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OPTIMISATION OF MUNICIPAL WASTEWATER BIOLOGICAL NUTRIENT REMOVAL USING COMPUTER SIMULATION

by

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ABSTRACT

Due to more stringent regulations for secondary municipal wastewater treatment, municipalities are beginning to implement tertiary treatment in their wastewater treatment plants. Tertiary treatment would be the removal of either phosphorous or nitrogen or both from the wastewater before it is discarded from the plant. Biological treatment is becoming an increasingly popular process used to accomplish this extra removal. There are several processes available that will provide acceptable levels of biological nutrient and BOD removal from wastewater. Three well-known processes were considered in this study - the Modified Bardenpho Process, the Modified UCT Process and the A^2/O Process. For each of these processes, 2 level fractional factorial designs along with least squares analysis were performed in order to determine the optimal operating variables (recycle rates and anaerobic, anoxic and aerobic zone retention times), with respect to the final nitrogen concentration, the final phosphorous concentration and a combination of the final nitrogen and phosphorous concentrations. The analyses were performed at 10°C and 20°C with low, medium and high primary effluent concentrations. Due to the complexity of the processes, lab scale experiments were not feasible. Therefore, a widely accepted calibrated biokinetic model (Activated Sludge Model No 2d) was used in a computer simulation program (GPS-X) to gather the necessary data for analysis. Actual plant data were used to test the validity of the simulation model with respect to organic and nitrogen removal. Using the published kinetic and stoichiometric parameters for both temperature levels, the Activated Sludge Model provided a good estimation of outlet concentration levels.

It was found that all three biological nutrient removal (BNR) process were capable of achieving an effluent soluble phosphorous concentration below the required limit of 1 mgP/L at 10 and 20°C with low, medium and high primary effluent concentration when the effluent nitrogen concentration was neglected. Neither the Modified Bardenpho, the Modified UCT nor the A^2/O process were capable of producing an effluent with nitrogen concentrations below the required limit of 5 mgN/L at high primary effluent concentrations. The Modified Bardenpho and the Modified UCT processes were both successful in achieving a combined nitrogen and phosphorous removal below their regulatory limits for low primary effluent concentrations at 10 and 20°C. The Modified Bardenpho process, at 20°C with medium primary effluent concentrations, was found to achieve an effluent with nitrogen and phosphorous concentrations below 5 mgN/L and 1 mgP/L, respectively.

After analyzing the effects of individual operating variables, it was found that the anoxic recycle for the Modified UCT process had an insignificant effect on total nitrogen (TN) and soluble phosphorous (sP) removals and did not need to be included in future experimental studies. All of the input variables to the MB and A^2/O process proved to be somewhat significant and it is recommended that they be kept within future experimental designs.

From this study it was found that both the MB and MUCT process are capable of achieving the TN, sP and $cBOD_5$ removals that ROPEC requires. However only the MB process proved to be a robust system when subjected to storm conditions (i.e., peaks in influent flow rate) with respect to sP and $cBOD_5$ removal. Neither the MB nor the MUCT process provided acceptable TN removals when subjected to storm conditions.

It is recommended that ROPEC further evaluate the MB process as a possible means to achieve simultaneous $cBOD_5$, TN and sP removal.

RESUME

En raison des normes rigoureuses sur le traitement secondaire des eaux municipales, des municipalités commencent à implémenter du traitement tertiaire dans leurs usines de traitement d'eaux usées. Le traitement tertiaire implique l'élimination du phosphore et/ou de l'azote des eaux usées avant qu'elles soient déchargées de l'usine. Le traitement biologique est un processus de plus en plus utilisé pour ces réductions additionnelles. De nombreux processus peuvent produire le même niveau de réduction des nutriments biologiques et de la DBO de l'eau usée. Trois processus bien connus furent évalués dans cette étude; le "Modified Bardenpho", le "Modified UCT" et le "A^2/O". Pour chaque procédé, des analyses fractionnelles factorielles à deux niveaux et des analyses par moindres carrés furent employées pour déterminer les variables opérationnelles optimales (taux de recyclage et temps de rétention des zones anaérobiques, anoxiques et aérobiques). Les variables optimales furent trouvées par rapport à la concentration finale d'azote, la concentration finale de phosphore et une combinaison des deux. Les analyses furent effectuées à 10°C et 20°C avec des effluents primaires de concentrations basses, moyennes et élevées. En raison de la complexité des procédés, l'expérimentation en laboratoire serait longue et pénible. Par conséquent, un modèle biokinétique calibré ("Activated Sludge Model No 2d") accepté globalement fut utilisé avec un logiciel de simulation (GPS-X) pour amasser les données nécessaires pour fins d'analyses. Des données réelles provenant d'une usine furent utilisées pour tester la validité du modèle en ce qui à trait à l'enlèvement de l'azote et des matières organiques. En utilisant les paramètres kinétiques et stoïchiométriques publiés pour les deux niveaux différents de température, le "Activated Sludge Model" a fourni un bon estimé des niveaux de concentrations à la sortie du système.

Il fut déterminé que les trois procédés de RNB sont capables d'atteindre une concentration finale de phosphore soluble en deçà de la limite de 1 mgP/L, à 10°C et 20°C, pour des effluents primaires de concentrations basses, moyennes et élevées lorsque la concentration finale d'azote est négligée. Les modèles "Bardenpho", "Modified UCT" ou "A^2/O" n'étaient pas capable de produire un effluent avec des concentrations d'azote en deçà de la limite requise de 5 mgN/L pour un effluent primaire de concentration élevée. Les processus "Modified Bardenpho" et "Modified UCT" ont tous deux réussi à atteindre un taux combiné de réduction d'azote et de phosphore en deçà des limites établies pour un effluent primaire de faible concentration à 10 et 20°C. Le processus "Modified Bardenpho" a aussi réussi à atteindre un effluent

avec des concentrations d'azote et de phosphore en deçà de 5 mgN/L et 1 mgP/L respectivement, pour un effluent primaire de concentration moyenne à 20°C.

