0.0065	0.0139	0.0139	
		Anaerobic	1	1	1	1	1	1	
	Dilution	Anoxic	2	2	2	2	2	2	
		Filt. Effluent	20	20	20	20	20	20	
	Nitrate	Anaerobic	0.000	0.000	0.000	0.000	0.000	0.000	***0.000***

	Conc. (mgN/l)	Anoxic	2.39	2.38	1.72	2.38	2.65	0.61	***2.023***
		Filt. Effluent	12.11	12.88	13.02	11.42	12.77	12.11	***12.386***
	Nitrite Conc. (mgN/l)	Anaerobic	0.000	0.000	0.000	0.000	0.000	0.000	***0.000***
		Anoxic	0.064	1.734	1.988	0.000	0.703	0.402	***0.815***
		Filt. Effluent	0.000	0.000	0.000	0.000	0.000	0.000	***0.000***

Sewage Batch 9

Character	***Function***	***Sample Point***	***Measurements***						***Average***
			Date						
			20-Dec-07	**22-Dec-07**	**24-Dec-07**	**26-Dec-07**	**28-Dec-07**	**31-Dec-07**	
Phosphates	**Total Phosphates Measurement**	Influent	0.089	0.09	0.081	0.094	0.093	0.086	
		Filt. Influent	0.074	0.08	0.065	0.078	0.074	0.078	
		Anaerobic	0.147	0.127	0.104	0.116	0.153	0.136	
		Anoxic	0.13	0.124	0.075	0.114	0.094	0.088	
		Aerobic	0.148	0.125	0.086	0.077	0.07	0.062	
		Mixed liquor	0.135	0.126	0.11	0.121	0.147	0.137	
		Filt. Effluent	0.156	0.135	0.09	0.084	0.07	0.045	
	Ortho-Phosphates Reading	Influent	0.236	0.112	0.108	0.102	0.475	0.098	
		Anaerobic	0.276	0.190	0.170	0.197	0.221	0.240	
		Aerobic	0.413	0.104	0.140	0.124	0.218	0.161	
		Filt. Effluent	0.438	0.092	0.152	0.129	0.201	0.089	
	Line Functions TP	Slope	160.91	164.41	164.41	164.41	160.97	160.97	
		Intercept	-0.4762	-0.9265	-0.9265	-0.9265	-0.4162	-0.4162	
	Line Functions OP	Slope	114.45	172.95	172.95	172.95	106.65	106.65	
		Intercept	0.6793	2.6755	2.6755	2.6755	0.04004	0.04004	
	Dilution TP	Influent	4	4	4	4	4	4	
		Filt. Influent	4	4	4	4	4	4	
		Anaerobic	5	5	5	5	5	5	
		Anoxic	4	4	4	4	4	4	
		Aerobic (filt)	2	2	2	2	2	2	
		Mixed liquor	40	40	40	40	40	40	
		Filt. Effluent	2	2	2	2	2	2	
	Dilution OP	Influent	2	4	5	5	4	5	
		Anaerobic	5	5	5	5	4	5	
		Aerobic	1	5	2	2	1	2	
		Filt. Effluent	1	5	2	2	1	2	
	Total Phosphates Conc. (mgP/l)	Influent	59.19	62.89	56.97	65.52	61.55	57.04	***61.23***
		Filt. Influent	49.53	56.32	46.45	55.00	49.31	51.89	***51.32***
		Anaerobic	120.65	109.03	90.13	99.99	125.22	111.54	***109.00***
		Anoxic	85.58	85.25	53.03	78.68	62.19	58.33	***72.95***
		Aerobic (filt)	48.58	42.96	30.13	27.17	23.37	20.79	***34.44***
		Mixed liquor	887.96	865.69	760.46	832.80	963.15	898.76	***862.01***
		Filt. Effluent	51.16	46.24	31.45	29.47	23.37	15.32	***36.34***

	Ortho-Phosphates Conc. (mgP/l)	Influent	52.66	66.78	80.02	74.83	202.47	52.06	***95.35***
		Aerobic	46.59	76.56	43.08	37.54		34.26	***50.94***
		Filt. Effluent	49.45	66.18	47.23	39.27		18.90	***50.53***
OUR	Aerobic Tank	(mgO/l)	65.00	58.00	62.45	62.33	59.85	60.12	***61.29***

Sewage Batch 9

Character	***Function***	***Sample Point***	***Measurements***						***Average***
			Date						
			20-Dec-07	**22-Dec-07**	**24-Dec-07**	**26-Dec-07**	**28-Dec-07**	**31-Dec-07**	
Mg	**mg/l**	Influent	98.74	101.75	96.70	98.82			***99.00***
		Aerobic (filt)	77.01	71.96	75.75	71.96			***74.17***
		Aerobic (unfilt)	256.00	289.11	275.23	299.84			***280.05***
		Effluent	72.24	68.53	71.23	79.16			***72.79***
K		Influent	99.25	104.83	103.49	92.77			***100.08***
		Aerobic (filt)	84.40	89.88	83.45	71.90			***82.41***
		Aerobic (unfilt)	406.00	413.00	398.00	385.00			***400.50***
		Effluent	89.35	92.33	92.00	81.97			***88.91***
Ca		Influent	22.33	21.50	21.95	23.07			***22.21***
		Aerobic (filt)	22.63	23.45	24.10	24.55			***23.68***
		Aerobic (unfilt)	51.33	58.39	54.01	52.20			***53.98***
		Effluent	16.35	16.86	16.39	17.50			***16.78***
VFA		Aerobic	0						***0***
Alk		Aerobic	230						***230***
pH		Aerobic	7.6						***7.6***
System Parameters	**Volumes (litres)**	Anaerobic Vol.	19	19	19	19	19	19	***19***
		Anoxic Vol.	21	21	21	21	21	21	***21***
		Re-aeration Vol.	3	3	3	3	3	3	***3***
		Fully Aerated	32	32	32	32	32	32	***32***
		Total Aerobic	35	35	35	35	35	35	***35***
		Total Vol.	75	75	75	75	75	75	***75***
	Temp.(ºC)		20	20	20	20	20	20	***20***
	Sludge Recycle (ratios)	a-recycle	3.4	3.4	3.4	3.4	3.4	3.4	***3.4***
		r-recycle	1.15	1.15	1.15	1.15	1.15	1.15	***1.15***
		n-recycle	2.8	2.8	2.8	2.8	2.8	2.8	***2.8***
	Flow Rates (litres/day)	Influent (Qi)	150	150	150	150	150	150	***150***
		Waste (Qw)	5.7	5.7	5.7	5.7	5.7	5.7	***5.7***
		Effluent (Qe)	144.3	144.3	144.3	144.3	144.3	144.3	***144.3***

A.1.8. Sewage Batch no. 10

UCT Membrane AS system (NDBEPR)

Sewage Batch 10

Character	*Function*	*Sample Point*	*Measurements*					*Average*
			Date					
			31-Mar-08	**2-Apr-08**	**4-Apr-08**	**6-Apr-08**	**8-Apr-08**	
Chemical Oxygen Demand (COD)	***Measurement***	Influent	3.70	4.00	5.20	4.90	5.50	
		Filt. Influent	15.40	16.40	15.80	15.90	17.20	
		Mixed liquor	10.00	11.23	12.01	12.80	12.45	
		Effluent	21.90	22.90	23.80	23.60	24.30	
		Blank	22.60	23.50	24.20	24.70	25.10	
		FAS Norm.	0.0512	0.0512	0.0512	0.0512	0.0504	
	Dilution	Influent	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	
	Calculation	Influent	774.1	798.7	778.2	811.0	790.3	***790.5***
		Filt. Influent	294.9	290.8	344.1	360.4	318.5	***321.8***
		Mixed liquor	10321.9	10051.6	9986.0	9748.5	10201.0	***10061.8***
		Effluent	28.7	24.6	16.4	45.1	32.3	***29.4***
Total Kjeldahl Nitrogen (TKN)	**Measurement**	Influent	33.5	30.6	32.5	33.1	31.0	
		Filt. Influent	24.5	23.0	28.0	30.0	30.5	
		Mixed liquor	21.3	21.6	20.9	21.1	11.0	
		Effluent	4.5	3.3	3.4	4.5	3.5	
	Dilution	Influent	1	1	1	1	1	
		Mixed liquor	10	10	10	10	5	
	Calculation	Influent	46.90	42.84	45.50	46.34	43.40	***45.00***
		Filt. Influent	34.30	32.20	39.20	42.00	42.70	***38.08***
		Mixed liquor	596.40	604.80	585.20	590.80	616.00	***598.64***
		Effluent	6.30	4.62	4.76	6.30	4.90	***5.38***
Free and Saline Ammonia (FSA)	**Measure**	Influent	12.0	22.6	22.0	13.5	27.0	
		Effluent	4.5	3.0	2.9	2.5	2.5	
	Dilution	Influent	1	1	1	1	1	
		Effluent	10	10	10	10	5	
	Calc.	Influent	33.6	31.64	30.8	37.8	37.8	***34.33***
		Effluent	6.3	4.2	4.06	3.5	3.5	***4.31***

Sewage Batch 10								
Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			31-Mar-08	**2-Apr-08**	**4-Apr-08**	**6-Apr-08**	**8-Apr-08**	
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	48.0604	19.3986	19.3770	19.3746	19.3794	
		Weight B	48.2472	19.5802	19.5483	19.5570	19.5580	
		Weight C	48.1001	19.4356	19.4065	19.4064	19.4110	
	Sample size (ml)		50	50	50	50	50	
	Anaerobic Tank (Calc.)	TSS	3736.0	3632.0	3426.0	3648.0	3572.0	***3602.8***
		VSS	2942.0	2892.0	2836.0	3012.0	2940.0	***2924.4***
		ISS	794.0	740.0	590.0	636.0	632.0	***678.4***
	Anoxic Tank (Measured)	Weight A	28.4032	32.3199	43.5972	32.3150	32.3194	
		Weight B	28.7398	32.6421	43.9104	32.6420	32.6515	
		Weight C	28.5000	32.4107	43.6688	32.3932	32.3961	
	Sample size (ml)		50	50	50	50	50	
	Anoxic Tank (Calc.)	TSS	6732.0	6444.0	6264.0	6540.0	6642.0	***6524.4***
		VSS	4796.0	4628.0	4832.0	4976.0	5108.0	***4868.0***
		ISS	1936.0	1816.0	1432.0	1564.0	1534.0	***1656.4***
	Re-aeration Tank (Measured)	Weight A	53.2069	30.3940	32.3212	43.5886	39.4124	
		Weight B	53.5369	30.7258	32.6379	43.9153	39.7614	
		Weight C	53.2915	30.4765	32.4060	43.6597	39.4896	
	Sample size (ml)		50	50	50	50	50	
	Re-aeration Tank (Calc.)	TSS	6600.0	6636.0	6334.0	6534.0	6980.0	***6616.8***
		VSS	4908.0	4986.0	4638.0	5112.0	5436.0	***5016.0***
		ISS	1692.0	1650.0	1696.0	1422.0	1544.0	***1600.8***
	Aerobic Tank (Measured)	Weight A	55.6919	43.6225	30.3961	30.3667	30.3428	
		Weight B	56.1651	44.0893	30.8473	30.8122	30.8000	
		Weight C	55.8112	43.7360	30.5119	30.4708	30.4537	
	Sample size (ml)		50	50	50	50	50	
	Aerobic Tank (Calc.)	TSS	9464.0	9336.0	9024.0	8910.0	9144.0	***9175.6***
		VSS	7078.0	7066.0	6708.0	6828.0	6926.0	***6921.2***
		ISS	2386.0	2270.0	2316.0	2082.0	2218.0	***2254.4***
Nitrates& Nitrites	***Nitrate + nitrite Height (cm)***	Anaerobic	0.00	0.00	0.00	0.00	0.00	
		Anoxic	5.00	3.50	5.50	6.50	3.50	
		Filt. Effluent	5.00	3.50	2.00	1.50	0.00	
	Nitrite Height (cm)	Anaerobic	0.00	0.00	0.00	0.00	0.00	
		Anoxic	0.00	0.00	0.00	0.00	0.00	
		Filt. Effluent	0.00	0.00	0.00	0.00	0.00	
	Slope	m	0.1095	0.1068	0.0908	0.1029	0.1143	
	Intercept	c	0	0	0	0	0	
	Slope	m	0.0058	0.0608	0.0667	0.133	0.043	
	Intercept	c	0	0	0	0	0	
		Anaerobic	1	1	1	1	1	
	Dilution	Anoxic	2	2	2	2	2	
		Filt. Effluent	20	20	20	20	20	

	Nitrate Conc. (mgN/l)	Anaerobic	0.000	0.000	0.000	0.000	0.000	***0.000***
		Anoxic	1.10	0.75	1.00	1.34	0.80	***0.996***
		Filt. Effluent	10.95	7.48	3.63	3.09	0.00	***5.029***
	Nitrite Conc. (mgN/l)	Anaerobic	0.000	0.000	0.000	0.000	0.000	***0.000***
		Anoxic	0.000	0.000	0.000	0.000	0.000	***0.000***
		Filt. Effluent	0.000	0.000	0.000	0.000	0.000	***0.000***

Sewage Batch 10								
Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			31-Mar-08	**2-Apr-08**	**4-Apr-08**	**6-Apr-08**	**8-Apr-08**	
Phosphates	**Total Phosphates Measurement**	Influent	0.1	0.096	0.098	0.092	0.099	
		Filt. Influent	0.093	0.095	0.092	0.0841	0.095	
		Anaerobic	0.139	0.128	0.132	0.128	0.124	
		Anoxic	0.104	0.1	0.101	0.083	0.099	
		Aerobic	0.15	0.074	0.08	0.084	0.083	
		Mixed liquor	0.148	0.141	0.138	0.15	0.148	
		Filt. Effluent	0.14	0.066	0.075	0.085	0.072	
	Ortho-Phosphates Reading	Influent	0.133	0.126	0.135	0.123	0.130	
		Anaerobic	0.216	0.153	0.173	0.168	0.186	
		Aerobic	0.207	0.098	0.165	0.183	0.235	
		Filt. Effluent	0.198	0.115	0.186	0.202	0.208	
	Line Functions TP	Slope	181.4	181.4	178.34	178.34	178.34	
		Intercept	3.684	3.684	2.8344	2.8344	2.8344	
	Line Functions OP	Slope	108.21	108.21	107.29	107.29	107.29	
		Intercept	1.2101	1.2101	1.5228	1.5228	1.5228	
	Dilution TP	Influent	4	4	4	4	4	
		Filt. Influent	4	4	4	4	4	
		Anaerobic	5	5	5	5	5	
		Anoxic	4	4	4	4	4	
		Aerobic (filt)	1	2	2	2	2	
		Mixed liquor	40	40	40	40	40	
		Filt. Effluent	1	2	2	2	2	
	Dilution OP	Influent	4	4	4	4	4	
		Anaerobic	5	5	5	5	4	
		Aerobic	1	2	1	1	1	
		Filt. Effluent	1	2	1	1	1	
	Total Phosphates Conc. (mgP/l)	Influent	57.82	54.92	58.57	54.29	59.29	***56.98***
		Filt. Influent	52.74	54.20	54.29	48.66	56.43	***53.26***
		Anaerobic	107.65	97.68	103.53	99.97	96.40	***101.05***
		Anoxic	60.73	57.82	60.71	47.87	59.29	***57.28***

		Aerobic (filt)	23.53	19.48	22.87	24.29	23.94	***22.82***
		Mixed liquor	926.53	875.74	871.06	956.66	942.40	***914.48***
		Filt. Effluent	21.71	16.58	21.08	24.65	20.01	***20.81***
	Ortho-Phosphates Conc. (mgP/l)	Influent	52.73	49.70	51.85	46.70	49.70	***50.13***
		Aerobic	21.19	18.79	16.18	18.11	23.69	***19.59***
		Filt. Effluent	20.22	22.47	18.43	20.15	20.79	***20.41***
OUR	Aerobic Tank	(mgO/l)	55.56		59.20	54.24	53.90	***55.73***