Suite aux analyses des effets individuels des variables opérationnelles, le recyclage anoxique du processus "Modified UCT" fut observé d'avoir un effet insignifiant sur la réduction de l'NT et du Ps. Il ne serait toutefois pas nécessaire de l'inclure dans des études expérimentales futures. L'ensemble des variables d'entrée pour les processus MB et A^2/O étaient toutefois quelques peu significatives et il serait recommandé de les inclure dans des conceptions expérimentales éventuelles.

D'après cette étude, les processus MB et MUCT sont capables d'atteindre les réductions d'NT, de Ps et de $DBOc_5$ requises par C.E.R.O.P. Le système MB a démontré de la robustesse lorsque soumis à des conditions de tempête (e.g., débit accru d'affluent) en ce qui à trait à la réduction de Ps et $DBOc_5$. Les processus MB et MUCT n'ont pas donné des réductions acceptables d'NT lorsque soumis à des conditions de tempête.

Il est recommandé que le C.E.R.O.P. considère à la fois le procédé MB comme un moyen d'atteindre la réduction simultanée de $DBOc_5$, d'NT et de Ps.

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LIST OF ABBREVIATIONS

%R	Percent Removed
A/O	Anaerobic/Oxic
A^2/O	Anaerobic/Anoxic/Aerobic Process patented by Air Products, Inc
AR	Anoxic Recycle
AS	Activated Sludge
ASM 1	Activated Sludge Model No 1
ASM 2	Activated Sludge Model No 2
ASM2d	Activated Sludge Model No 2d
AT	Anaerobic Zone Hydraulic Retention Time
AX	Anoxic Zone Hydraulic Retention Time
BNR	Biological Nutrient Removal
BOD	Biochemical Oxygen Demand
$cBOD_5$	5 day Carbonaceous Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
EPA	Environmental Protection Agency
F/M	Food to Microorganism Ratio
HRT	Hydraulic Retention Time
IAWPRC	International Association on Water Pollution Research and Control
IAWQ	International Association on Water Quality
IR	Internal Recycle
K_o	Switching Function Parameter
MB	Modified Bardenpho Process
MCRT	Mean Cell Retention Time
MLE	Modified Ludzack and Ettinger Process
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
MUCT	Modified University of Capetown Process
N	Nitrogen
NDBEPR	Nitrification/Denitrification/Biological Excess Phosphorous Removal
NR	Nitrified Recycle
OT	Aerobic Zone Hydraulic Retention Time
P	Phosphorous
PAO	Phosphorous Accumulating Organisms
PHB	Polyhydroxybutyrate
Q	Influent Flow Rate
RAS	Return Activated Sludge
ROPEC	Robert O. Pickard Environmental Centre
SBR	Sequencing Batch Reactors
sCOD	Soluble Chemical Oxygen Demand
S_o	Dissolved Oxygen (DO) Concentration
sP	Soluble Phosphorous
SRT	Solids Retention Time
SS	Suspended Solids
Temp	Temperature
TKN	Total Keidjel Nitrogen
TN	Total Nitrogen
TP	Total Phosphorous
TR	Total Recycle
TSS	Total Suspended Solids

UCT	University of Capetown
USA	United States of America
VFA	Volatile Fatty Acid
WAS	Waste Activated Sludge
WWTP	Wastewater Treatment Plant
y_{sP}	Effluent Soluble Phosphorous Concentration
y_{TN}	Effluent Total Nitrogen Concentration
y_{TN+sP}	Combination of Effluent Total Nitrogen and Soluble Phosphorous Concentrations

NOMENCLATURE

Symbol	Definition	Units
β_j	Least Squares Parameter j	
b_A	Organism Decay Rate	1/d
b_{AUT}	Decay Rate of X_{AUT}	1/d
b_H	Organism Decay Rate	1/d
b_H	Rate Constant for Lysis and Decay	1/d
b_{PAO}	Rate for Lysis of X_{PAO}	1/d
b_{PHA}	Rate for Lysis of X_{PHA}	1/d
b_{PP}	Rate for Lysis of X_{PP}	1/d
f_{BOD}	BOD_5/BOD_u Ratio	-
f_{BOD}	BOD5/BODu Ratio	-
f_{BOD}	BOD_5/BOD_u Ratio	-
f_{NH}	Ammonium/TKN Ratio	-
f_{NH}	Ammonium/TKN Ratio	-
f_{NI}	Soluble Inert N/TKN Ratio	-
f_{SA}	VFA Fraction of Soluble COD	-
f_{SF}	Fermentable Fraction of Particulate COD	-
f_{SI}	Inert Fraction of Soluble COD	-
f_{SI}	Inert Fraction of Soluble COD	-
f_{SI}	Production of S_I in Hydrolysis	gCOD/gCOD
f_U	Endogenous Fraction	-
f_{XBH}	Biomass Fraction of Particulate COD	-
f_{XH}	Biomass Fraction of Particulate COD	-
f_{XI}	Fraction of Inert COD Generated in Biomass Lysis	gCOD/gCOD
f_{XI}	Fraction of Inert COD Generated in Biomass Lysis	gCOD/gCOD
f_{XI}	Fraction of Inert COD Generated in Biomass Lysis	gCOD/gCOD
f_{XN}	Particulate Organic N/Total Organic N	-
F_{XN}	Particulate Organic N/Total Organic N	-
f_{XS}	Degradable Fraction of Particulate COD	-
f_{XS}	Degradable Fraction of Particulate COD	-
i_{cv}	Particulate COD to VSS Ratio	gCOD/gVSS
i_{cv}	Particulate COD to VSS Ratio	gCOD/gVSS
i_{cv}	Particulate COD to VSS Ratio	gCOD/gVSS
i_{NBM}	N Content of Biomass, X_H, X_{PAO}, X_{AUT}	gN/gCOD
i_{NSF}	N Content of Fermentable Substrates S_F	gN/gCOD
i_{NSI}	N Content of Inert Soluble COD S_I	gN/gCOD
i_{NXI}	N Content of Inert Particulate COD X_I	gN/gCOD
i_{NXS}	N Content of Slowly Biodegradable Substrate X_S	gN/gCOD

i_{PBM}	P Content of Biomass, X_H, X_{PAO}, X_{AUT}	gP/gCOD
i_{PSF}	P Content of Fermentable Substrates S_F	gP/gCOD
i_{PSI}	P Content of Inert Soluble COD S_I	gP/gCOD
i_{PXI}	P Content of Inert Particulate COD X_I	gP/gCOD
i_{PXS}	P Content of Slowly Biodegradable Substrate X_S	gP/gCOD
i_{TSSBM}	TSS to COD Ratio for Biomass, X_H, X_{PAO}, X_A	gTSS/gCOD
i_{TSSXI}	TSS to COD Ratio for X_I	gTSS/gCOD
i_{TSSXS}	TSS to COD Ratio for X_S	gTSS/gCOD
i_{vt}	VSS/TSS Ratio	gVSS/gTSS
i_{vt}	VSS/TSS Ratio	gVSS/gTSS
i_{vt}	VSS/TSS Ratio	gVSS/gTSS
i_{XB}	N Content of Active Mass	gN/gCOD
i_{XP}	N Content of Endogenous Mass	gN/gCOD
ka	Ammonification Rate	m^3/gCOD/d
K_A	Saturation Coefficient for Growth on Acetate	gCOD/m^3
K_A	Saturation Coefficient for Acetate, S_A	gCOD/m^3
K_{ALK}	Saturation Coefficient for Alkalinity (HCO_3^-)	moleHCO_3^-/m^3
K_{ALK}	Saturation Coefficient for Alkalinity (HCO_3^-)	moleHCO_3^-/m^3
K_{ALK}	Saturation Coefficient for Alkalinity (HCO_3^-)	moleHCO_3^-/m^3
K_{ALK}	Saturation Coefficient for Alkalinity	moleHCO_3^-/m^3
K_F	Saturation Coefficient for Growth on S_F	gCOD/m^3
K_{fc}	Saturation Coefficient for Fermentation of S_F	gCOD/m^3
k_H	Maximum Specific Hydrolysis Rate	1/d
K_h	Hydrolysis Rate Constant	1/d
K_{IPP}	Inhibition Coefficient for PP Storage	gX_{PP}/gX_{PAO}
K_{MAX}	Maximum Ratio of X_{PP}/X_{PAO}	gX_{PP}/gX_{PAO}
K_{NH}	Half Saturation Coefficient	gN/m^3
K_{NH4}	Saturation Coefficient for Ammonium (nutrient)	gN/m^3
K_{NH4}	Saturation Coefficient for Ammonium (nutrient)	gN/m^3
K_{NH4}	Saturation Coefficient for Ammonium (substrate)	gN/m^3
K_{NO}	Nitrate Half Saturation	gN/m^3
K_{NO3}	Saturation/Inhibition Coefficient for Nitrate	gN/m^3
K_{NO3}	Saturation/Inhibition Coefficient for Nitrate	gN/m^3
K_{NO3}	Saturation Coefficient for Nitrate, S_{NO3}	gN/m^3

$K_{O,A}$	Autotrophic Oxygen Half Saturation	gO_2/m^3
$K_{O,H}$	Heterotrophic Oxygen Half Saturation	gO_2/m^3
K_{O2}	Saturation/Inhibition Coefficient for Oxygen	gO_2/m^3
K_{O2}	Saturation/Inhibition Coeficient for Oxygen	gO_2/m^3
K_{O2}	Saturation/Inhibition Coefficient for Oxygen	gO_2/m^3
K_{O2}	Saturation Coefficient for Oxygen	gO_2/m^3
K_P	Saturation Coefficient for Phosphate (nutrient)	gP/m^3
K_P	Saturation Coefficient for Phosphate (nutrient)	gP/m^3
K_P	Saturation Coefficient for Phosphorous (nutrient)	gP/m^3
k_{PE}	Rate Constant for P Precipitation	$m^3/gFe(OH)_3$ d
K_{PHA}	Saturation Coefficient for PHA	gX_{PHA}/gX_{PAO}
K_{PP}	Saturation Coefficient for Poly-Phosphate	gX_{PP}/gX_{PAO}
K_{PS}	Saturation Coefficient for Phosphorus in Storage of PP	gP/m^3
k_{RED}	Rate Constant for Redissolution	1/d
K_S	Half Saturation Coefficient	$gCOD/m^3$
K_X	Hydrolysis Half Saturation	-
K_X	Saturation Coefficient for Particulate COD	gX_S/gX_H
ζ_j	Least Squares Parameter j	
q_{fe}	Maximum Rate for Fermentation	gS_F/gX_H d
q_{PHA}	Rate Constant for Storage of X_{PHA} (base X_{PP})	gX_{PHA}/gX_{PAO} d
q_{PP}	Rate Constant for Storage of X_{PP}	gX_{PP}/gX_{PAO} d
S_{ALK}	Alkalinity	$mole/m^3$
S_{ALK}	Alkalinity	$mole/m^3$
S_{N2}	Dinitrogen	gN/m^3
S_{NN}	Dinitrogen	gN/m^3
S_{NO}	Nitrite-Nitrate-N	gN/m^3
S_{NO3}	Nitrite-Nitrate-N	gN/m^3
S_O	Dissolved Oxygen	gO_2/m^3
S_{O2}	Dissolved Oxygen	gO_2/m^3
X_{AUT}	Autotrophic Organisms	$gCOD/m^3$
X_{BA}	Autotrophic Organisms	$gCOD/m^3$
X_{gly}	Stored Glycogen	$gCOD/m^3$
X_I	Inert Cell Residue	$gCOD/m^3$
x_j	Coded Variable j	
X_{PAO}	Polyphosphate Accumulating Biomass	$gCOD/m^3$
X_{PHA}	Poly-Hydroxy-Alkanoate	$gCOD/m^3$
X_{PP}	Stored Polyphosphate	gP/m^3
X_{PPr}	Stored Polyphosphate	gP/m^3
X_{STO}	Cell Internal Storage Product	$gCOD/m^3$
X_U	Inert Cell Residue	$gCOD/m^3$