Sewage Batch 10								
Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			31-Mar-08	**2-Apr-08**	**4-Apr-08**	**6-Apr-08**	**8-Apr-08**	
Mg	**mg/l**	Influent	95.95	90.9	80.8	95.95	89.1	***90.54***
		Aerobic (filt)	65.65	55.55	50.5	60.6	65.65	***59.59***
		Aerobic (unfilt)	323.2	242.4	282.8	262.6	343.4	***290.88***
		Effluent	55.55	70.7	50.5	65.65	64.3	***61.34***
K		Influent	108	115.3	101	110.6	115	***109.98***
		Aerobic (filt)	87.7	88.5	77	73.3	76.5	***80.60***
		Aerobic (unfilt)	512	525	498	479	456	***494.00***
		Effluent	92.4	93.4	105	98.9	98	***97.54***
Ca		Influent	23.3	22.5	22.6	22.6	23.5	***22.90***
		Aerobic (filt)	20.8	22.7	24.4	24.2	22.1	***22.84***
		Aerobic (unfilt)	55.5	59	51	51.5	53	***54.00***
		Effluent	22	22.3	22.2	22.5	21.4	***22.08***
VFA		Aerobic	0					***0***
Alk		Aerobic	230					***230***
pH		Aerobic	7.6					***7.6***
System Parameters	**Volumes (litres)**	Anaerobic Vol.	19	19	19	19	19	***19***
		Anoxic Vol.	21	21	21	21	21	***21***
		Re-aeration Vol.	3	3	3	3	3	***3***
		Fully Aerated	32	32	32	32	32	***32***
		Total Aerobic	35	35	35	35	35	***35***
		Total Vol.	75	75	75	75	75	***75***
	Temp.(ºC)		20	20	20	20	20	***20***
	Sludge Recycle (ratios)	a-recycle	3.4	3.4	3.4	3.4	3.4	***3.4***
		r-recycle	1.15	1.15	1.15	1.15	1.15	***1.15***
		n-recycle	2.8	2.8	2.8	2.8	2.8	***2.8***
	Flow Rates (litres/day)	Influent (Qi)	150	150	150	150	150	***150***
		Waste (Qw)	5.7	5.7	5.7	5.7	5.7	***5.7***
		Effluent (Qe)	144.3	144.3	144.3	144.3	144.3	***144.3***

A.1.9. Sewage Batch no. 11

UCT Membrane AS system (NDBEPR)									
Sewage Batch 11									
Character	***Function***	***Sample Point***	***Measurements***						***Average***
			Date						
			2-Jun-08	**4-Jun-08**	**6-Jun-08**	**8-Jun-08**	**10-Jun-08**	**11-Jun-08**	
Chemical Oxygen Demand (COD)	***Measurement***	Influent	3.50	4.10	5.10	3.40	5.00	5.70	
		Filt. Influent	16.50	16.30	18.10	17.00	18.10	18.00	
		Mixed liquor	12.60	11.80	11.20	11.50	12.10	12.50	
		Effluent	24.30	23.70	23.90	23.40	24.30	24.20	
		Blank	25.00	24.50	24.20	24.70	24.70	25.10	
		FAS Norm.	0.0512	0.0512	0.0512	0.0512	0.0512	0.0504	
	Dilution	Influent	1	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	20	
	Calculation	Influent	880.6	835.6	782.3	872.4	806.9	782.2	***826.7***
		Filt. Influent	348.2	335.9	249.9	315.4	270.3	286.3	***301.0***
		Mixed liquor	10158.1	10403.8	10649.6	10813.4	10321.9	10160.6	***10417.9***
		Effluent	28.7	32.8	12.3	53.2	16.4	36.3	***29.9***
Total Kjeldahl Nitrogen (TKN)	**Measurement**	Influent	32	29.6	33.5	33.4	33.4	31.0	
		Filt. Influent	18.5	23.0	21.5	24.5	23.9	27.7	
		Mixed liquor	24.3	24.6	23.5	23.6	23.6	12.0	
		Effluent	4.5	3.0	6.5	5.5	5.5	3.5	
	Dilution	Influent	1	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	20	
	Calculation	Influent	44.80	41.44	46.90	46.76	46.76	43.40	***45.01***
		Filt. Influent	25.90	32.20	30.10	34.30	33.45	38.71	***32.44***
		Mixed liquor	680.40	688.80	658.00	660.80	660.80	672.00	***670.13***
		Effluent	6.30	4.20	9.10	7.70	7.70	4.90	***6.65***
Free and Saline Ammonia (FSA)	**Measure**	Influent	10.0	18.5	22.0	11.4	9.9	21.5	
		Effluent	4.5	3.0	2.9	4.1	4.1	3.2	
	Dilution	Influent	1	1	1	1	1	1	
		Effluent	20	20	20	20	20	20	
	Calc.	Influent	28	25.9	30.8	31.92	27.692	30.1	***29.07***
		Effluent	6.3	4.2	4.06	5.74	5.74	4.48	***5.09***

Sewage Batch 11

Character	Function	Sample Point	Measurements						Average
			Date						
			2-Jun-08	**4-Jun-08**	**6-Jun-08**	**8-Jun-08**	**10-Jun-08**	**11-Jun-08**	
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	13.7314	19.3986	13.7360	12.7247	12.7247	19.3794	
		Weight B	13.9151	19.5802	13.9421	13.1920	12.9129	19.5580	
		Weight C	13.7727	19.4356	13.7840	12.7675	12.7697	19.4110	
	Sample size (ml)		50	50	50	100	50	50	
	Anaerobic Tank (Calc.)	TSS	3674.0	3632.0	4122.0	4673.0	3764.0	3572.0	***3906.2***
		VSS	2848.0	2892.0	3162.0	4245.0	2864.0	2940.0	***3158.5***
		ISS	826.0	740.0	960.0	428.0	900.0	632.0	***747.7***
	Anoxic Tank (Measured)	Weight A	30.3754	32.3199	28.3848	27.9369	28.3848	32.3194	
		Weight B	30.7409	32.6421	28.7856	28.3057	28.7535	32.6515	
		Weight C	30.4673	32.4107	28.5123	28.0260	28.4978	32.3961	
	Sample size (ml)		50	50	50	50	50	50	
	Anoxic Tank (Calc.)	TSS	7310.0	6444.0	8016.0	7376.0	7374.0	6642.0	***7193.7***
		VSS	5472.0	4628.0	5466.0	5594.0	5114.0	5108.0	***5230.3***
		ISS	1838.0	1816.0	2550.0	1782.0	2260.0	1534.0	***1963.3***
	Re-aeration Tank (Measured)	Weight A	58.7655	30.3940	39.3889	27.3243	51.6886	39.4124	
		Weight B	59.1264	30.7258	39.8138	27.7020	52.0478	39.7614	
		Weight C	58.8306	30.4765	39.5370	27.4345	51.8199	39.4896	
	Sample size (ml)		50	50	50	50	50	50	
	Re-aeration Tank (Calc.)	TSS	7218.0	6636.0	8498.0	7554.0	7184.0	6980.0	***7345.0***
		VSS	5916.0	4986.0	5536.0	5350.0	4558.0	5436.0	***5297.0***
		ISS	1302.0	1650.0	2962.0	2204.0	2626.0	1544.0	***2048.0***
	Aerobic Tank (Measured)	Weight A	39.3987	51.7088	30.3680	30.8210	57.8297	30.3428	
		Weight B	39.8921	52.2130	30.8578	31.3241	58.3268	30.8200	
		Weight C	39.5425	51.8440	30.5072	30.9575	57.8200	30.4637	
	Sample size (ml)		50	50	50	50	50	50	
	Aerobic Tank (Calc.)	TSS	9868.0	10084.0	9796.0	10062.0		9544.0	***9870.8***
		VSS	6992.0	7380.0	7012.0	7332.0		7126.0	***7168.4***
		ISS	2876.0	2704.0	2784.0	2730.0		2418.0	***2702.4***
Nitrates& Nitrites	***Nitrate + nitrite Height (cm)***	Anaerobic	10.00	3.50	0.05	3.50	3.50	0.50	
		Anoxic	5.00	3.00	0.50	0.50	0.50	3.50	
		Filt. Effluent	5.00	1.50	3.90	1.50	1.00	0.00	
	Nitrite Height (cm)	Anaerobic	2.00	4.50	0.50	12.00	12.00	2.00	
		Anoxic	1.00	11.00	0.50	10.00	10.00	3.50	
		Filt. Effluent	6.00	7.50	0.60	10.50	10.50	0.50	
	Slope	m	0.0095	0.0868	0.0608	0.1029	0.1029	0.1143	
	Intercept	c	-0.1215	-0.1121	-0.0274	-0.154	-0.154	-0.2758	
	Slope	m	0.0058	0.0608	0.0667	0.133	0.133	0.043	
	Intercept	c	-0.0459	-0.0274	0	-0.0818	-0.0818	0.0139	
	Dilution	Anaerobic	1	1	1	1	1	1	
		Anoxic	2	2	2	2	2	2	
		Filt. Effluent	20	20	20	20	20	20	

	Nitrate Conc. (mgN/l)	Anaerobic	0.217	0.416	0.030	0.514	0.514	0.333	***0.337***
		Anoxic	0.34	0.75	0.12	0.41	0.41	1.35	***0.562***
		Filt. Effluent	3.38	4.85	5.29	6.17	5.14	5.52	***5.056***
	Nitrite Conc. (mgN/l)	Anaerobic	0.058	0.301	0.033	1.678	1.678	0.072	***0.637***
		Anoxic	0.103	1.392	0.067	0.000	0.000	0.273	***0.306***
		Filt. Effluent	0.000	0.000	0.000	0.000	0.000	0.000	***0.000***

Sewage Batch 11

Character	***Function***	***Sample Point***	***Measurements***						***Average***
			Date						
			2-Jun-08	**4-Jun-08**	**6-Jun-08**	**8-Jun-08**	**10-Jun-08**	**11-Jun-08**	
Phosphates	**Total Phosphates Measurement**	Influent	0.1	0.105	0.085	0.096	0.092	0.091	
		Filt. Influent	0.075	0.068	0.074	0.065	0.069	0.064	
		Anaerobic	0.103	0.12	0.135	0.151	0.149	0.152	
		Anoxic	0.108	0.1	0.107	0.13	0.081	0.099	
		Aerobic	0.075	0.077	0.081	0.119	0.076	0.081	
		Mixed liquor	0.155	0.153	0.13	0.142	0.15	0.145	
		Filt. Effluent	0.074	0.075	0.07	0.128	0.065	0.077	
	Ortho-Phosphates Reading	Influent	0.085	0.090	0.109	0.095	0.097	0.093	
		Anaerobic	0.225	0.129	0.201	0.228	0.208	0.232	
		Aerobic	0.174	0.183	0.195	0.196	0.168	0.194	
		Filt. Effluent	0.184	0.190	0.187	0.186	0.160	0.190	
	Line Functions TP	Slope	181.4	181.4	178.34	178.34	178.34	178.34	
		Intercept	3.684	3.684	2.8344	2.8344	2.8344	2.8344	
	Line Functions OP	Slope	108.21	108.21	107.29	107.29	107.29	107.29	
		Intercept	1.2101	1.2101	1.5228	1.5228	1.5228	1.5228	
	Dilution TP	Influent	4	4	4	4	4	4	
		Filt. Influent	4	4	4	4	4	4	
		Anaerobic	5	5	5	5	5	5	
		Anoxic	4	4	4	4	4	4	
		Aerobic (filt)	2	2	2	1	2	2	
		Mixed liquor	40	40	40	40	40	40	
		Filt. Effluent	2	2	2	1	2	2	
	Dilution OP	Influent	4	4	4	4	4	4	
		Anaerobic	5	5	5	5	5	4	
		Aerobic	1	1	1	1	1	1	
		Filt. Effluent	1	1	1	1	1	1	
	Total Phosphates Conc. (mgP/l)	Influent	57.82	61.45	49.30	57.14	54.29	53.58	***55.60***
		Filt. Influent	39.68	34.60	41.45	35.03	37.88	34.32	***37.16***
		Anaerobic	75.00	90.42	106.21	120.47	118.69	121.37	***105.36***
		Anoxic	63.63	57.82	64.99	81.40	46.44	59.29	***62.26***

		Aerobic (filt)	19.84	20.57	23.22	18.39	21.44	23.22	***21.11***
		Mixed liquor	977.32	962.81	813.99	899.60	956.66	921.00	***921.90***
		Filt. Effluent	19.48	19.84	19.30	19.99	17.52	21.80	***19.65***
	Ortho-Phosphates Conc. (mgP/l)	Influent	31.95	34.12	40.69	34.68	35.54	33.82	***35.13***
		Aerobic	17.62	18.59	19.40	19.51		19.29	***18.88***
		Filt. Effluent	18.70	19.35	18.54	18.43		18.86	***18.78***
OUR	Aerobic Tank	(mgO/l)	51.96	51.57	52.44	49.99	49.85	50.32	***51.02***

Sewage Batch 11

Character	***Function***	***Sample Point***	***Measurements***						***Average***
			Date						
			2-Jun-08	**4-Jun-08**	**6-Jun-08**	**8-Jun-08**	**10-Jun-08**	**11-Jun-08**	
Mg	**mg/l**	Influent	94.4	101.9	99.7	98.3	99.3		***98.72***
		Aerobic (filt)	91.92	92.726	91.918	94.847	94.645		***93.21***
		Aerobic (unfilt)	275.35	281.23	296	274	270		***279.32***
		Effluent	90.2	91.9	92.3	93.4	91.5		***91.86***
K		Influent	112.6	102.6	105	106	103		***105.84***
		Aerobic (filt)	99.3	94.9	99.7	95.6	100.8		***98.06***
		Aerobic (unfilt)	390	410	402	393	414		***401.80***
		Effluent	91.8	96.5	97	97.3	94.2		***95.36***
Ca		Influent	22	20.56	21.3	21.5			***21.34***
		Aerobic (filt)	21.76	19.8	20.82	22			***21.10***
		Aerobic (unfilt)	53.75	60.25	53.75	57.75			***56.38***
		Effluent	20.2	19.5	19.8	20.1			***19.90***
VFA		Aerobic	0						***0***
Alk		Aerobic	230						***230***
pH		Aerobic	7.6						***7.6***
System Parameters	**Volumes (litres)**	Anaerobic Vol.	19	19	19	19	19	19	***19***
		Anoxic Vol.	21	21	21	21	21	21	***21***
		Re-aeration Vol.	3	3	3	3	3	3	***3***
		Fully Aerated	32	32	32	32	32	32	***32***
		Total Aerobic	35	35	35	35	35	35	***35***
		Total Vol.	75	75	75	75	75	75	***75***
	Temp.(ºC)		20	20	20	20	20	20	***20***
	Sludge Recycle (ratios)	a-recycle	3.4	3.4	3.4	3.4	3.4	3.4	***3.4***
		r-recycle	1.15	1.15	1.15	1.15	1.15	1.15	***1.15***
		n-recycle	2.8	2.8	2.8	2.8	2.8	2.8	***2.8***
	Flow Rates (litres/day)	Influent (Qi)	150	150	150	150	150	150	***150***
		Waste (Qw)	5.7	5.7	5.7	5.7	5.7	5.7	***5.7***
		Effluent (Qe)	144.3	144.3	144.3	144.3	144.3	144.3	***144.3***

A.1.10. Sewage Batch no. 12

UCT Membrane AS system (NDBEPR)

Character	Function	Sample Point	Measurements					Average
			Date					
			25-Jun-08	27-Jun-08	29-Jun-08	1-Jul-08	3-Jul-08	
Sewage Batch 12								
Chemical Oxygen Demand (COD)	*Measurement*	Influent	5.80	5.40	5.30	6.30	4.90	
		Filt. Influent	18.90	18.80	18.50	18.60	19.50	
		Mixed liquor	12.50	13.00	12.60	12.70	12.30	
		Effluent	25.10	24.80	24.70	24.30	24.60	
		Blank	25.20	25.20	25.00	24.90	25.00	
		FAS Norm.	0.051	0.051	0.051	0.051	0.0504	
	Dilution	Influent	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	
	Calculation	Influent	791.5	807.8	803.8	758.9	810.4	***794.5***
		Filt. Influent	257.0	261.1	265.2	257.0	221.8	***252.4***
		Mixed liquor	10363.2	9955.2	10118.4	9955.2	10241.3	***10126.7***
		Effluent	4.1	16.3	12.2	24.5	16.1	***14.6***
Total Kjeldahl Nitrogen (TKN)	Measurement	Influent	18	14.0	18.0	16.0	16.5	
		Filt. Influent	17	11.5	10.5	11.0	13.0	
		Mixed liquor	21.5	19.5	22.4	18.0	21.5	
		Effluent	3.5	3.5	4.5	3.5	6.0	
	Dilution	Influent	5	5	5	5	5	
		Mixed liquor	20	20	20	20	20	
	Calculation	Influent	50.40	39.20	50.40	44.80	46.20	***46.20***
		Filt. Influent	47.60	32.20	29.40	30.80	36.40	***35.28***
		Mixed liquor	602.00	546.00	627.20	504.00	602.00	***576.24***
		Effluent	4.90	4.90	6.30	4.90	8.40	***5.88***
Free and Saline Ammonia (FSA)	**Measure**	Influent	13.5	11.5	13.0	10.5	14.5	
		Effluent	3.5	6.0	6.5	4.5	3.5	
	Dilution	Influent	5	5	5	5	5	
		Effluent	20	20	20	20	20	
	Calc.	Influent	37.8	32.2	36.4	29.4	40.6	***35.28***
		Effluent	4.9	4.2	4.55	6.3	4.9	***4.97***