Y_A	Yield	-
Y_A	Yield of Autotrophic Biomass per NO_3^--N	gCOD/gN
Y_H	Yield	-
Y_H	Yield Coefficient	gCOD/gCOD
Y_{PAO}	Yield Coefficient (Biomass/PHA)	gCOD/gCOD
Y_{PHA}	PHA Requirement for PP Storage	gCOD/gP
Y_{PO4}	PP Requirement (PO_4 Release) per PHA Stored	gP/gCOD
η_{fe}	Anaerobic Hydrolysis Reduction Factor	-
η_g	Anoxic Growth Factor	-
η_h	Anoxic Hydrolysis Factor	-
η_{NO3}	Anoxic Hydrolysis Reduction Factor	-
η_{NO3}	Reduction Factor for Denitrification	-
η_{NO3}	Reduction Factor for Anoxic Activity	-
μ_A	Maximum Specific Growth Rate	1/d
μ_{AUT}	Maximum Growth Rate of X_{AUT}	1/d
μ_H	Maximum Specific Growth Rate	1/d
μ_H	Maximum Specific Growth Rate	gX_S/gX_H d
μ_{PAO}	Maximum Growth Rate of PAO	1/d

CHAPTER 1:

INTRODUCTION

Current secondary municipal wastewater treatment regulations set by the Ontario's Ministry of Environment are shown in Table 1 (OWRA, 1994).

Table 1: Current Regulations for Secondary Municipal Wastewater

$cBOD_5$ (5 day carbonaceous biochemical oxygen demand)	25 mg/L
SS (suspended solids)	25 mg/L
sP (soluble phosphorous)	1 mg/L
TN (total nitrogen) [proposed regulation, Scott Hull, ROPEC, 2001]	5 mg/L

Of course it is recognized that, in order to achieve regulatory compliance with 95 % confidence, secondary municipal wastewater treatment plants (WWTP) must be designed to achieve effluent concentrations of between 50-65% of the regulatory limit.

The concern for removing nutrients, nitrogen (N) and phosphorous (P), from secondary municipal wastewater comes as a result of cultural eutrophication of water bodies (Nathanson, 1997). Cultural eutrophication is the acceleration of the natural aging process of lakes and rivers by human activity that results in excessive nutrient discharges. To achieve this goal there are many processes (chemical, biological, physical) that can remove BOD, SS and nutrients from wastewaters. This thesis focuses on the evaluation of three biological nutrient removal (BNR) processes - Modified Bardenpho (MB), Modified University of Cape Town (MUCT) and Anaerobic/Anoxic/Oxic (A^2/O) processes. Although there are a number of important operating variables within each of the above BNR processes, only recycle rates and hydraulic retention times (HRT) were considered for evaluation purposes. In order to evaluate single and combined effects of each of the operating variables on process performance, a series of 2-level fractional factorial design experiments were carried out. Data gathered from these design experiments were used in fitting models with least squares regression. The models were analyzed using steepest descent strategy to obtain optimal operating variables for each BNR process with respect to effluent TN and soluble phosphorous (sP) concentrations. Optimal values were determined for a variety of seasonal and loading conditions (i.e., temperature and influent concentration changes). Due to the complexity of each of the BNR processes it is impractical to run a full set of laboratory optimization experiments. Consequently, the widely accepted Activated Sludge Model No. 2d, (Henze et al, 1999) were calibrated and then used to generate the data to optimize the plant layout and operation. Based on the results from the computer-simulated system, it is recommended that laboratory tests be conducted on the best BNR process.

1.1 Project Background

The Robert O. Pickard Environmental Centre (ROPEC) is a state of the art secondary wastewater treatment plant that handles all wastewater from the Ottawa-Carleton (Ontario, Canada) region. Table 2 shows typical ROPEC influent data.

Table 2: Typical Influent Data for ROPEC

Flow	545,000 m^3/d
$CBOD_5$	110 mg/L
COD	200 mg/L
SS	150 mg/L
sP	2 mg/L
TN	20 mg/L

ROPEC currently accomplishes P removal by adding ferric chloride to activated sludge effluent in the flow channel prior to secondary clarification producing a precipitate that settles out in the secondary clarifier. In anticipation of new N removal regulations, ROPEC has begun investigating possible upgrade scenarios that would allow removal of BOD, N and P simultaneously. Concomitantly, in conjunction with ROPEC, it was decided to evaluate three BNR processes that would be simple to operate and control, and that are relatively compatible with their current basin layout and geometry.

1.2 Scope of Research

Investigation of BNR processes in a laboratory setting is a time consuming job since there are many parameters and variables involved and time to reach steady state is long. Because of advances in structured biological wastewater modeling, gathering data by way of computer simulation is becoming more prevalent. However, a common concern with computer modelling is the reliability of the data that are produced. Before simulation data could be considered reliable, the model is first calibrated using actual plant data. Once calibrated the model can be used to run "what if" scenarios taking care that any assumptions used for the calibration are not violated. In this study, important BNR process variables such as recycle rates and zone retention times were varied. The impact of these changes on nutrient removal were determined via computer experiments and performance data gathered according to a 2-level fractional factorial design. Least squares regression is used to fit a linear model to the data. This model was used in a steepest descent procedure to find the direction and location of the minimum response variables, which in this case would be the final effluent TN or sP concentrations. For the MB and MUCT processes, effects of seven operating variables were explored with the goal of finding the optimum set of operating variables to give the minimum effluent concentration. For the A^2/O process there were five operating variables. Once the optimal operating conditions were found for each BNR process under the various seasonal and loading conditions, the most appropriate process with respect to ROPEC's current operation were recommended for further laboratory and pilot plant studies. Also, if merited by the data, any operating variable that did not affect the performance of the BNR process were removed from any further laboratory testing thereby reducing the number of experimental runs to be done.

1.3 Objectives

The overall goal of this project is to use a computer simulation program to optimize three BNR processes (MB, MUCT and A^2/O) of interest to ROPEC. Specific goals are:

- Calibration of Activated Sludge Model 2d (ASM 2d) to steady-state seasonal ROPEC data for BOD and N removal.
- Determine effects of recycle rates and anaerobic/anoxic/aerobic zone retention times with respect to N, P and combined N and P removal for each BNR process at steady state.
- Determine the effect of changing both influent strength and temperature on N and P removal.
- Determine equations for the optimum regions for steady-state N and P removal.
- Evaluate transient (non steady state) effects on the optimized BNR designs.
- Based on treatment efficiencies as well as ease of incorporation of systems into present ROPEC layout, recommend one of the processes for future testing and evaluation.

1.4 Layout of Thesis

Background for this project along with review of previous work related to BNR is found in Chapter 2. Chapter 3 presents the methodology and statistical design used to accomplish the objectives of the thesis.

Chapter 4 presents three case studies that help explain the statistical process used to find the optimum operating conditions for the three BNR processes. Chapter 5 presents a discussion of the findings from the project. Chapter 6 is a summary of conclusions as well as recommendations for future research. Chapter 7 contains the references cited.

CHAPTER 2:

LITERATURE REVIEW

2.1 Biological Nutrient Removal

There exist many different treatment processes for nutrient removal. Table 3 shows some of the better-known biological and chemical/physical processes.

Table 3: Nutrient Removal Processes

Process	Nutrient(s) Removed	Type of Process	Reference
Metal Salt Addition	P	Chemical	Cooper et al., 1994
Lime Addition	P	Chemical	EPA, 1987
Phostrip	P	Chemical/Biological	Cooper et al., 1994
Anaerobic/Oxic (A/O)	P	Biological	Eun Lee et al., 1997
Ion Exchange	N	Physical	EPA, 1993
Ammonia Stripping	N	Physical	EPA, 1993
Modified Ludzack and Ettinger (MLE)	N	Biological	EPA, 1993
A^2/O	N, P	Biological	EPA, 1993
MUCT	N, P	Biological	EPA, 1993
MB	N, P	Biological	EPA, 1993

Biological processes are becoming more popular than chemical processes for several reasons; their tolerance to variations in flow and concentration, lower operating cost because of little or no chemical use, lower sludge production and retrofitting can be done at lower cost since the original plant layout is often used (Mines, 1996).

This thesis focuses on three of the more accepted BNR processes: MB, MUCT and A^2/O processes. Before describing each process, let us first consider the microbiology of BNR.

2.1.1 Microbiology of Biological Nutrient Removal

2.1.1.1 Nitrogen Removal

Although the use of biological treatment to remove organics (BOD) from wastewater dates back to the 1800s, BNR processes are relatively new and only date back to about the 1960s (Jeppsson, 1996). Nutrient removal in general can be broken down into N removal and P removal. Biological N removal involves two processes: nitrification and denitrification. Nitrification is the process where ammonia is biologically oxidized first to nitrite and then to nitrate. Nitrification occurs under aerobic conditions simultaneously with BOD removal. Denitrification occurs when nitrate is converted back to nitrite then to nitrogen gas, which is released to the atmosphere. Nitrification involves the autotrophic microorganisms *Nitrosomonas* and *Nitrobacter* (Viessman and Hammer, 1998). *Nitrosomonas* first converts ammonium nitrogen to nitrite by the following reaction:

$$NH_4^+ + 1.5O_2 \rightarrow 2H^+ + H_2O + NO_2^- \qquad [1]$$

Nitrobacter then converts nitrite to nitrate as follows:

$$NO_2^- + 0.5O_2 \rightarrow NO_3^- \qquad [2]$$

The first reaction is the rate-limiting step; consequently once nitrite is produced, *Nitrobacter* quickly transforms it into nitrate. Since the maximum growth rate of *Nitrobacter* is considerably higher than that of *Nitrosomonas*, the controlling step is the maximum growth rate of *Nitrosomonas* which is typically reported in the range of 0.26 - 1.62 d^{-1} (Randall et al., 1992). One important practical issue with respect to nitrification is the long biomass retention time requirements (> 7 days, Droste, 1997) and the concomitant production of bulking sludge.

From the first reaction (Equation 1), it can be seen that H^+ atoms are released into the system during nitrification. These atoms will lower the pH of the wastewater and consume alkalinity. However, during denitrification, alkalinity is created and pH stabilization occurs.

Unlike nitrification, a variety of facultative heterotrophic organisms accomplish denitrification under anoxic conditions, that is, without oxygen present. In the absence of oxygen, the organisms use nitrate as their terminal electron acceptor when oxidizing organic substrate (EPA, 1993). Heterotrophic denitrifiers also require a carbon source in order to sustain the denitrification process. Since denitrification usually follows nitrification, a significant portion of the readily degradable carbon has been consumed during nitrification (Aerobic zone). Therefore, treatment plants that have denitrification often have to add an extra source of organics (e.g., methanol) to the anoxic zone of the denitrification treatment process. For wastewaters high in nitrate it is possible to place the anoxic denitrification process before the aerobic process and use the raw wastewater for the carbon source.