Sewage Batch 12

Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			25-Jun-08	**27-Jun-08**	**29-Jun-08**	**1-Jul-08**	**3-Jul-08**	
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	13.5514	13.7251	13.7356	13.7500	13.7510	
		Weight B	13.9263	13.9313	13.9376	13.9262	13.9830	
		Weight C	13.7744	13.7833	13.8525	13.8000	13.8086	
	Sample size (ml)		50	50	50	50	50	
	Anaerobic Tank (Calc.)	TSS	7498.0	4124.0	4040.0	3524.0	4640.0	***4765.2***
		VSS	3038.0	2960.0	1702.0	2524.0	3488.0	***2742.4***
		ISS	4460.0	1164.0	2338.0	1000.0	1152.0	***2022.8***
	Anoxic Tank (Measured)	Weight A	39.3858	27.3505	28.4190	27.3584	27.3609	
		Weight B	39.7365	28.0787	28.7731	27.7078	27.7258	
		Weight C	39.4930	27.4495	28.5381	27.4681	27.4750	
	Sample size (ml)		50	50	50	50	50	
	Anoxic Tank (Calc.)	TSS	7014.0		7082.0	6988.0	7298.0	***7095.5***
		VSS	4870.0		4700.0	4794.0	5016.0	***4845.0***
		ISS	2144.0		2382.0	2194.0	2282.0	***2250.5***
	Re-aeration Tank (Measured)	Weight A	39.3858	43.5908	30.3639	30.3887	46.4673	
		Weight B	39.7165	43.9545	30.7408	30.7408	47.0970	
		Weight C	39.4730	43.7042	30.5022	30.4995	46.0000	
	Sample size (ml)		50	50	50	50	50	
	Re-aeration Tank (Calc.)	TSS	6614.0	7274.0	7538.0	7042.0		***7117.0***
		VSS	4870.0	5006.0	4772.0	4826.0		***4868.5***
		ISS	1744.0	2268.0	2766.0	2216.0		***2248.5***
	Aerobic Tank (Measured)	Weight A	43.5761	39.4074	32.3505	30.9152	30.9338	
		Weight B	44.0528	39.8850	32.0000	31.3886	31.4050	
		Weight C	43.6912	39.5354	30.5119	31.0448	31.0619	
	Sample size (ml)		50	50	50	50	50	
	Aerobic Tank (Calc.)	TSS	9534.0	9552.0		9468.0	9424.0	***9494.5***
		VSS	7232.0	6992.0		6876.0	6862.0	***6990.5***
		ISS	2302.0	2560.0		2592.0	2562.0	***2504.0***
Nitrates& Nitrites	***Nitrate + nitrite Height (cm)***	Anaerobic	0.00	0.00	2.00	0.00	1.00	
		Anoxic	3.00	2.50	0.50	0.00	0.00	
		Filt. Effluent	1.00	1.10	0.90	2.00	3.00	
	Nitrite Height (cm)	Anaerobic	0.00	0.00	0.00	0.00	1.00	
		Anoxic	0.00	0.00	0.00	0.00	0.00	
		Filt. Effluent	0.00	2.50	0.00	0.00	0.00	
	Slope	m	0.13	0.125	0.125	0.1223	0.125	
	Intercept	c	-0.15	-0.1875	-0.188	-0.0911	-0.125	
	Slope	m	0.07	0.0667	0.0685	0.06851	0.0585	
	Intercept	c	-0.133	-0.1	-0.016	-0.0126	-0.0433	
		Anaerobic	1	1	1	1	1	

	Dilution	Anoxic	2	2	2	2	2	
		Filt. Effluent	20	20	20	20	20	
	Nitrate Conc. (mgN/l)	Anaerobic	0.150	0.188	0.438	0.091	0.250	***0.223***
		Anoxic	1.08	1.00	0.50	0.18	0.25	***0.603***
		Filt. Effluent	5.60	6.50	6.01	6.71	10.00	***6.965***
	Nitrite Conc. (mgN/l)	Anaerobic	0.133	0.100	0.016	0.013	0.102	***0.073***
		Anoxic	0.266	0.200	0.032	0.000	0.087	***0.117***
		Filt. Effluent	0.000	0.000	0.000	0.000	0.000	***0.000***

Sewage Batch 12

Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			25-Jun-08	**27-Jun-08**	**29-Jun-08**	**1-Jul-08**	**3-Jul-08**	
Phosphates	**Total Phosphates Measurement**	Influent	0.095	0.1	0.095	0.101	0.099	
		Filt. Influent	0.087	0.09	0.085	0.088	0.089	
		Anaerobic	0.092	0.12	0.11	0.13	0.13	
		Anoxic	0.127	0.111	0.117	0.115	0.114	
		Aerobic	0.079	0.068	0.079	0.072	0.077	
		Mixed liquor	0.14	0.13	0.145	0.137	0.15	
		Filt. Effluent	0.08	0.075	0.07	0.082	0.088	
	Ortho-Phosphates Reading	Influent	0.128	0.120	0.123	0.129	0.121	
		Anaerobic	0.138	0.213	0.218	0.216	0.214	
		Aerobic	0.129	0.198	0.202	0.206	0.204	
		Filt. Effluent	0.226	0.192	0.195	0.199	0.209	
	Line Functions TP	Slope	177.05	177.05	162.81	162.81	162.81	
		Intercept	3.3074	3.3074	2.2582	2.2582	2.2582	
	Line Functions OP	Slope	93.374	93.374	99.318	99.318	99.318	
		Intercept	0.9109	0.9109	1.805	1.805	1.805	
	Dilution TP	Influent	4	4	4	4	4	
		Filt. Influent	4	4	4	4	4	
		Anaerobic	5	5	5	5	5	
		Anoxic	4	4	4	4	4	
		Aerobic (filt)	2	2	2	2	2	
		Mixed liquor	40	40	40	40	40	
		Filt. Effluent	2	2	2	2	2	
	Dilution OP	Influent	4	4	4	4	4	
		Anaerobic	5	5	5	5	4	
		Aerobic	1	1	1	1	1	
		Filt. Effluent	1	1	1	1	1	
	Total Phosphates	Influent	54.05	57.59	52.84	56.74	55.44	***55.33***
		Filt. Influent	48.38	50.51	46.32	48.28	48.93	***48.48***

	Conc. (mgP/l)	Anaerobic	64.91	89.69	78.25	94.54	94.54	***84.38***
		Anoxic	76.71	65.38	67.16	65.86	65.21	***68.06***
		Aerobic (filt)	21.36	17.46	21.21	18.93	20.56	***19.90***
		Mixed liquor	859.18	788.36	853.97	801.87	886.53	***837.98***
		Filt. Effluent	21.71	19.94	18.28	22.18	24.14	***21.25***
	Ortho-Phosphates Conc. (mgP/l)	Influent	44.16	41.18	41.64	44.03	40.85	***42.37***
		Aerobic	11.13	17.58	18.26	18.65		***16.41***
		Filt. Effluent	20.19	17.02	17.56	17.96		***18.18***
OUR	Aerobic Tank	(mgO/l)	59.00	61.00	60.00	64.24	53.90	***59.63***

Sewage Batch 12

Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			25-Jun-08	**27-Jun-08**	**29-Jun-08**	**1-Jul-08**	**3-Jul-08**	
Mg	**mg/l**	Influent	97	104	104	100	100.5	***101.10***
		Aerobic (filt)	70.7	75.75	90.9	95.95	75.75	***81.81***
		Aerobic (unfilt)	290.375	353.5	328.25	277.75	315.625	***313.10***
		Effluent	92	62	93	84	72	***80.60***
K		Influent	85.6	86.1	83.1	83.1	84.6	***84.50***
		Aerobic (filt)	74	78.5	74.3	74	76.2	***75.40***
		Aerobic (unfilt)	462.5	489	425	418.875	444.25	***447.93***
		Effluent	65.8	76	71.5	75.1	71.9	***72.06***
Ca		Influent	20.8	19.1	20.8	21.7	24.9	***21.46***
		Aerobic (filt)	23.1	20.1	22.5	21.97	21.1	***21.75***
		Aerobic (unfilt)	52.8	52.3	56.8	52.3	50.1	***52.86***
		Effluent	21.4	20.1	21.3	22.3	21.5	***21.32***
VFA		Aerobic	0					***0***
Alk		Aerobic	230					***230***
pH		Aerobic	7.6					***7.6***
System Parameters	**Volumes (litres)**	Anaerobic Vol.	19	19	19	19	19	***19***
		Anoxic Vol.	21	21	21	21	21	***21***
		Re-aeration Vol.	3	3	3	3	3	***3***
		Fully Aerated	32	32	32	32	32	***32***
		Total Aerobic	35	35	35	35	35	***35***
		Total Vol.	75	75	75	75	75	***75***
	Temp.(ºC)		20	20	20	20	20	***20***
	Sludge Recycle (ratios)	a-recycle	3.4	3.4	3.4	3.4	3.4	***3.4***
		r-recycle	1.15	1.15	1.15	1.15	1.15	***1.15***
		n-recycle	2.8	2.8	2.8	2.8	2.8	***2.8***
	Flow Rates (litres/day)	Influent (Qi)	150	150	150	150	150	***150***
		Waste (Qw)	5.7	5.7	5.7	5.7	5.7	***5.7***
		Effluent (Qe)	144.3	144.3	144.3	144.3	144.3	***144.3***

A.1.11. Sewage Batch no. 13

UCT Membrane AS system (NDBEPR)								
Sewage Batch 13								
Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			18-Sep-08	**20-Sep-08**	**25-Sep-08**	**26-Sep-08**	**28-Sep-08**	
Chemical Oxygen Demand (COD)	***Measurement***	Influent	6.1	8.5	4.7	4.3	6.5	
		Filt. Influent	15.7	17.3	16.6	15.8	17.8	
		Mixed liquor	13.5	12.0	13.0	12.5	10.0	
		Effluent	23.7	24.0	23.5	23.6	23.1	
		Blank	24.6	24.4	24.6	24.5	24.4	
		FAS Norm.	0.0512	0.0512	0.0506	0.0506	0.0506	
	Dilution	Influent	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	
	Calculation	Influent	757.8	651.3	805.6	817.7	724.6	**751.37**
		Filt. Influent	364.5	290.8	323.8	352.2	267.2	**319.71**
		Mixed liquor	9093.1	10158.1	9391.4	9715.2		**9589.44**
		Effluent	36.9	16.4	44.5	36.4	52.6	**37.37**
Total Kjeldahl Nitrogen (TKN)	**Measurement**	Influent	20.5	18.0	18.0	19.0	18.0	
		Filt. Influent	14	16.0	15.0	15.0	13.0	
		Mixed liquor	22	22.0	21.5	20.0	21.0	
		Effluent	4	3.5	3.5	3.5	3.5	
	Dilution	Influent	1	1	1	1	1	
		Mixed liquor	10	10	10	10	10	
	Calculation	Influent	57.40	50.40	50.40	53.20	50.40	***52.36***
		Filt. Influent	39.20	44.80	42.00	42.00	36.40	***40.88***
		Mixed liquor	616.00	616.00	602.00	560.00	588.00	***596.40***
		Effluent	5.60	4.90	4.90	4.90	4.90	***5.04***
Free and Saline Ammonia (FSA)	**Measure**	Influent	14.0	15.5	14.5	16.0	14.5	
		Effluent	3.5	3.0	3.5	4.0	3.5	
	Dilution	Influent	1	1	1	1	1	
		Effluent	10	10	10	10	10	
	Calc.	Influent	39.2	21.7	20.3	44.8	40.6	***33.32***
		Effluent	4.9	4.2	4.9	5.6	4.9	***4.90***

Character	Function	Sample Point	18-Sep-08	20-Sep-08	25-Sep-08	26-Sep-08	28-Sep-08	Average
Sewage Batch 13								
			Measurements					***Average***
			Date					
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	55.8765	55.8805	51.7256	12.7620		
		Weight B	56.1000	56.0730	51.9037	12.9566		
		Weight C	55.9455	55.9343	51.7591	12.8192		
	Sample size (ml)		50	50	50	50		
	Anaerobic Tank (Calc.)	TSS	4470.0	3850.0	3562.0	3892.0		***3943.5***
		VSS	3090.0	2774.0	2892.0	2748.0		***2876.0***
		ISS	1380.0	1076.0	670.0	1144.0		***1067.5***
	Anoxic Tank (Measured)	Weight A	51.6888	51.7072	48.0745	19.3920	19.3620	
		Weight B	52.0558	52.0489	48.4052	19.7677	19.7258	
		Weight C	51.8238	51.8213	48.1583	19.5100	19.4950	
	Sample size (ml)		50	50	50	50	50	
	Anoxic Tank (Calc.)	TSS	7340.0	6834.0	6614.0	7514.0	7276.0	***7115.6***
		VSS	4640.0	4552.0	4938.0	5154.0	4616.0	***4780.0***
		ISS	2700.0	2282.0	1676.0	2360.0	2660.0	***2335.6***
	Re-aeration Tank (Measured)	Weight A	28.3887	41.5902	48.4627	54.6544		
		Weight B	28.7480	41.9547	48.8170	55.0253		
		Weight C	28.5220	41.7040	48.5639	54.7969		
	Sample size (ml)		50	50	50	50		
	Re-aeration Tank (Calc.)	TSS	7186.0	7290.0	7086.0	7418.0		***7245.0***
		VSS	4520.0	5014.0	5062.0	4568.0		***4791.0***
		ISS	2666.0	2276.0	2024.0	2850.0		***2454.0***
	Aerobic Tank (Measured)	Weight A	53.2370	53.2688	50.2871	53.8259	53.8159	
		Weight B	53.7122	53.7526	50.7642	54.3612	54.3150	
		Weight C	53.3966	53.4356	50.4317	54.0137	53.9819	
	Sample size (ml)		50	50	50	50	50	
	Aerobic Tank (Calc.)	TSS	9504.0	9676.0	9542.0	10706.0	9982.0	***9882.0***
		VSS	6312.0	6340.0	6650.0	6950.0	6662.0	***6582.8***
		ISS	3192.0	3336.0	2892.0	3756.0	3320.0	***3299.2***
Nitrates& Nitrites	***Nitrate + nitrite Height (cm)***	Anaerobic	0.5	0.5	1.5	1	2.5	
		Anoxic	0.5	0	1.5	2.5	0.5	
		Filt. Effluent	5.5	7.5	3.5	6	1.5	
	Nitrite Height (cm)	Anaerobic	0	0	0	0	0.5	
		Anoxic	9.5	0	0	0	0	
		Filt. Effluent	12.5	2.5	3.5	3.5	1	
	Slope	m	0.0349	0.0259	0.0627	0.0349	0.1098	
	Intercept	c	-0.0479	-0.0356	-0.0513	-0.0496	-0.0687	
	Slope	m	0.0625	0.108	0.0349	0.0625	0.0743	
	Intercept	c	-0.031	-0.198	-0.0196	-0.0513	0	
	Dilution	Anaerobic	1	1	1	1	1	
		Anoxic	2	2	2	2	2	

		Filt. Effluent	20	20	20	20	20	
	Nitrate Conc. (mgN/l)	Anaerobic	0.065	0.049	0.145	0.085	0.343	***0.137***
		Anoxic	0.13	0.07	0.29	0.27	0.25	***0.203***
		Filt. Effluent	4.80	4.60	5.42	5.18	4.67	***4.931***
	Nitrite Conc. (mgN/l)	Anaerobic	0.031	0.198	0.020	0.051	0.037	***0.067***
		Anoxic	1.250	0.396	0.039	0.000	0.000	***0.337***
		Filt. Effluent	0.000	0.000	0.000	0.000	0.000	***0.000***