2.1.1.2 Phosphorous Removal

Biological phosphorous removal is more complicated than biological nitrogen removal. Figure 1 (EPA, 1987) explains the major steps of biological P removal. The first steps in phosphorous removal occur under anaerobic conditions where phosphorous is released into the system. The final steps occur under aerobic conditions where P is taken up. More P is taken up in the aerobic phase than is release in the anaerobic phase leading to a net positive removal of P from the system. More explicitly, fermentation occurs in an anaerobic zone by facultative organisms. Volatile fatty acids (VFA) such as acetic acid are

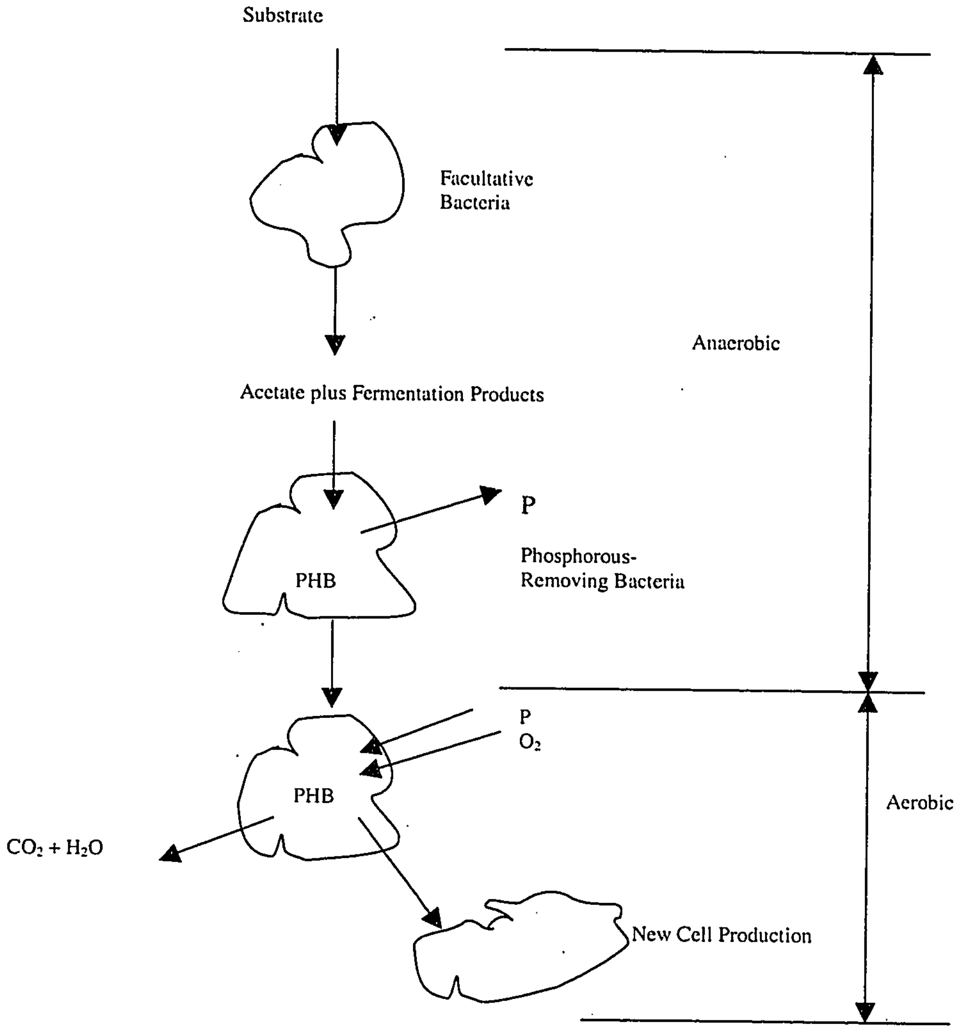

Figure 1: Phosphorous Removal (EPA, 1987)

produced from readily consumed soluble BOD. It is thought that most of the VFAs actually come from readily degradable BOD because there is insufficient time for hydrolysis of less readily biodegradable particulate BOD to occur (Sedlak, 1991). These fermentation products (particularly acetic acid) are readily assimilated and stored by microorganisms known as phosphorous accumulating organisms (PAO). The majority of PAOs are from the genus *Acinetobacter.* The energy required for the assimilation and storage of acetic acid by *Acinetobacter* is made available from hydrolysis and extracellular release of stored polyphosphates (Cooper et al., 1994). The stored polyphosphates provide energy for active transport of substrate and for formation of acetoacetate, which is converted to polyhydroxybutyrate (PHB). It is important to maintain both an oxygen free and nitrate free environment in the anaerobic zone. The presence of oxygen will lead to the oxidation of BOD and reduce the amount of fermentable substrate available. The presence of nitrates in the anaerobic zone is also known to be detrimental to the removal of P. However, the reason is still unclear. It is believed that nitrates in the anaerobic zone increase the redox potential of the reaction and reduce the degree of anaerobic stress necessary to induce P release (Barnard, 1976). Others studies suggest that nitrates in the anaerobic zone use substrate for denitrification that would otherwise be available for assimilation by PAO (EPA, 1987). Both of these situations will cause a reduction in the amount of P removed.

During the aerobic phase, stored substrate products (PHB) are depleted and soluble phosphorous is taken up by *Acinetobacter* with excess amounts stored as polyphosphates. P uptake is referred to as luxurious P uptake since more P is taken up by *Acinetobacter* during the aerobic phase than is released during the anaerobic phase. The amount of P taken up by *Acinetobacter* is directly related to the amount of substrate that can be fermented and stored in the anaerobic phase (Sedlack, 1991).

2.1.2 BNR Processes

One of the first BNR processes was described by Wuhrmann and is shown in Figure 2 (Applegate et al., 1980). The Wuhrmann process is a simplistic system to accomplish N removal. Raw wastewater first travels through an aerobic zone for BOD oxidation and nitrification. It then goes through an anoxic zone for denitrification. One of the problems with this system is the probability of insufficient carbon in the anoxic zone for denitrification, since the majority of carbonaceous material is consumed in the aerobic zone. Ludwzack and Ettinger (Ludzack and Ettinger, 1962) improved on Wuhrmann's design, by placing the anoxic zone before the aerobic zone so that some of the carbon for denitrification would come from the raw wastewater (Figure 3). In 1973, Barnard improved on the Ludzack and Ettinger process by adding an internal recycle from the aerobic zone to the anoxic zone (Figure 4 Modified Ludzack and Ettinger process (MLE)). The internal recycle increases the amount of nitrates going to the anoxic zone for denitrification. It was from the MLE process that the more common N and P removal processes, such as the A^2/O, MB and the MUCT processes, were developed.