Sewage Batch 13

Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			18-Sep-08	**20-Sep-08**	**25-Sep-08**	**26-Sep-08**	**28-Sep-08**	
Phosphates	**Total Phosphates Measurement**	Influent	0.1	0.101	0.108	0.104	0.105	
		Filt. Influent	0.082	0.1113	0.098	0.085	0.099	
		Anaerobic	0.138	0.162	0.183	0.204	0.241	
		Anoxic	0.14	0.135	0.14	0.014	0.032	
		Aerobic	0.06	0.08	0.202	0.155	0.166	
		Mixed liquor	0.17	0.141	0.179	0.14	0.184	
		Filt. Effluent	0.17	0.16	0.185	0.169	0.154	
	Ortho-Phosphates Reading	Influent	0.100	0.221	0.144	0.133	0.128	
		Anaerobic	0.260	0.215	0.258	0.227	0.209	
		Aerobic	0.295	0.213	0.295	0.280	0.283	
		Filt. Effluent	0.291	0.251	0.271	0.275	0.275	
	Line Functions TP	Slope	177.05	177.05	162.81	162.81	162.81	
		Intercept	3.3074	3.3074	2.2582	2.2582	2.2582	
	Line Functions OP	Slope	93.374	93.374	99.318	99.318	99.318	
		Intercept	0.9109	0.9109	1.805	1.805	1.805	
	Dilution TP	Influent	4	4	4	4	4	
		Filt. Influent	4	4	4	4	4	
		Anaerobic	5	5	5	5	5	
		Anoxic	4	4	4	4	4	
		Aerobic (filt)	2	2	2	2	2	
		Mixed liquor	40	40	40	40	40	
		Filt. Effluent	1	1	1	1	1	
	Dilution OP	Influent	4	4	4	4	4	
		Anaerobic	5	5	5	5	4	
		Aerobic	1	1	1	1	1	
		Filt. Effluent	1	1	1	1	1	
	Total Phosphates Conc. (mgP/l)	Influent	57.59	58.30	61.30	58.70	59.35	***59.05***
		Filt. Influent	44.84	65.59	54.79	46.32	55.44	***53.40***
		Anaerobic	105.63	126.87	137.68	154.78	184.90	***141.97***
		Anoxic	85.92	82.38	82.14	0.08	11.81	***52.47***
		Aerobic (filt)	14.63	21.71	61.26	45.95	49.54	***38.62***

		Mixed liquor	1071.64	866.27	1075.39	821.41	1107.95	***988.53***
		Filt. Effluent	26.79	25.02	27.86	25.26	22.81	***25.55***
	Ortho-Phosphates Conc. (mgP/l)	Influent	33.59	78.72	50.06	45.57	43.70	***50.33***
		Aerobic	26.63	18.98	27.49	26.00		***24.78***
		Filt. Effluent	26.26	22.53	25.11	25.51		***24.85***
OUR	Aerobic Tank	(mgO/l)	45.56	51.50	49.20	54.24	53.90	***50.88***

Sewage Batch 13

Character	*Function*	*Sample Point*	*Measurements*					*Average*
			Date					
			18-Sep-08	**20-Sep-08**	**25-Sep-08**	**26-Sep-08**	**28-Sep-08**	
Mg	**mg/l**	Influent	95.95	92.5	94			***94.15***
		Aerobic (filt)	75.75	75.75	70.7			***74.07***
		Aerobic (unfilt)	323.2	282.8	262.6			***289.53***
		Effluent	65.65	75	78			***72.88***
K		Influent	102.4	118.4	131.15			***117.32***
		Aerobic (filt)	93	105	98			***98.67***
		Aerobic (unfilt)	425	432	470			***442.33***
		Effluent	109.5	109.4	102			***106.97***
Ca		Influent	22.2	22.3	22.5			***22.33***
		Aerobic (filt)	24.1	30.3	27.2			***27.20***
		Aerobic (unfilt)	55.75	62.5	57.25			***58.50***
		Effluent	22	25	22			***23.00***
VFA		Aerobic	0					***0***
Alk		Aerobic	230					***230***
pH		Aerobic	7.6					***7.6***
System Parameters	**Volumes (litres)**	Anaerobic Vol.	19	19	19	19	19	***19***
		Anoxic Vol.	21	21	21	21	21	***21***
		Re-aeration Vol.	3	3	3	3	3	***3***
		Fully Aerated	32	32	32	32	32	***32***
		Total Aerobic	35	35	35	35	35	***35***
		Total Vol.	75	75	75	75	75	***75***
	Temp.(ºC)		20	20	20	20	20	***20***
	Sludge Recycle (ratios)	a-recycle	3.4	3.4	3.4	3.4	3.4	***3.4***
		r-recycle	1.15	1.15	1.15	1.15	1.15	***1.15***
		n-recycle	2.8	2.8	2.8	2.8	2.8	***2.8***
	Flow Rates (litres/day)	Influent (Qi)	150	150	150	150	150	***150***
		Waste (Qw)	5.7	5.7	5.7	5.7	5.7	***5.7***
		Effluent (Qe)	144.3	144.3	144.3	144.3	144.3	***144.3***

A.1.12. Sewage Batch no. 14

UCT Membrane AS system (NDBEPR)

Sewage Batch 14

Character	*Function*	*Sample Point*	*Measurements*					*Average*
			Date					
			26-Oct-08	27-Oct-08	28-Oct-08	30-Oct-08	1-Nov-08	
Chemical Oxygen Demand (COD)	*Measurement*	Influent	6.9	7.7	6.6	6.6	6.7	
		Filt. Influent	19	17.6	18.8	20.1	17.1	
		Mixed liquor	14.1	14.2	13.9	14.1	13.5	
		Effluent	24.2	24.6	24.1			
		Blank	25	25.5	25	25.2	25	
		FAS Norm.	0.0523	0.0523	0.0523	0.0523	0.0523	
	Dilution	Influent	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	
	Calculation	Influent	757.3	744.8	769.9	778.2	765.7	**763.2**
		Filt. Influent	251.0	330.5	259.4	213.4	330.5	**277.0**
		Mixed liquor	9121.1	9455.8	9288.5	9288.5	9623.2	**9355.4**
		Effluent	33.5	37.7	37.7			**36.3**
Total Kjeldahl Nitrogen (TKN)	**Measurement**	Influent	46	46.3	50.2	42	44	
		Filt. Influent	40.2	41.7	37.1	35	42	
		Mixed liquor	20.5	19.6	18.5	19.8	19.9	
		Effluent	4.2	3.5	4.2	4	4.1	
	Dilution	Influent	1	1	1	1	1	
		Mixed liquor	20	20	20	20	20	
	Calculation	Influent	64.40	64.82		58.80	61.60	***62.41***
		Filt. Influent	56.28	58.38	51.94	49.00	58.80	***54.88***
		Mixed liquor	574.00	548.80	518.00	554.40	557.20	***550.48***
		Effluent	5.88	4.90	5.88	5.60	5.74	***5.60***
Free and Saline Ammonia (FSA)	**Measure**	Influent	46.0	46.3	50.2	42.0	44.0	
		Effluent	40.2	41.7	37.1	35.0	42.0	
	Dilution	Influent	1	1	1	1	1	
		Effluent	1	1	1	1	1	
	Calc.	Influent	51.52	52.5	50.68	46.2	54.74	***51.13***
		Effluent	1.68	1.96	2.38	1.68	1.54	***1.85***

Sewage Batch 14								
Character	*Function*	*Sample Point*	*Measurements*					*Average*
			Date					
			26-Oct-08	**27-Oct-08**	**28-Oct-08**	**30-Oct-08**	**1-Nov-08**	
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	19.2762	19.2847	19.2994	19.3158	19.3132	
		Weight B	19.4493	19.4633	19.4693	19.4902	19.5043	
		Weight C	19.3180	19.3292	19.3398	19.3629	19.3681	
	Sample size (ml)		50	50	50	50	50	
	Anaerobic Tank (Calc.)	TSS	3462.0	3572.0	3398.0	3488.0	3822.0	***3548.4***
		VSS	2626.0	2682.0	2590.0	2546.0	2724.0	***2633.6***
		ISS	836.0	890.0	808.0	942.0	1098.0	***914.8***
	Anoxic Tank (Measured)	Weight A	39.3350	39.3409	41.6601	41.6688	32.1669	
		Weight B	39.6469	39.6560	41.9618	41.9560	32.4739	
		Weight C	39.4061	39.4275	41.7409	41.7388	32.2452	
	Sample size (ml)		50	50	50	50	50	
	Anoxic Tank (Calc.)	TSS	6238.0	6302.0	6034.0	5744.0	6140.0	***6091.6***
		VSS	4816.0	4570.0	4418.0	4344.0	4574.0	***4544.4***
		ISS	1422.0	1732.0	1616.0	1400.0	1566.0	***1547.2***
	Re-aeration Tank (Measured)	Weight A	32.0881	32.1034	32.1220	32.1520	41.6775	
		Weight B	32.4077	32.4082	32.4321	32.4286	41.9868	
		Weight C	32.1691	32.1940	32.1930	32.2262	41.7664	
	Sample size (ml)		50	50	50	50	50	
	Re-aeration Tank (Calc.)	TSS	6392.0	6096.0	6202.0	5532.0	6186.0	***6081.6***
		VSS	4772.0	4284.0	4782.0	4048.0	4408.0	***4458.8***
		ISS	1620.0	1812.0	1420.0	1484.0	1778.0	***1622.8***
	Aerobic Tank (Measured)	Weight A	41.6402	41.6485	39.3483	39.3637	39.3710	
		Weight B	42.0569	42.0831	39.7763	39.7794	39.8250	
		Weight C	41.7376	41.7626	39.4571	39.4586	39.4842	
	Sample size (ml)		50	50	50	50	50	
	Aerobic Tank (Calc.)	TSS	8334.0	8692.0	8559.4	8314.0	9080.0	***8595.9***
		VSS	6386.0	6410.0	6384.0	6416.0	6816.0	***6482.4***
		ISS	1948.0	2282.0	2175.4	1898.0	2264.0	***2113.5***
Nitrates& Nitrites	***Nitrate + nitrite Height (cm)***	Anaerobic	0	0	0	0	0	
		Anoxic	15	15	13.5	13	11	
		Filt. Effluent	8.5	9.7	9.4	9.3	10	
	Nitrite Height (cm)	Anaerobic	0	0	0	0	0	
		Anoxic	18.5	18	19	16.5	17	
		Filt. Effluent	0	0	0	0	0	
	Slope	m	0.1093	0.1093	0.1093	0.1093	0.1093	
	Intercept	c	0.2193	0.2193	0.2193	0.2193	0.2193	
	Slope	m	0.043	0.043	0.043	0.043	0.043	
	Intercept	c	0.0139	0.0139	0.0139	0.0139	0.0139	
	Dilution	Anaerobic	1	1	1	1	1	
		Anoxic	2	2	2	2	2	
		Filt. Effluent	10	10	10	10	10	
	Nitrate Conc. (mgN/l)	Anaerobic	0	0	0	0	0	***0***
		Anoxic	2.84	2.84	2.51	2.40	1.97	***2.51***
		Filt. Effluent	7.10	8.41	8.08	7.97	8.74	***8.06***
	Nitrite Conc. (mgN/l)	Anaerobic	0.00	0.00	0.00		0.00	***0.00***
		Anoxic	1.56	1.52	1.61		1.43	***1.53***
		Filt. Effluent	0.00	0.00	0.00	0.00	0.00	***0.00***

Sewage Batch 14								
Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			26-Oct-08	**27-Oct-08**	**28-Oct-08**	**30-Oct-08**	**1-Nov-08**	
Phosphates	**Total Phosphates Measurement**	Influent	0.096	0.077	0.078	0.08	0.084	
		Filt. Influent	0.07	0.073	0.074	0.069	0.075	
		Anaerobic	0.106	0.111	0.124	0.115	0.136	
		Anoxic	0.066	0.075	0.073	0.074	0.088	
		Aerobic	0.055	0.039	0.06	0.09	0.038	
		Mixed liquor	0.152	0.133	0.11	0.13	0.135	
		Filt. Effluent	0.063	0.049	0.058	0.091	0.042	
	Ortho-Phosphates Reading	Influent	0.11	0.102	0.108	0.109	0.179	
		Anaerobic	0.211	0.182	0.215	0.17	0.14	
		Aerobic	0.202	0.156	0.178	0.172	0.129	
		Filt. Effluent	0.19	0.17	0.18	0.16	0.13	
	Line Functions TP	Slope	160.97	160.97	160.97	160.97	160.97	
		Intercept	0	0	0	0	0	
	Line Functions OP	Slope	106.25	106.25	106.25	106.25	106.25	
		Intercept	0.031	0.031	0.031	0.031	0.031	
	Dilution TP	Influent	4	4	4	4	4	
		Filt. Influent	4	4	4	4	4	
		Anaerobic	5	5	5	5	5	
		Anoxic	4	4	4	4	4	
		Aerobic (filt)	2	2	2	2	2	
		Mixed liquor	40	40	40	40	40	
		Filt. Effluent	2	2	2	2	2	
	Dilution OP	Influent	4	4	4	4	4	
		Anaerobic	1	1	1	1	1	
		Aerobic	1	1	1	1	1	
		Filt. Effluent	1	1	1	1	1	
	Total Phosphates Conc. (mgP/l)	Influent	63.48	51.24	51.89	53.18	55.75	***55.11***
		Filt. Influent	46.74	48.67	49.31	46.09	49.96	***48.15***
		Anaerobic	87.40	91.42	101.88	94.64	111.54	***97.38***
		Anoxic	44.16	49.96	48.67	49.31	58.33	***50.08***
		Aerobic (filt)	18.54	13.39	20.15	29.81	13.07	***18.99***
		Mixed liquor	995.35	873.01	724.92	853.69	885.89	***866.57***
		Filt. Effluent	21.11	16.61	19.50	30.13	14.35	***20.34***
	Ortho-Phosphates Conc. (mgP/l)	Influent	46.63	43.23	45.78	46.20	75.95	***51.56***
		Aerobic	21.43	16.54	18.88	18.24		***18.78***
		Filt. Effluent	20.16	18.03	19.09	16.97		***18.56***
OUR	Aerobic Tank	(mgO/l)	63.56	61.35	63.17	62.11	62.58	***62.55***

Sewage Batch 14

Character	***Function***	***Sample Point***	***Measurements***					***Average***
			Date					
			26-Oct-08	**27-Oct-08**	**28-Oct-08**	**30-Oct-08**	**1-Nov-08**	
Mg	**mg/l**	Influent	106.05	101	95.95			***101.00***
		Aerobic (filt)	95.95	80.8	90.9			***89.22***
		Aerobic (unfilt)	252.5	245	285			***260.83***
		Effluent	75.75	85.85	90.9			***84.17***
K		Influent	101	99.5	98.7			***99.73***
		Aerobic (filt)	92.9	97.5	94.5			***94.97***
		Aerobic (unfilt)	405	295.1	408.5			***369.53***
		Effluent	89.7	90.5	89.5			***89.90***
Ca		Influent	16	16	15			***15.67***
		Aerobic (filt)	12.5	12.2	12.3			***12.33***
		Aerobic (unfilt)	45	43.5	51			***46.50***
		Effluent	10	13	12			***11.67***
VFA		Aerobic	0					***0***
Alk		Aerobic	230					***230***
pH		Aerobic	7.6					***7.6***
System Parameters	**Volumes (litres)**	Anaerobic Vol.	19					***19***
		Anoxic Vol.	21					***21***
		Re-aeration Vol.	3					***3***
		Fully Aerated	32					***32***
		Total Aerobic	35					***35***
		Total Vol.	75					***75***
	Temp.(ºC)		20					***20***
	Sludge Recycle (ratios)	a-recycle	3.4					***3.4***
		r-recycle	1.15					***1.15***
		n-recycle	2.8					***2.8***
	Flow Rates (litres/day)	Influent (Qi)	150					***150***
		Waste (Qw)	5.7					***5.7***
		Effluent (Qe)	144.3					***144.3***

A.2.1. 10 day Sludge Age

AD system (fed NDBEPR)

Sludge Age 10 day (fed Sewage Batch 14)