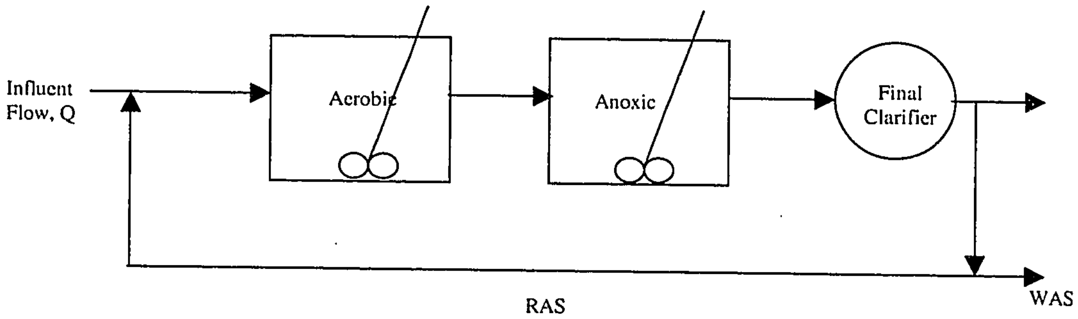

Figure 2: Wuhrmann BNR Process

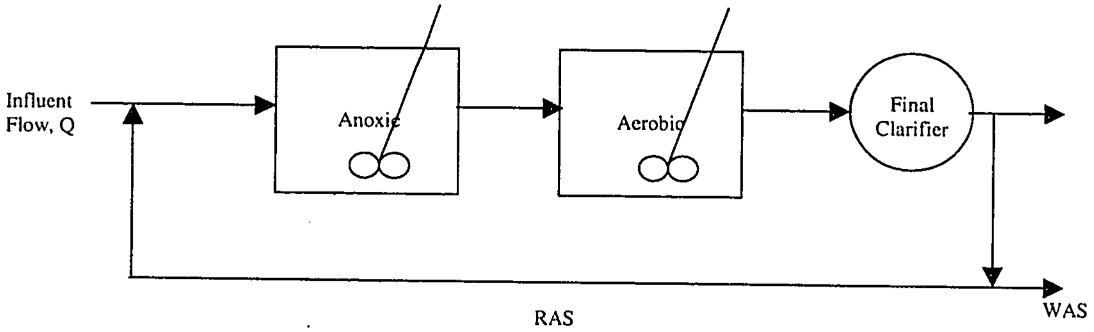

Figure 3: Ludzack-Ettinger BNR Process

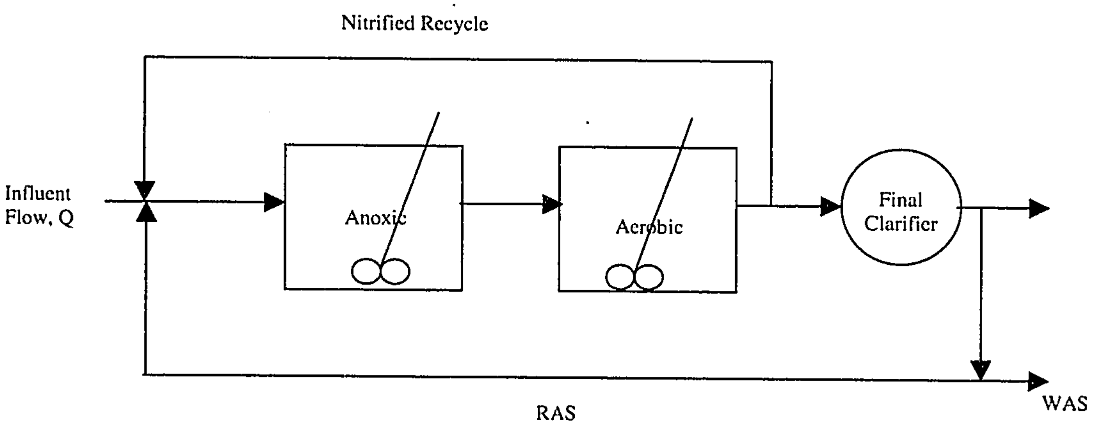

Figure 4: Modified Ludzack-Ettinger BNR Process

2.1.2.1 A^2/O Process

The A^2/O process is a single anoxic zone process and is shown in Figure 5. The A^2/O process consists of three zones. The anaerobic zone serves as a fermentation and P release zone, the anoxic zone serves as a denitrification zone and the aerobic zone serves as a BOD oxidation, nitrification and P uptake zone. The internal recycle stream circulates nitrified wastewater to the anoxic zone for denitrification. The A^2/O process is marketed by Air Products and Chemicals and is based on the A/O process, which was developed for phosphorous removal only. The A/O process consists of only two tanks. The first tank is kept under anaerobic conditions to facilitate fermentation of VFA's and P release. The second tank is kept under aerobic conditions to facilitate BOD removal and P uptake, (Figure 6). The A^2/O process was developed to accomplish both P and N removal and is reported to have the capability of producing an effluent with less than 1 mg/L of P and less then 10 mg/L of TN (EPA, 1993). For typical design criteria for the A^2/O process, see Table 4. This process has relatively short design solids retention times (SRT) and high volumetric organic loading rates. Compared to the MB process, it has more sludge production because of its short HRT and more P removal per unit of BOD treated (EPA, 1987).