Character	*Function*	*Sample Point*	*Measurements*										*Average*
			Date										
			26-Oct-08	**27-Oct-08**	**28-Oct-08**	**29-Oct-08**	**30-Oct-08**	**31-Oct-08**	**1-Nov-08**	**2-Nov-08**	**3-Nov-08**	**4-Nov-08**	
Chemical Oxygen Demand (COD)	***Measure.***	Effl. (unfil)	15.8	6.6	6.5	7.4	7.2	6.8		6.7	7.1		
		Effluent (fil)	23.3	22	23	22.4	22.5	23	22.8	23.1	22.9		
		Blank	25	25.5	25.1	25.6	25	25	25	25	25		
		FAS Norm.	0.0514	0.0514	0.0514	0.0514	0.0514	0.0514	0.0514	0.0514	0.0514		
	Dilution	Effl. (unfil)	20	10	10	10	10	10	10	10	10		
		Effluent (fil)	1	1	1	1	1	1	1	1	1		
	Calculation	Effl. (unfil)	7566.1	7771.7	7648.3	7483.8	7319.4	7483.8		7525.0	7360.5		**7519.8**
		Effluent (fil)	69.9	143.9	86.4	131.6	102.8	82.2	90.5	78.1	86.4		**96.9**
Total Kjeldahl Nitrogen (TKN)	***Measure.***	Effl. (unfil)	19.50	23.00	20.00	23.00	24.00	20.50	20.00	19.50	21.50	22.00	
		Effluent (fil)	11.38	12.33	12.33	13.28	16.60	11.38	13.75	12.81	14.23	13.75	
	Dilution	Effl. (unfil)	20	20	20	20	20	20	20	20	20	20	
		Effluent (fil)	5	5	5	5	5	5	5	5	5	5	
	Calculation	Effl. (unfil)	546.0	644.0	560.0	644.0	672.0	574.0	560.0	546.0	602.0	616.0	***596.40***
		Effluent (fil)	79.7	86.3	86.3	93.0	116.2	79.7	96.3	89.6	99.6	96.3	***92.30***
FSA	***Measure.***	Effluent (fil)	11.8	12.3	12.8	13.2		11.8	12.8	12.8	13.7	13.2	
	Dilution	Effluent (fil)	5	5	5	5	5	5	5	5	5	5	
	Calc.	Effluent (fil)	82.41	85.84	89.27	92.71		82.41	89.27	89.27	96.14	92.71	***88.89***
MLSS and ISS (mg/l)	***Anaerobic (Measured)***	Weight A	54.7421	54.7172	58.1172	58.1149	58.1206	58.1590	58.1156	58.1319	59.5591		
		Weight B	55.1041	55.0652	58.4795	58.4795	58.4710	58.5148	58.5206	58.4902	59.8925		
		Weight C	54.8328	54.8178	58.2194	58.2215	58.2499	58.2100	58.2584	58.2412	59.6445		
	Sample size (ml)		50	50	50	50	50	50	50	50	50		
	Anaerobic Tank (Calc.)	TSS	7240.0	6960.0	7246.0	7292.0	7008.0		8099.0	7166.0	6668.0		***7209.9***
		VSS	5426.0	4948.0	5202.0	5160.0	4422.0		5243.0	4980.0	4960.0		***5042.6***
		ISS	1814.0	2012.0	2044.0	2132.0	2586.0		2856.0	2186.0	1708.0		***2167.3***

Sludge Age 10 day (fed Sewage Batch 14)													
Character	*Function*	*Sample Point*	*Measurements*										*Average*
			Date										
			26-Oct-08	**27-Oct-08**	**28-Oct-08**	**29-Oct-08**	**30-Oct-08**	**31-Oct-08**	**1-Nov-08**	**2-Nov-08**	**3-Nov-08**	**4-Nov-08**	
Phosphates	**TP Measure.**	Effl. (unfil)	0.143		0.139		0.13	0.132		0.137	0.142	0.131	
		Effluent (fil)	0.073	0.056	0.079	0.082	0.088	0.074	0.075	0.072		0.081	
	OP Measure.	Effluent (fil)	0.093	0.084	0.11	0.102	0.119	0.107	0.102	0.095		0.094	
	Line Functions TP	Slope	166.06	166.06	166.06	166.06	166.06	166.06	166.06	166.06	166.06	166.06	
		Intercept	-0.1871	-0.1871	-0.1871	-0.1871	-0.1871	-0.1871	-0.1871	-0.1871	-0.1871	-0.1871	
	Line Functions OP	Slope	121.9	121.9	121.9	121.9	121.9	121.9	121.9	121.9	121.9	121.9	
		Intercept	-0.0304	-0.0304	-0.0304	-0.0304	-0.0304	-0.0304	-0.0304	-0.0304	-0.0304	-0.0304	
	Dilution TP	Effl. (unfil)	40	40	40	40	40	40	40	40	40	40	
		Effluent (fil)	40	40	40	40	40	40	40	40	40	40	
	Dilution OP	Effluent (fil)	40	40	40	40	40	40	40	40	40	40	
	TP Conc. (mgP/l)	Effl. (unfil)	957.35		930.78		871.00	884.28		917.49	950.70	877.64	***912.75***
		Effluent (fil)	492.38	379.46	532.23	552.16	592.02	499.02	505.66	485.74		545.52	***509.35***
	OP (mgP/l)	Effluent (fil)	454.68	410.80	537.58	498.57	581.46	522.95	498.57	464.44		459.56	***492.07***
Mg	**mg/l**	Effl. (unfil)	286	227.25	245	265.125	261	258					***257.06***
		Effluent (fil)	25.25	29.29	28.28	24.24	18.18	19.19					***24.07***
K		Effl. (unfil)	345	336	353	328	331.25	398					***348.54***
		Effluent (fil)	325	324	342	305	310	348					***325.67***
Ca		Effl. (unfil)	39.5	49	44	45	42	44					***43.92***
		Effluent (fil)	38	45	42.6	43	41	41.2					***41.80***
VFA		Effl. (unfil)	32	30	1	10	40	48	28	58	0	0	***24.7***
Alk	**H_2CO_3* (mg as $CaCO_3$)**	with Ortho-P	178	286.9	146	310	130	226	270	433	250	243	***247.29***
		without OP											
pH		Aerobic	6.75	6.65	6.82	6.76	6.71	6.81	6.69	6.68	6.78	6.84	***6.749***
Gas	**Measure.(Q_{gas})**	(l/d)	3.7125	4.2075	4.4055	4.257	4.1085	4.356	4.257	4.356	4.2075	4.0095	***4.1877***
	Biomass	%	70										***70***
	CH_4	%	66.65										***66.65***
	CO_2	%	33.33										***33.33***

Sludge Age 12 day (fed Sewage Batch 14)													
Character	*Function*	*Sample Point*	*Measurements*										*Average*
			Date										
			26-Oct-08	**28-Oct-08**	**30-Oct-08**	**1-Nov-08**	**3-Nov-08**	**5-Nov-08**					
Chemical Oxygen Demand (COD)	***Measure.***	Effl. (unfil)	16	16.5	16.2	16.4	16.1	15.9					
		Effluent (fil)	23	23	22.5	23.5	22.9	22.5					
		Blank	25	25.5	25.1	25.6	25	25					
		FAS Norm.	0.0514	0.0514	0.0514	0.0514	0.0514	0.0514					
	Dilution	Effl. (unfil)	20	20	20	20	20	20					
		Effluent (fil)	1	1	1	1	1	1					
	Calculation	Effl. (unfil)	7401.6	7401.6	7319.4	7566.1	7319.4	7483.8					**7415.3**
		Effluent (fil)	82.2	102.8	106.9	86.4	86.4	102.8					**94.6**
Total Kjeldahl Nitrogen (TKN)	***Measure.***	Effl. (unfil)	42.00	43.00	45.00	40.00	42.00						
		Effluent (fil)	15.50	15.50	16.50	16.50	17.00	16.50					
	Dilution	Effl. (unfil)	10	10	10	10	10	10					
		Effluent (fil)	5	5	5	5	5	5					
	Calculation	Effl. (unfil)	588.0	602.0	630.0	560.0	588.0						***593.60***
		Effluent (fil)	108.5	108.5	115.5	115.5	119.0	115.5					***113.75***
FSA	***Measure.***	Effluent (fil)	5.0	5.0	5.0	5.0	5.0	5.0					
	Dilution	Effluent (fil)	10	10	10	10	10	10					
	Calc.	Effluent (fil)	119.00	108.50	112.00	126.00	140.00	115.50					***120.17***
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	59.3947	59.3960	59.4047	59.4088	59.3998	59.4325					
		Weight B	59.7734	59.7592	59.7732	59.7734	59.7738	59.7738					
		Weight C	59.5198	59.5108	59.5205	59.5258	59.5298	59.5288					
	Sample size (ml)		50	50	50	50	50	50					
	Anaerobic Tank (Calc.)	TSS	7574.0	7264.0	7370.0	7292.0	7480.0	6826.0					***7301.0***
		VSS	5072.0	4968.0	5054.0	4952.0	4880.0	4900.0					***4971.0***
		ISS	2502.0	2296.0	2316.0	2340.0	2600.0	1926.0					***2330.0***

Sludge Age 12 day (fed Sewage Batch 14)

Character	*Function*	*Sample Point*	*Measurements*										*Average*
			Date										
			26-Oct-08	**28-Oct-08**	**30-Oct-08**	**1-Nov-08**	**3-Nov-08**	**5-Nov-08**					
Phosphates	**TP Measure.**	Effl. (unfil)	0.27	0.26	0.28	0.25	0.29	0.28					
		Effluent (fil)	0.08	0.07	0.09	0.07	0.085	0.08					
	OP Measure.	Effluent (fil)	0.11	0.097	0.11	0.102	0.119	0.107					
	Line Functions TP	Slope	166.06	166.06	166.06	166.06	166.06	166.06					
		Intercept	-0.1871	-0.1871	-0.1871	-0.1871	-0.1871	-0.1871					
	Line Functions OP	Slope	121.9	121.9	121.9	121.9	121.9	121.9					
		Intercept	-0.0304	-0.0304	-0.0304	-0.0304	-0.0304	-0.0304					
	Dilution TP	Effl. (unfil)	20	20	20	20	20	20					
		Effluent (fil)	40	40	40	40	40	40					
	Dilution OP	Effluent (fil)	40	40	40	40	40	40					
	TP Conc. (mgP/l)	Effl. (unfil)	900.47	867.25	933.68	834.04	966.89	933.68					***906.00***
		Effluent (fil)	538.88	472.45	605.30	472.45	572.09	538.88					***533.34***
	OP Conc.(mgP/l)	Effluent (fil)	537.58	474.19	537.58	498.57	581.46	522.95					***525.39***
Mg	**mg/l**	Effl. (unfil)	252	275	245	245.45	234	261					***252.08***
		Effluent (fil)	24.3	27.56	18.97	26.64	24.45	20.89					***23.80***
K		Effl. (unfil)	395	385.6	390.45	389.45	401.56	389.54					***391.93***
		Effluent (fil)	277.5	348.5	387.5	371	380	370					***355.75***
Ca		Effl. (unfil)	37.5	49	44	43	42.6	44					***43.35***
		Effluent (fil)	35	36.5	39	37	39.6	37.56					***37.44***
VFA		Effl. (unfil)		28		25		20					***24.333333***
Alk	**H_2CO_3* (mg as $CaCO_3$)**	with Ortho-P		280		267		275					***274***
		without OP		725		705		685					***705***
pH		Aerobic		6.81		6.79		6.80					***6.80***
Gas	**Measure.(Q_{gas})**	(l/d)	3.168	3.2175	3.366	3.168	3.168	3.2175					***3.2175***
	Biomass	%											
	CH_4	%											
	CO_2	%											

A.2.3. 18 day Sludge Age

Sludge Age 18 day (fed Sewage Batch 10)													
Character	*Function*	*Sample Point*	*Measurements*										*Average*
			Date										
			31-Mar-08	**1-Apr-08**	**2-Apr-08**	**3-Apr-08**	**4-Apr-08**	**5-Apr-08**	**7-Apr-08**	**8-Apr-08**	**9-Apr-08**	**10-Apr-08**	
Chemical Oxygen Demand (COD)	***Measure.***	Effl. (unfil)	13.7			14.9	15.6	15.1	15.6	15.9	16.2		
		Effluent (fil)	19.5	20.7	20.4	19.9	21.4	20.9	21.7	21.8	22.1	22.6	
		Blank	22.6	23.4	23.5	23.7	24.2	23.8	24.7	25	25.1	25	
		FAS Norm.	0.0512	0.0512	0.0512	0.0512	0.0512	0.0512	0.0512	0.0504	0.0504	0.0512	
	Dilution	Effl. (unfil)	20	20	20	20	20	20	20	20	20	20	
		Effluent (fil)	1	1	1	1	1	1	1	1	1	1	
	Calculation	Effl. (unfil)	7290.9			7209.0	7045.1	7127.0	7454.7	7338.2	7177.0		**7234.6**
		Effluent (fil)	127.0	110.6	127.0	155.6	114.7	118.8	122.9	129.0	121.0	98.3	**122.5**
Total Kjeldahl Nitrogen (TKN)	***Measure.***	Effl. (unfil)	22.60	23.50	19.50	20.10	19.90	19.60	20.20	21.50	21.50	22.00	
		Effluent (fil)	10.00	23.00	24.50	24.00	19.50	21.50	18.50	18.00	19.00	22.00	
	Dilution	Effl. (unfil)	20	20	20	20	20	20	20	20	20	20	
		Effluent (fil)	10	5	5	5	5	5	5	5	5	5	
	Calculation	Effl. (unfil)	632.8	658.0	546.0	562.8	557.2	548.8	565.6	602.0	602.0	616.0	***589.12***
		Effluent (fil)	140.0	161.0	171.5	168.0	136.5	150.5	129.5	126.0	133.0	154.0	***147.00***
FSA	***Measure.***	Effluent (fil)	9.8	22.0	23.0	21.5	19.5	21.5	18.0	18.0	19.0	20.0	
	Dilution	Effluent (fil)	10	5	5	5	5	5	5	5	5	5	
	Calc.	Effluent (fil)	137.20	154.00	161.00	150.50	136.50	150.50	126.00	126.00	133.00	140.00	***141.47***
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	54.7421	54.7172	58.1172	58.1149	58.1206	58.1590	58.1156	58.1319	59.5591		
		Weight B	55.1121	55.0802	58.4945	58.4945	58.4860	58.4898	58.5356	58.5052	59.9075		
		Weight C	54.8628	54.8378	58.2394	58.2415	58.2699	58.2300	58.2784	58.2612	59.6645		
	Sample size (ml)		50	50	50	50	50	50	50	50	50		
	Anaerobic Tank (Calc.)	TSS	7400.0	7260.0	7546.0	7592.0	7308.0	6616.0	8399.0	7466.0	6968.0		***7395.0***
		VSS	4986.0	4848.0	5102.0	5060.0	4322.0	5196.0	5143.0	4880.0	4860.0		***4933.0***
		ISS	2414.0	2412.0	2444.0	2532.0	2986.0	1420.0	3256.0	2586.0	2108.0		***2462.0***

			Sludge Age 18 day (fed Sewage Batch 10)										
Character	***Function***	***Sample Point***	***Measurements***										***Average***
			Date										
			31-Mar-08	**1-Apr-08**	**2-Apr-08**	**3-Apr-08**	**4-Apr-08**	**5-Apr-08**	**7-Apr-08**	**8-Apr-08**	**9-Apr-08**	**10-Apr-08**	
Phosphates	**TP Measure.**	Effl. (unfil)	0.17	0.149	0.135	0.145	0.14	0.09	0.09	0.099	0.107	0.135	
		Effluent (fil)	0.08664	0.07695	0.09717		0.0961		0.0738	0.06503	0.07011	0.07665	
	OP Measure.	Effluent (fil)	0.12	0.085	0.128		0.159		0.085	0.092	0.167		
	Line Functions TP	Slope	181.4	181.4	181.4	181.4	178.34	178.34	178.34	178.34	178.34	178.34	
		Intercept	3.684	3.684	3.684	3.684	2.8344	2.8344	2.8344	2.8344	2.8344	2.8344	
	Line Functions OP	Slope	108.21	108.21	108.21	108.21	107.29	107.29	107.29	107.29	107.29	107.29	
		Intercept	1.2101	1.2101	1.2101	1.2101	1.5228	1.5228	1.5228	1.5228	1.5228	1.5228	
	Dilution TP	Effl. (unfil)	40	40	40	40	40	50	50	50	50	50	
		Effluent (fil)	40	40	40	40	40	40	40	40	40	40	
	Dilution OP	Effluent (fil)	40	40	40	40	40	40	40	40	40	40	
	TP Conc. (mgP/l)	Effl. (unfil)	1086.16	933.78	832.20	904.76	885.33	802.53	802.53	882.78	954.12	1062.08	***914.63***
		Effluent (fil)	481.30	410.99	557.71		572.16		413.08	350.52	386.76	433.41	***450.74***
	OP Conc.(mgP/l)	Effluent (fil)	471.00	319.51	505.63		621.45		303.87	333.92	655.79		***458.74***
Mg	**mg/l**	Effl. (unfil)	328.25	265.125	265.125	315.625	290.375	315.625					***296.69***
		Effluent (fil)	21.21	23.23	19.19	26.26	27.27	27.27					***24.07***
K		Effl. (unfil)	387.5	420	387.9	377.4	405.7	390					***394.75***
		Effluent (fil)	354	397.6	351.6	369.6	355.2	346.8					***362.47***
Ca		Effl. (unfil)	43.5	42.25	42.75	41.25	43	46.2					***43.16***
		Effluent (fil)	29.6	28	27.8	31	29	27.6					***28.83***
VFA		Effl. (unfil)	32	30	1	10	40	48	28	58	0	0	***24.7***
Alk	**H_2CO_3* (mg as $CaCO_3$)**	with Ortho-P	378	286.9	346	310	330	226	270	433	350	243	***317.29***
		without OP	819		799	901	851	822	857	851	899	892	***854.56***
pH		Aerobic	6.89	6.85	6.92	6.81	6.98	6.86	6.89	7.09	7	7.04	***6.93***
Gas	**Measure.(Q_{gas})**	(l/d)	1.91	2.01	2.04	1.94	1.91	1.84	1.91	1.97	1.94	1.97	***1.94***
	Biomass	%											
	CH_4	%											
	CO_2	%											

A.2.4. 20 day Sludge Age

Sludge Age 20 day (fed Sewage Batch 14)

Character	***Function***	***Sample Point***	***Measurements***										***Average***
			Date										
			26-Oct-08	**28-Oct-08**	**30-Oct-08**	**1-Nov-08**	**3-Nov-08**	**5-Nov-08**					
Chemical Oxygen Demand (COD)	***Measure.***	Effl. (unfil)	8	7.5	7.7	7.5	8.1	8.4					
		Effluent (fil)	21	22.6	22.4	22.5	22.5	21.8					
		Blank	25	25.5	25.1	25.6	25	25					
		FAS Norm.	0.0514	0.0514	0.0514	0.0514	0.0514	0.0514					
	Dilution	Effl. (unfil)	10	10	10	10	10	10					
		Effluent (fil)	1	1	1	1	1	1					
	Calculation	Effl. (unfil)	6990.4	7401.6	7154.9	7442.7	6949.3	6825.9					**7127.5**
		Effluent (fil)	164.5	119.2	111.0	127.5	102.8	131.6					**126.1**
Total Kjeldahl Nitrogen (TKN)	***Measure.***	Effl. (unfil)	21.00	42.00	42.00	44.00	41.00	40.00					
		Effluent (fil)	22.50	24.00	20.50	19.50	21.50	25.50					
	Dilution	Effl. (unfil)	20	10	10	10	10	10					
		Effluent (fil)	5	5	5	5	5	5					
	Calculation	Effl. (unfil)	588.0	588.0	588.0	616.0	574.0	560.0					***585.67***
		Effluent (fil)	157.5	168.0	143.5	136.5	150.5	178.5					***155.75***
FSA	***Measure.***	Effluent (fil)	23.5	25.0	25.5	24.5	24.0	25.0					
	Dilution	Effluent (fil)	5	5	5	5	5	5					
	Calc.	Effluent (fil)	164.50	175.00	178.50	171.50	168.90	175.00					***172.90***
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	59.2919	54.7421	54.7172	59.3226	58.1590	58.1156					
		Weight B	59.6663	55.1021	55.0902	59.6895	58.4998	58.4756					
		Weight C	59.4208	54.8628	54.8378	59.4515	58.2545	58.2284					
	Sample size (ml)		50	50	50	50	50	50					
	Anaerobic Tank (Calc.)	TSS	7488.0	7200.0	7460.0	7338.0	6816.0	7199.0					***7250.2***
		VSS	4910.0	4786.0	5048.0	4760.0	4906.0	4943.0					***4892.2***
		ISS	2578.0	2414.0	2412.0	2578.0	1910.0	2256.0					***2358.0***

Sludge Age 20 day (fed Sewage Batch 14)

Character	***Function***	***Sample Point***	***Measurements***										***Average***
			Date										
			26-Oct-08	**28-Oct-08**	**30-Oct-08**	**1-Nov-08**	**3-Nov-08**	**5-Nov-08**					
Phosphates	**TP Measure.**	Effl. (unfil)	0.12	0.29	0.24	0.25	0.3	0.3					
		Effluent (fil)	0.09	0.08	0.085	0.08	0.08	0.084					
	OP Measure.	Effluent (fil)	0.13	0.11	0.115	0.105		0.114					
	Line Functions TP	Slope	166.06	166.06	166.06	166.06	166.06	166.06					
		Intercept	-0.1871	-0.1871	-0.1871	-0.1871	-0.1871	-0.1871					
	Line Functions OP	Slope	121.9	121.9	121.9	121.9	121.9	121.9					
		Intercept	-0.0304	-0.0304	-0.0304	-0.0304	-0.0304	-0.0304					
	Dilution TP	Effl. (unfil)	40	20	20	20	20	20					
		Effluent (fil)	40	40	40	40	40	40					
	Dilution OP	Effluent (fil)	40	40	40	40	40	40					
	TP Conc. (mgP/l)	Effl. (unfil)	804.57	966.89	800.83	834.04	1000.10	1000.10					***901.09***
		Effluent (fil)	605.30	538.88	572.09	538.88	538.88	565.45					***559.91***
	OP Conc.(mgP/l)	Effluent (fil)	635.10	537.58	561.96	513.20		557.08					***560.98***
Mg	**mg/l**	Effl. (unfil)	281	286	295	255.125	258	264					***273.19***
		Effluent (fil)	23.21	20.1	25.5	21.5	22	23.5					***22.64***
K		Effl. (unfil)	355	401	353.75	385	387	358					***373.29***
		Effluent (fil)	354	397.6	351.6	369.6	355.2	346.8					***362.47***
Ca		Effl. (unfil)	37.5	49	44	43	39.5	44					***42.83***
		Effluent (fil)	32.5	33	35	31	36	37					***34.08***
VFA		Effl. (unfil)	25		35			18					***26***
Alk	**H_2CO_3* (mg as $CaCO_3$)**	with Ortho-P	385		355			401					***380.33333***
		without OP	758		789			805					***784.00***
pH		Aerobic	6.898		6.95			6.91					***6.92***
Gas	**Measure.(Q_{gas})**	(l/d)	1.48	1.51	1.48	1.55	1.48	1.48					***1.50***
	Biomass	%											
	CH_4	%											
	CO_2	%											

A.2.5. 25 day Sludge Age

Sludge Age 25 day (fed Sewage Batch 13)

Character	***Function***	***Sample Point***	***Measurements***										***Average***
			Date										
			18-Sep-08	**19-Sep-08**	**20-Sep-08**	**21-Sep-08**	**23-Sep-08**	**24-Sep-08**	**25-Sep-08**	**26-Sep-08**	**27-Sep-08**	**28-Sep-08**	
Chemical Oxygen Demand (COD)	***Measure.***	Effl. (unfil)	16	16.3	15.9	16	15.8	15.7	16.1	16.1	15.8		
		Effluent (fil)	21.8	21.9	22.2	21.7	22.1	19.8	21.6	22	22.4		
		Blank	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5	24.5		
		FAS Norm.	0.0512	0.0512	0.0512	0.0512	0.0512	0.0506	0.0506	0.0506	0.0506		
	Dilution	Effl. (unfil)	20	20	20	20	20	20	20	20	20		
		Effluent (fil)	1	1	1	1	1	1	1	1	1		
	Calculation	Effl. (unfil)	6963.2	6717.4	7045.1	6963.2	7127.0	7124.5	6800.6	6800.6	7043.5		**6953.9**
		Effluent (fil)	110.6	106.5	94.2	114.7	98.3	190.3	117.4	101.2	85.0		**113.1**
Total Kjeldahl Nitrogen (TKN)	***Measure.***	Effl. (unfil)	19.50	23.00	20.00	23.00	24.00	20.50	20.00	19.50	21.50	22.00	
		Effluent (fil)	11.38	12.33	12.33	13.28	16.60	11.38	13.75	12.81	14.23	13.75	
	Dilution	Effl. (unfil)	20	20	20	20	20	20	20	20	20	20	
		Effluent (fil)	10	10	10	10	10	10	10	10	10	10	
	Calculation	Effl. (unfil)	546.0	644.0	560.0	644.0	672.0	574.0	560.0	546.0	602.0	616.0	***596.40***
		Effluent (fil)	159.4	172.6	172.6	185.9	232.4	159.4	192.6	179.3	199.2	192.6	***184.60***
FSA	***Measure.***	Effluent (fil)	11.8	12.3	12.8	13.2	16.7	11.8	12.8	12.8	13.7	13.2	
	Dilution	Effluent (fil)	10	10	10	10	10	10	10	10	10	10	
	Calc.	Effluent (fil)	164.81	171.68	178.55	185.42		164.81	178.55	178.55	192.28	185.42	***177.79***
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	54.7421	54.7172	58.1172	58.1149	58.1206	58.1590	58.1156	58.1319	59.5591		
		Weight B	55.1041	55.0652	58.4795	58.4795	58.4710	58.5148	58.5206	58.4902	59.8925	0.0450	
		Weight C	54.8528	54.8378	58.2394	58.2415	58.2699	58.2300	58.2784	58.2612	59.6645	0.0600	
	Sample size (ml)		50	50	50	50	50	50	50	50	50	50	
	Anaerobic Tank (Calc.)	TSS	7240.0	6960.0	7246.0	7292.0	7008.0	7116.0	8099.0	7166.0	6668.0		***7199.4***
		VSS	5026.0	4548.0	4802.0	4760.0	4022.0	5696.0	4843.0	4580.0	4560.0		***4759.7***
		ISS	2214.0	2412.0	2444.0	2532.0	2986.0	1420.0	3256.0	2586.0	2108.0		***2439.8***

Sludge Age 25 day (fed Sewage Batch 13)

Character	*Function*	*Sample Point*	*Measurements*										*Average*
			Date										
			18-Sep-08	**19-Sep-08**	**20-Sep-08**	**21-Sep-08**	**23-Sep-08**	**24-Sep-08**	**25-Sep-08**	**26-Sep-08**	**27-Sep-08**	**28-Sep-08**	
Phosphates	**TP Measure.**	Effl. (unfil)	0.15	0.148	0.144	0.125	0.143	0.14	0.15	0.147	0.145	0.13	
		Effluent (fil)	0.057	0.087	0.091	0.065	0.077	0.108	0.085	0.088	0.105	0.071	
	OP Measure.	Effluent (fil)	0.1	0.13	0.141	0.1	0.129	0.123	0.152	0.135	0.165	0.114	
	Line Functions TP	Slope	177.05	177.05	177.05	177.05	177.05	162.81	162.81	162.81	162.81	162.81	
		Intercept	3.3074	3.3074	3.3074	3.3074	3.3074	2.2582	2.2582	2.2582	2.2582	2.2582	
	Line Functions OP	Slope	93.374	93.374	93.374	93.374	93.374	99.318	99.318	99.318	99.318	99.318	
		Intercept	0.9109	0.9109	0.9109	0.9109	0.9109	1.805	1.805	1.805	1.805	1.805	
	Dilution TP	Effl. (unfil)	40	40	40	40	40	40	40	40	40	40	
		Effluent (fil)	60	40	40	40	40	40	40	40	40	40	
	Dilution OP	Effluent (fil)	60	40	40	40	40	40	40	40	40	40	
	TP Conc. (mgP/l)	Effl. (unfil)	930.00	915.84	887.51	752.95	880.43	821.41	886.53	866.99	853.97	756.28	***855.19***
		Effluent (fil)	407.07	483.84	512.17	328.03	413.02	613.01	463.23	482.76	593.47	372.05	***466.86***
	OP (mgP/l)	Effluent (fil)	505.59	449.11	490.19	337.06	445.37	416.44	531.65	464.12	583.30	380.69	***460.35***
Mg	**mg/l**	Effl. (unfil)	282.8	323.2	303	262.6	323.2						***298.96***
		Effluent (fil)	27.27	24.24	28.28	22.22	23.23						***25.05***
K		Effl. (unfil)	381	415	372.5	427	406						***400.30***
		Effluent (fil)	371.6	390	354	375	371.2						***372.36***
Ca		Effl. (unfil)	39.895	41.25	39.25	38.75	39.75						***39.78***
		Effluent (fil)	27	33.5	23.5	22.5	27.25						***26.75***
VFA		Effl. (unfil)	32	30	1	10	40	48	28	58	0	0	***24.7***
Alk	**$H_2CO_3^*$ (mg as $CaCO_3$)**	with Ortho-P	612	606	744	625	612	599	508	724	721		***639***
		without OP	901	926	913	927	844	901	978	965	985		***926.67***
pH		Aerobic	6.8	6.75	6.8	6.82	6.8	6.83	6.79	6.79	6.85	6.82	***6.81***
Gas	**Measure.(Q_{gas})**	(l/d)	1.02	0.99	0.96	0.99	0.94	0.91	0.99	0.96	0.96	0.94	***0.97***
	Biomass	%											
	CH_4	%											
	CO_2	%											

A.2.6. 40 day Sludge Age

Sludge Age 40 day (fed Sewage Batch 12)

Character	***Function***	***Sample Point***	***Measurements***										***Average***
			Date										
			25-Jun-08	**26-Jun-08**	**27-Jun-08**	**28-Jun-08**	**29-Jun-08**	**30-Jun-08**	**1-Jul-08**	**2-Jul-08**	**3-Jul-08**	**4-Jul-08**	
Chemical Oxygen Demand (COD)	***Measure.***	Effl. (unfil)	17	17.5	17.6	16.8		16.8	17.6	17.4	16.9		
		Effluent (fil)	23.2	23.1	22.5	22.6	22.2	23.1	22.4	22.8	22.8	23.1	
		Blank	25.2	25.1	25.2	25	25	24.8	24.9	25	25	25.1	
		FAS Norm.	0.051	0.051	0.051	0.051	0.051	0.051	0.051	0.051	0.0504	0.0504	
	Dilution	Effl. (unfil)	20	20	20	20	20	20	20	20	20	20	
		Effluent (fil)	1	1	1	1	1	1	1	1	1	1	
	Calculation	Effl. (unfil)	6691.2	6201.6	6201.6	6691.2		6528.0	5956.8	6201.6	6531.8		**6375.5**
		Effluent (fil)	81.6	81.6	110.2	97.9	114.2	69.4	102.0	89.8	88.7	80.6	**91.6**
Total Kjeldahl Nitrogen (TKN)	***Measure.***	Effl. (unfil)	22.00	21.00	23.00	21.00	19.00	22.00	18.50	23.00	21.00	24.50	
		Effluent (fil)	14.00	14.00	17.50	15.00	14.50	18.00	17.50	16.50	16.50	13.00	
	Dilution	Effl. (unfil)	20	20	20	20	20	20	20	20	20	20	
		Effluent (fil)	616	588	644	588	532	616	518	644	588	686	
	Calculation	Effl. (unfil)	196.0	196.0	245.0	210.0	203.0	252.0	245.0	231.0	231.0	182.0	***602.00***
		Effluent (fil)	13.0	13.0	17.5	14.0	14.0	17.5	17.0	16.5	15.0	13.0	***219.10***
FSA	***Measure.***	Effluent (fil)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	
	Dilution	Effluent (fil)	10	10	10	10	10	10	10	10	10	10	
	Calc.	Effluent (fil)	182.00	182.00	245.00	196.00	196.00	245.00	238.00	231.00	210.00	182.00	***210.70***
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	52.7504	52.7238	52.7475	52.7770			52.7708	52.7734	59.3675	52.7736	
		Weight B	53.0963	53.0648	53.0910	53.0953			53.1116	53.1230	59.6997	53.0931	
		Weight C	52.8825	52.8459	52.8791	52.8952			52.8782	52.8953	59.4819	52.8888	
	Sample size (ml)		50	50	50	50			50	50	50	50	
	Anaerobic Tank (Calc.)	TSS	6918.0	6820.0	6870.0	6366.0			6816.0	6992.0	6644.0	6390.0	***6727.0***
		VSS	4276.0	4378.0	4238.0	4002.0			4668.0	4554.0	4356.0	4086.0	***4319.7***
		ISS	2642.0	2442.0	2632.0	2364.0			2148.0	2438.0	2288.0	2304.0	***2407.3***

Sludge Age 40 day (fed Sewage Batch 12)

Character	***Function***	***Sample Point***	***Measurements***										***Average***
			Date										
			25-Jun-08	**26-Jun-08**	**27-Jun-08**	**28-Jun-08**	**29-Jun-08**	**30-Jun-08**	**1-Jul-08**	**2-Jul-08**	**3-Jul-08**	**4-Jul-08**	
Phosphates	**TP Measure.**	Effl. (unfil)	0.146	0.145	0.135	0.149	0.142	0.146	0.15	0.148	0.158	0.15	
		Effluent (fil)		0.101	0.102	0.1	0.104	0.105	0.1	0.11	0.094	0.096	
	OP Measure.	Effluent (fil)	0.146	0.144	0.153	0.148	0.15	0.165	0.151	0.165	0.145	0.15	
	Line Functions TP	Slope	177.05	177.05	177.05	177.05	177.05	162.81	162.81	162.81	162.81	162.81	
		Intercept	3.3074	3.3074	3.3074	3.3074	3.3074	2.2582	2.2582	2.2582	2.2582	2.2582	
	Line Functions OP	Slope	93.374	93.374	93.374	93.374	93.374	99.318	99.318	99.318	99.318	99.318	
		Intercept	0.9109	0.9109	0.9109	0.9109	0.9109	1.805	1.805	1.805	1.805	1.805	
	Dilution TP	Effl. (unfil)	40	40	40	40	40	40	40	40	40	40	
		Effluent (fil)	40	40	40	40	40	40	40	40	40	40	
	Dilution OP	Effluent (fil)	40	40	40	40	40	40	40	40	40	40	
	TP Conc. (mgP/l)	Effl. (unfil)	901.68	894.59	823.77	922.92	873.35	860.48	886.53	873.51	938.63	886.53	***886.20***
		Effluent (fil)		582.99	590.07	575.90	604.23	593.47	560.91	626.04	521.84	534.86	***576.70***
	OP Conc.(mgP/l)	Effluent (fil)	508.87	501.40	535.01	516.34	523.81	583.30	527.68	583.30	503.84	523.71	***530.73***
Mg	**mg/l**	Effl. (unfil)	245	222.2	262.6	276	242.4	262.6					***251.80***
		Effluent (fil)	31.31	28.28	24.24	22.22	19.19	28.28					***25.59***
K		Effl. (unfil)	389	397	385	347.6	376	364.8					***376.57***
		Effluent (fil)	398	350	374	364	385	343					***369.00***
Ca		Effl. (unfil)	25.4	25	27.8	26.8	26.2	25.6					***26.13***
		Effluent (fil)	23	18.75	19.25	20	19.75	19.5					***20.04***
VFA		Effl. (unfil)	32	30	1	10	40	48	28	58	0	0	***24.7***
Alk	**$H_2CO_3^*$ (mg as $CaCO_3$)**	with Ortho-P	696	713	888.6	676	680	862	731	752	736	760	***749.46***
		without OP	926	942	1002	734	885	1029	999.7	913	917	975	***932.27***
pH		Aerobic	6.97	6.98	6.95	6.97	6.95	6.99	6.95	6.95	7.01	6.97	***6.97***
Gas	**Measure.(Q_{gas})**	(l/d)	0.52	0.50	0.41	0.47	0.54	0.50	0.56	0.52	0.52	0.50	***0.50***
	Biomass	%											
	CH_4	%											
	CO_2	%											

A.2.7. 60 day Sludge Age

Character	Function	Sample Point	*Sludge Age 60 day (fed Sewage Batch 11)*										
			Measurements										*Average*
			Date										
			2-Jun-08	**3-Jun-08**	**4-Jun-08**	**5-Jun-08**	**6-Jun-08**	**7-Jun-08**	**8-Jun-08**	**9-Jun-08**	**10-Jun-08**	**11-Jun-08**	
Chemical Oxygen Demand (COD)	***Measure.***	Effl. (unfil)	17	17.4	17	17	17.8	17	16.1	16.9	17.3	17.9	
		Effluent (fil)	19.6	21.5	20.8	20	20.4	20.8	21.1	20.7	22.9	21.3	
		Blank	24.8	24.5	24.7	24.6	24.5	24.3	24	24.2	24.8	24.5	
		FAS Norm.	0.05	0.05	0.05	0.05	0.05	0.051	0.051	0.051	0.051	0.051	
	Dilution	Effl. (unfil)	1	1	1	1	1	1	1	1	1	1	
		Effluent (fil)	20	20	20	20	20	20	20	20	20	20	
	Calculation	Effl. (unfil)	6240.0	5680.0	6160.0	6080.0		5956.8	6446.4	5956.8	6120.0		**6080.0**
		Effluent (fil)	208.0	120.0	156.0	184.0	164.0	142.8	118.3	142.8	77.5	130.6	**144.4**
Total Kjeldahl Nitrogen (TKN)	***Measure.***	Effl. (unfil)	22.60	23.50	19.50	20.10	19.90	19.60	20.20	21.50	21.50	22.00	
		Effluent (fil)	10.00	23.00	24.50	24.00	19.50	21.50	18.50	18.00	19.00	22.00	
	Dilution	Effl. (unfil)	20	20	20	20	20	20	20	20	20	20	
		Effluent (fil)	632.8	658	546	562.8	557.2	548.8	565.6	602	602	616	
	Calculation	Effl. (unfil)	280.0	322.0	343.0	336.0	273.0	301.0	259.0	252.0	266.0	308.0	***589.12***
		Effluent (fil)	9.8	22.0	23.0	21.5	19.5	21.5	18.0	18.0	19.0	20.0	***294.00***
FSA	***Measure.***	Effluent (fil)	20.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	
	Dilution	Effluent (fil)	10	10	10	10	10	10	10	10	10	10	
	Calc.	Effluent (fil)	274.40	308.00	322.00	301.00	273.00	301.00	252.00	252.00	266.00	280.00	***282.94***
MLSS and ISS (mg/l)	***Anaerobic Tank (Measured)***	Weight A	54.7421	54.7172	58.1172	58.1149	58.1206	58.1590	58.1156	58.1319	59.5591		
		Weight B	55.0791	55.0502	58.4545	58.4545	58.4560	58.4498	58.4756	58.4652	59.8475		
		Weight C	54.8778	54.8528	58.2344	58.2165	58.2649	58.2750	58.2634	58.2062	59.6095		
	Sample size (ml)		50	50	50	50	50	50	50	50	50		
	Anaerobic Tank (Calc.)	TSS	6740.0	6660.0	6746.0	6792.0	6708.0	5816.0	7199.0	6666.0	5768.0		***6566.1***
		VSS	4026.0	3948.0	4402.0	4760.0	3822.0	3496.0	4243.0		4760.0		***4182.1***
		ISS	2714.0	2712.0	2344.0	2032.0	2886.0	2320.0	2956.0	1486.0	1008.0		***2273.1***

App 2.2 : Sludge Age 60 day (fed Sewage Batch 11)													
Character	***Function***	***Sample Point***	***Measurements***										***Average***
			Date										
			2-Jun-08	**3-Jun-08**	**4-Jun-08**	**5-Jun-08**	**6-Jun-08**	**7-Jun-08**	**8-Jun-08**	**9-Jun-08**	**10-Jun-08**	**11-Jun-08**	
Phosphates	**TP Measure.**	Effl. (unfil)	0.12	0.114	0.116	0.119	0.123	0.117	0.13	0.112	0.119	0.118	
		Effluent (fil)	0.064	0.057	0.075	0.065	0.065	0.069	0.06	0.076	0.059	0.065	
	OP Measure.	Effluent (fil)	0.09	0.091	0.103	0.098	0.103	0.1	0.1	0.109	0.087	0.101	
	Line Functions TP	Slope	181.4	181.4	181.4	181.4	178.34	178.34	178.34	178.34	178.34	178.34	
		Intercept	3.684	3.684	3.684	3.684	2.8344	2.8344	2.8344	2.8344	2.8344	2.8344	
	Line Functions OP	Slope	108.21	108.21	108.21	108.21	107.29	107.29	107.29	107.29	107.29	107.29	
		Intercept	1.2101	1.2101	1.2101	1.2101	1.5228	1.5228	1.5228	1.5228	1.5228	1.5228	
	Dilution TP	Effl. (unfil)	40	40	40	40	40	40	40	40	40	40	
		Effluent (fil)	40	40	40	40	40	40	40	40	40	40	
	Dilution OP	Effluent (fil)	40	40	40	40	40	40	40	40	40	40	
	TP Conc. (mgP/l)	Effl. (unfil)	870.72	827.18	841.70	863.46	877.43	834.63	927.37	798.96	848.90	841.76	***853.21***
		Effluent (fil)	464.38	413.59	544.20	471.64	463.68	492.22	428.02	542.15	420.88	463.68	***470.45***
	OP Conc.(mgP/l)	Effluent (fil)	389.56	393.88	445.83	424.18	442.03	429.16	429.16	467.78	373.37	433.45	***422.84***
Mg	**mg/l**	Effl. (unfil)	280.8	292	252	263	292	266					***274.30***
		Effluent (fil)	25.5	19.4	32.74	15.67	26.3	29					***24.77***
K		Effl. (unfil)	397.5	382.25	402	423	415	409					***404.79***
		Effluent (fil)	360	392	364	390	378	410					***382.33***
Ca		Effl. (unfil)	45.57	51.2	49.87	47.89							***48.63***
		Effluent (fil)	40.68	48.7	47.78	45.68							***45.71***
VFA		Effl. (unfil)	22			20		22			18		***20.5***
Alk	**H_2CO_3* (mg as $CaCO_3$)**	with Ortho-P	1025	785	876		1024	1017	940	792	916	972	***927.4***
		without OP	1238	1130	1285		1399	1424	1284	1228	1238	1304	***1281.1***
pH		Aerobic	6.97	6.99	7.05		7.08	7.08	7.1	7.07	7.13	7.08	***7.06***
Gas	**Measure.(Q_{gas})**	(l/d)	0.24	0.28	0.32	0.30	0.26	0.32	0.30	0.26	0.26	0.28	***0.28***
	Biomass	%											
	CH_4	%											
	CO_2	%											

Appendix B: Mass Balances and Other Calculations

Content of Appendix B

1. Mass Balance Procedures and Results (COD, N, P and C)
2. Mass Balance Results
3. Precipitation Potential Calculation
4. Methane (CH_4) gas fluxed related to COD removal

1. Mass Balance Procedures and Results

(The COD, Nitrogen, Phosphorus and Carbon mass balances

The mass balance performed over a system accounts for all masses of a specific character that enter, exits and gained/lost within the boundaries set for the mass balance. Equation B1 below gives this,

$$\begin{bmatrix} Mass \\ Change \\ in \quad system \end{bmatrix} = \begin{bmatrix} Mass \quad flow \\ \operatorname{int} o \quad system \end{bmatrix} - \begin{bmatrix} Mass \quad flow \\ out \quad of \quad system \end{bmatrix} + \begin{bmatrix} Mass \quad gain \\ by \quad bio-process \end{bmatrix} - \begin{bmatrix} Mass \quad loss \\ by \quad bio-process \end{bmatrix}.$$

… (***B1)***

This Equation B1 was applied for system that operates at steady state in this study. Also Equation B1 is applied to determine the mass balances for the COD, Nitrogen, Phosphorus and Carbon characters over the AS and AD system studied during this experimental investigation.

A. The COD Mass Balance

I. *AS System*

The COD balance over the AS system consider the COD mass flow of the influent organics compared to that leaving the system and used/ lost in the AS system as that contained by the UPO and USO, or transformed by the biomass to conserve in a different form, or that transferred to O_2 to produce H_2O.

a. COD in the influent {mgCOD/d} = Q_i x S_{ti}

b. COD exiting the AS system {mgCOD/d}

i. COD in the effluent flow (assuming only soluble context) = $Q_e \times S_{te}$

ii. COD in waste flow = $(S_{use} + f_{cv} .X_V)Q_w$

iii. Mass of N generated in AS system (based on nitrification oxygen demand)

$$MO_n = 4.57\ (MNO_d + MNO_{eff})$$
$$= 4.57\ [MNO_d + Q_e(NO_{2.eff} + NO_{3.eff})]$$

Where $MNO_d = (r).Q.(NO_2+NO_3)_{anox} + (a).Q.(NO_2+NO_3)_{aer} - (1+r+a+s).Q.(NO_2+NO_3)_{anox} + (s).Q.(NO_2+NO_3)_{eff}$

iv. Carbonaceous oxygen utilization Mass flow (MO_c) = $O_c.V.24 - MO_n$

Where O_c refer to the Oxygen Utilization Rate (OUR)

v. Total COD exiting the AS system = $[Q_e \times S_{te}] + [(S_{use} + f_{cv} .X_V)Q_w] + [MO_c]$

c. The COD mass balance over the AS system

= (Total COD Out / Total COD In) x 100 [%]

II. *AD system*

The COD balance over the AD system consider the influent COD mass flow of the WAS to that exiting the AD in the effluent sludge and the COD content of the methane (CH_4) leaving the system.

a. COD in the influent {mgCOD/d} = $Q_i \times S_{ti}$

b. COD exiting the AD system

i. COD in the effluent sludge flow = $Q_e \times S_{te}$

ii. COD content of the CH_4 gas = COD of CH_4 (Appendix B3)

c. The COD mass balance over the AD system

= (Total COD Out / Total COD In) x 100 [%]

B. <u>The Nitrogen Mass Balance</u>

I. *AS System*

The N balance over the AS system consider the N mass flow of the influent compared to that leaving the system and gained/lost in the AS system as the (i) the nitrogen that is denitrified, (ii) the nitrogen contained by the waste sludge (by the PO and USO), and that contained by the effluent (TKN + NO_2 and NO_3).

a. TKN in the influent {mgN/d} $= Q_i \times N_{ti}$

b. N exiting the AS system {mgN/d}

i. Total mass of NO_2 and NO_3 ($NO_2 + NO_3 = NO_x$) denitrified (NO_{xd}) in the Anoxic (anox) and Anaerobic (ana) reactors (MNO_{xd}) $= MNO_{xd(ana)} + MNO_{xd(anox)}$

where:

$$MNO_{xd\ ana} = (r).Q.(NO_2+NO_3)_{anox} - (1+r).Q.(NO_2+NO_3)_{ana}$$

$$MNO_{xd\ anox} = (1+r).Q.(NO_2+NO_3)_{ana} + (a).Q.(NO_2+NO_3)_{aer} - (1+r+a+s).Q.(NO_2+NO_3)_{anox} + (s).Q.(NO_2+NO_3)_{eff}$$

ii. N in waste flow (MX_n) $= f_n .X_V.Q_w$

iii. N in the effluent (MN_{eff}) $= Q_e (N_{te} + NO_{2.eff} + NO_{3.eff})$

iv. Total N exiting the AS system $= MN_{eff} + MX_n + MNO_{xd}$

d. The N mass balance over the AS system

= (Total N Out / Total N In) x 100 [%]

II. ***AD system***

The N balance over the AD system consider the influent N mass flow of the WAS to that exiting the AD in the effluent sludge.

a. N in the influent {mgN/d} $= Q_i \times N_{ti}$

b. N exiting the AD system {mgN/d} $= Q_e \times N_{te}$

c. The N mass balance over the AD system

= (Total N Out / Total N In) x 100 [%]

C. The Phosphorus Mass Balance

I. *AS System*

The P balance over the AS system consider the influent P mass flow of the influent organics compared to that leaving the system and used/ lost in the AS system as that contained by the UPO and USO.

a. P in the influent {mgP/d} = Qi x Pti

b. P exiting the AS system {mgP/d}

  i. P in the effluent flow (assuming only soluble context) = $Q_e \times P_{te}$

  ii. P in waste flow = $(P_{use} + f_{cv} .X_V)Q_w$

  iii. Total P exiting the AS system = $[Q_e \times P_{te}] + [(P_{use} + f_{cv} .X_V)Q_w] + [O_c.V.24]$

c. The P mass balance over the AS system

= (Total P Out / Total P In) x 100 [%]

II. *AD system*

The P balance over the AD system consider the influent P mass flow of the WAS to that exiting the AD in the effluent sludge.

a. P in the influent {mgP/d} = $Q_i \times P_{ti}$

b. P exiting the AD system {mgP/d} = $Q_e \times P_{te}$

c. The P mass balance over the AD system

= (Total P Out / Total P In) x 100 [%]

D. The Carbon Mass Balance *(over the AD only)*

The Carbon Mass Balance performed over the AD system is not a direct measured component on the influent and effluent of the AD system. However, the carbon mass balances were performed at the different sludge ages selected for the AD system based on the assumed fractions allocated to the VSS(PO) and UPO components, at 0.52 and 0.51 respectively, and that calculated for the BPO based on the difference from the PO and UPO components.

a. C in the influent {mgP/d}

(*The carbon mass content of the influent to the AD system was determined from the f_C of the VSS concentration and the H_2CO_3* Alkalinity of the influent WAS)*

i. C content of the influent PO flow = ([VSS (PO)]/MM_{PO}) x $n_{C(\text{in PO})}$ x 12

ii. C content of HCO_3^- = (H_2CO_3* Alk)/50 x 12 { in *mg as* $CaCO_3$ the MM = 100/2 eq.}

b. C exiting the AD {mgP/d}

{The carbon mass content exiting the AD system was determined as the sum of the C content of (i) UPO C content, (ii) residual BPO C content, (iii) HCO_3^- C content (based on H_2CO_3 Alk), (iv) CH_4 C content , (v) CO_2 C content and (vi) the C content of the Biomass (not included because the Biomass are not measured).}*

i. C content of the UPO flow = ([UPO]/MM_{UPO}) x $n_{C(\text{in UPO})}$ x 12

ii. C content of the Res. BPO flow = ([Res. BPO]/MM_{BPO}) x $n_{C(\text{in BPO})}$ x 12

iii. C content of effluent HCO_3^- = (H_2CO_3* Alk)/50 x 12
{in *mg as* $CaCO_3$ the MM = 100/2 eq.}

iv. C of CH_4 = (nCH_4/Q_e) x 12

v. C of CO_2 = (nCO_2/Q_e) x 12
where the mmoles/d of CH_4 and CO_2 is determined in Appendix B3

vi. C in Biomass can be calculated from the predicted results

2. *Mass Balance Results*

a.AS system mass balances

Table 5.2a presents the COD, TN, TP, Mg, K and Ca character mass balance results for Sewage Batches 3 to 14 used during the experimental investigation related to this study.

TABLE 5.2a :UCT Membrane AS Material Mass Balances

Sewage Batch No.	Components of % Mass Balance					
	COD	TKN	TP	Mg	K	Ca
Batch 3	97%	109%	90%	***Used Batch 6 measurements***		
Batch 4	102%	112%	95%			
Batch 5	96%	109%	98%			
Batch 6	92%	131%	94%	81%	101%	82%
Batch 7	91%	108%	94%	***Used Batch 6 measurements***		
Batch 8	95%	112%	95%			
Batch 9	105%	98%	95%			
Batch 10	101%	101%	96%	77%	102%	102%
Batch 11	92%	115%	97%	100%	101%	100%
Batch 12	102%	120%	94%	88%	102%	105%
Batch 13	99%	92%	105%	86%	102%	109%
Batch 14	110%	81%	95%	89%	102%	84%

b.AD system mass balances

Table 5.2b presents the COD, TN, TP, TC, Mg, K and Ca character mass balance results for Sludge Age 10, 12, 18, 20, 25, 40 and 60 day used during the experimental investigation related to this study.

TABLE 5.2b : Anaerobic Digester Material Mass Balances

Data Set Application	AD SS Sludge Age	Components of % Mass Balance						
		COD	TKN	TP	TC	Mg	K	Ca
Model Calibration	**10 Day**	100%	108%	105%	91.7%	96%	77%	85%
	18 Day	99%	98%	100%	91.7%	102%	80%	80%
	25 Day	100%	100%	87%	92.2%	103%	91%	91%
	40 Day	98%	104%	106%	92.1%	80%	84%	85%
	60 Day	98%	87%	93%	92.1%	98%	101%	86%
Model Validation	**12 Day**	101%	108%	104%	90.3%	107%	98%	86%
	20 Day	104%	106%	104%	96.7%	116%	93%	85%

3. Determination of Precipitation Potential

Struvite ($MgNH_4PO_4.6H_2O$) precipitation occurs when the ionic product of the molar concentrations of Mg^{2+}, NH_4^+ and PO_4^{-3} in solution exceed the thermodynamic solubility product (K_{spm}) of struvite in the aqueous phase (Bhuiyan *et al.*, 2008). The solubility product of struvite in the negative log form is 12.6 (pK_{spm}) and can be applied in the equation (Loewenthal *et al.*, 1994). The ionic product (K_{is}) of the molar concentrations of Mg^{2+}, NH_4^+ and PO_4^{-3} in solution at determine with the equation state below,

$$K_{is} = f_d\left[Mg^{2+}\right]\cdot f_m\left[NH_4^+\right]\cdot f_t\left[PO_4^{3-}\right]$$

Where f_m, f_d and f_t refer to the activity coefficients of mono- , di- and tri-valent ionic species, respectively. The method used to determine the activity coefficients of the ionic species is described based on a modification of the Debye-Huckel theory, by Davies, describing the activity of ions in low salinity water (Butler *et al.*, 1964). This method is shown for the mono- valent ionic species below but the same methodology is repeated for the di- and tri-valent ionic species,

$$f_m = 10^{-\log fm}$$

where:

$$-\log f_m = -A.Z_m^2\left[\frac{\mu^{1/2}}{1+\mu^{1/2}} - 0.3\mu\right]$$

and where:

$$A = 1.825\times10^6\left(78.3\times T\right)^{-1,5}$$

$$\mu = \left(Conductivity\{mS/m\}\right)\times\left(1.68\times10^{-4}\right)$$

T in Kelvin

Z = 1 for mono-, 2 for di- and 3 for tri-valent ionic species

Next, the concentration of Mg^{2+}, NH_4^+ and PO_4^{-3} dissolved ionic species are determined in mmol/l as follows,

i. [Mg] is measured (mg/l) and converted to molar concentration (mmol/l)

ii. $[NH_4^+]$ is determined as follows,

$$\left[NH_4^+\right]=\frac{N_t}{\left(10^{pH-pK_n}+1\right)}$$

iii. $[PO_4^{3-}]$ is determined as follows,

$$\left[PO_4^{3-}\right]=\frac{P_t}{\left(10^{pK_{p2}+pK_{p3}-2pH}+10^{pK_{p3}-pH}+1\right)}$$

Where pK_n, pK_{p2} and pK_{p3} can be found in Loewenthal *et al.* (1989)

4. Gas measurement to COD removal

This section describes (a) the conversion of gas volumetric flow rate (ml/d) to molar flux (mmoles/d) for the biogas contents of CH_4 and CO_2 and than (b) determining, the COD value of the CH_4 removed from the AD on the daily bases. This is done to compared the COD content by the CH4 released from the AD system to the COD concentration removal of the WAS in the AD system. Theoretically, the COD concentration removal should be reflected in the COD value of the CH_4 gas leaving the AD system as the COD loss in the methanogenic AD system is through the CH_4 gas.

a. Conversion of gas volumetric flow rate (ml/d) to molar flux (mmoles/d)

i. The gas volumetric flow rate (ml/d) is measured using the gas flow meter shown in Figure 3.5 described in Section 3.3.8. This unit is connected to a counter that is calibrated in ml per count.

ii. The biogas released from the experimental AD system is captured in gas bags and this gas is than analysed in an external laboratory to determine the CH_4 and CO_2 composition of the biogas. This gas composition is used to determine the volumetric flux f CH_4 (V_{CH4}) and CO_2 (V_{CO2}) released from the AD system as shown below,

$$V_{CH4} = Q_{Gas} \times \%Biogas \times \%CH_4$$
$$V_{CO2} = Q_{Gas} \times \%Biogas \times \%CO_2$$

iii. Next, the Ideal Gas Law is applied to determine the molar flux for the CH_4 and CO_2 gases,

$$n_{CH_4} = \frac{[PV_{CH4}]}{RT} \quad \text{and} \quad n_{CO_2} = \frac{[PV_{CO2}]}{RT}$$

Where
P = absolute pressure within the AD system (Pa or atm)
T = AD system temperature (K)
R = universal gas constant = 8.314J/mol K or 0.08206atm.l / mol. K
n_X = moles/d

b. Determine the COD content (mgCOD/l) of the CH_4 gas molar flux (mol/d)

The CH_4 gas released during the AD process is related to the COD removal in the aqueous phase while the CO_2 gas contains none of the COD removed from the system but needs to be included in the carbon balance over the system. The theoretical COD content of 1 gram of CH_4 contain 4 grams of COD. The method used to determine the COD content of CH_4 is described below.

$$COD_{CH_4} = \frac{n_{CH_4}.MM_{CH_4}.4(gCOD/gCH_4).1000}{Q_i} \qquad \textbf{\textit{(mgCOD/l)}}$$

Where n_{CH4} = determined in step (a) *(ml/d)*

MM_{CH4} = molar mass of CH_4 = 16 *mg/mol*

Q_i = feed rate *(l/d)*

Appendix C: Expected results for Fractionation of UCT MBR AS system

A. Prediction of Experimental Results

In order to give a quantitative impression of the performance and check the quantities and characteristics of the WAS available for the five ADs and the adequacy of the experimental setup, to meet the experimental objectives, the steady state AS system models (WRC, 1984 and Wentzel *et al.,* 1990; both modified to include the ISS model of Ekama and Wentzel, 2004) were applied to predict the AS system experimental outcomes. These predictions are as presented in Table C2 below, with the kinetic constants and system parameters shown in Table C3 and C4. Ramphao *et al.* (2004) give the relationships between the volume and sludge mass fractions for the membrane UCT system in terms of reactor volumes and recycle ratios. The detail of the effect of the side stream aerobic reactor was ignored in the calculation.

Table C1: Prediction of Experimental Results Using Assumed Influent Values and Kinetic Constants

	Influent Assumed Values			Mixed liquor-Predicted Values					Effluent Pred. values	
MBR UCT NDBEPR AS System	Settled WW (+ 200 mgCOD/l Acetate)				Anaerobic Conc.	Anoxic Conc.	Aerobic Conc.		Effluent	
	S_{ti}	800.00		Conc. Frac	0.52	0.96	1.28		COD	32.00
	f_{up}	0.200		TSS	4161.96	7632.91	10182.51		TKN	3.20
	f_{us}	0.040		VSS	2783.01	5103.96	6808.82		TP	16.20
	f_{bs}	0.400		ISS	1378.95	2528.95	3373.69		Mg	7.60
	S_{bi}	608.00		OUR			66.96		K	97.53
	S_{bsi}	243.20		TP			905.77		Ca	16.49
	TKN/COD	0.100		COD			10077.05			
	TP/COD	0.025		TKN			680.88			
	N_{ti}	80.00		PAOs (X_{BG})			2004.32			
	P_{ti}	50.00		PolyP			701.51			
	Mg	14.00		Mg			176.0791			
	K	100.70		K			180.9897			
	Ca	20.00		Ca			108.7341			
	Q_i	150.00		OHOs (X_{BH})			1237.96			

Table C2: Kinetic and Stoichiometric Constants

OHOs				PAOs			
Y_H	b_H	f_H	f_{cv}	Y_G	f_G	b_G	f_{cv}
0.45	0.24	0.2	1.48	0.45	0.25	0.04	1.48

Table C3: AS System parameters and Sludge fractions		
		NDBEPR
Volumes (litres)	Anaerobic Vol.	19.00
	Anoxic Vol.	21.00
	Reaeration Vol.	3.00
	Fully Aerated	32.00
	Total Aerobic	35.00
	Total Vol.	75.00
Flow Rates (litres/day)	Influent (Q_i)	150.00
	Waste (Q_w)	5.70
	Effluent (Q_e)	144.30
Sludge Age (R_s)		10
Sludge Fractions	f_{av} OHO	0.182
	f_{av} PAO	0.294
	f_{xBGP}	0.380
	f_p(OHO)	0.030
	f_p (PolyP)	0.350
	Mg/PolyP	0.251
	K/PolyP	0.258
	Ca/PolyP	0.155
	f_{cv} (COD/VSS)	1.480
	f_i (VSS/TSS)	0.669

The above calculations (Table C2) were also used, together with the known AD volumes, to calculate the AD influent feed quantities for each digester sludge age, as shown below (Table C4).

Table C4: Prediction of Anaerobic Digester Feed Quantities								
Anaerobic Digester	**Diegester Feed**	**Parameters**	**units**	**Retention time**				
				10.00	**18.00**	**25.00**	**40.00**	**60.00**
AD 1	**NDBEPR WAS**	Flow (Q_i)	l/d	1.60	0.89	0.64	0.40	0.27
		Concentration	gCOD/l	10.00	10.00	10.00	10.00	10.00
		Flux	gCOD/d	16.00	8.89	6.40	4.00	2.67
		Volume	l	16.00	16.00	16.00	16.00	16.00

Appendix D: AD Batch Tests Total and Ortho Phosphate measurement

AD Batch Tests Total and Ortho Phosphates measurements

Test	Batch Test No.1			Batch test No.2			Batch test No.3		
	Concetrated 50:50			Concetrated 50:50			Concentrated 50:50		
Day	Date	Unfilt. Conc.	Filt. Conc.	Date	Unfilt. Conc.	Filt. Conc.	Date	Unfilt. Conc.	Filt. Conc.
0	11-Feb-08	981.4	316.8	01-Mar-08	979.0	242.9	8-Jul-08	837.99	299.25
1	12-Feb-08	979.6	437.7	02-Mar-08	975.6	445.6	9-Jul-08	837.99	299.25
2	13-Feb-08	984.8	550.6	03-Mar-08	989.3	610.5	10-Jul-08	936.19	431.83
3	14-Feb-08	986.5	694.6	04-Mar-08	975.6	656.4	11-Jul-08	948.47	494.94
4	15-Feb-08	869.1	610.2	05-Mar-08	989.3	487.4	12-Jul-08	981.79	488.78
5	16-Feb-08	976.2	655.0	06-Mar-08	960.1	612.0	13-Jul-08	964.25	611.97
6	17-Feb-08	899.6	739.6	07-Mar-08	966.6	748.0	14-Jul-08	948.11	469.03
7	18-Feb-08	873.3	689.0	08-Mar-08	945.1	707.2	15-Jul-08	961.80	516.94
8	19-Feb-08	918.9	721.0	09-Mar-08	955.9	688.5	16-Jul-08	925.76	571.69
9	20-Feb-08	885.6	528.8	10-Mar-08	938.0	545.7	17-Jul-08	920.73	482.72
10	21-Feb-08	924	645.00	11-Mar-08	961.2	572.9	18-Jul-08	920.73	523.78

Test	Batch test No.4			Batch test No.5		
	Diluted 50:50			Diluted 25:75		
Day	Date	Unfilt. Conc.	Filt. Conc.	Date	Unfilt. Conc.	Filt. Conc.
0	2-Aug-08	539.58	156.00	2-Aug-08	532.98	44.94
1	3-Aug-08	546.59	198.00	3-Aug-08	532.98	65.67
2	4-Aug-08	532.56	270.00	4-Aug-08	540.00	292.84
3	5-Aug-08	504.78	355.84	5-Aug-08	445.30	321.38
4	6-Aug-08	536.35	385.89	6-Aug-08	462.84	327.03
5	7-Aug-08	518.81	377.30	7-Aug-08	410.23	370.83
6	8-Aug-08	554.47	340.60	8-Aug-08	450.10	299.53
7	9-Aug-08	532.23	326.91	9-Aug-08	409.04	316.64
8	10-Aug-08	535.65	337.17	10-Aug-08	484.32	296.11
9	11-Aug-08	539.07	340.60	11-Aug-08	467.21	296.11
10	12-Aug-08	542.49	330.33	12-Aug-08	456.94	320.06