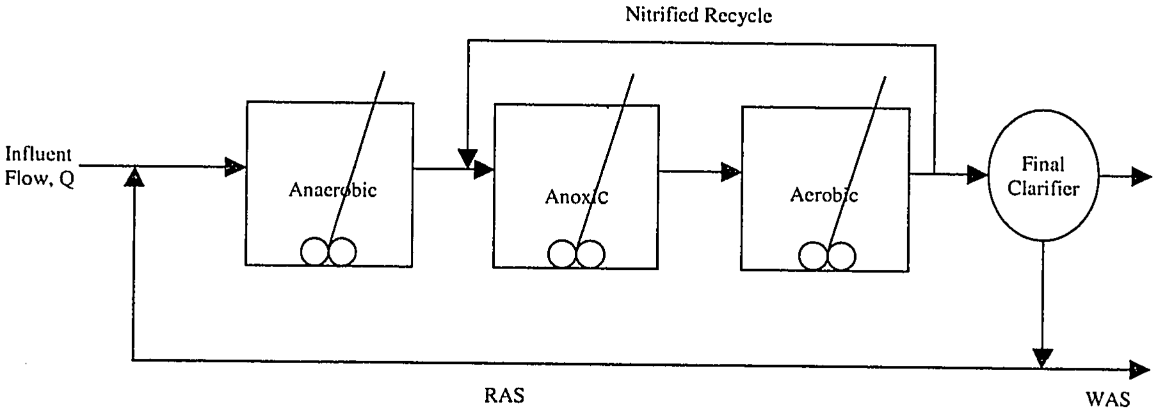

Figure 5: A^2/O BNR Process

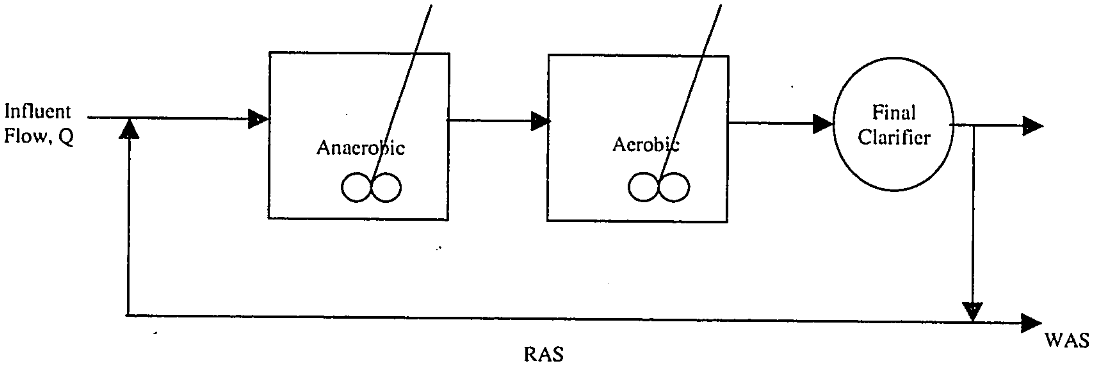

Figure 6: A/O BNR Process

Table 4: A^2/O Process Typical Design Criteria

Mixed Liquor Suspended Solids (MLSS), mg/L	3000-5000
Anaerobic HRT, hr	0.5-1
Anoxic HRT, hr	0.5-1
Aerobic HRT, hr	3.5-6
Solids Retention Time (SRT), d	5-10
Food to Microorganism Ratio (F/M), g $cBOD_5$ applied/g MLVSS/d	0.15-0.25
Internal Recycle, % Influent Plant Flow (Q)	100-200
Total Recycle, % Q	20-50

MLVSS – Mixed Liquor Volatile Suspended Solids
HRT – Hydraulic Retention Time

The EPA's Nitrogen Control manual (1993) estimates the theoretical efficiency of N removal from a mass balance analysis on nitrates for the A^2/O process. The removal efficiency is based on the internal recycle flow (IR) as well as the total recycle flow (TR) (RAS is equivalent to TR). This relationship, shown graphically in Figure 7, demonstrates the positive relationship between both TR and IR and percent nitrate removed. It can be seen that for a change in IR from 40 – 140 % (TR = 100 %), there is a corresponding change in percent NO_3 removed of 58 – 71 %. However, when IR is increased from 400 – 500 %, there is only a slight increase in percent NO_3 removed of 80 – 83 %. The same relationship appears for the effect of TR. At low IR, an increase in TR (50 – 200 %) has a more drastic effect on percent NO_3 removed (47 – 71 %) than at high values of IR (recycled activated sludge, RAS – 50 – 200 %, percent NO_3 removed – 87 – 89%). Along with the combined effect of IR and TR, it would also be important to know the combined effect of the two recycle flows with zone retention times.

One major draw back of the A^2/O process is its high sensitivity to small changes in pH, alkalinity and temperature because of the susceptibility of chemoautotrophic nitrifiers to shock loadings of BOD and ammonia (EPA, 1993).

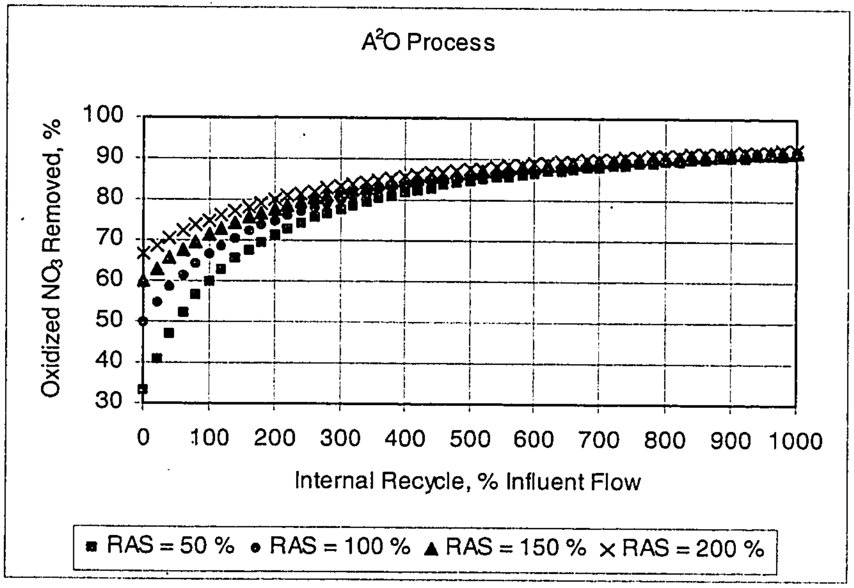

Figure 7: Effect of RAS and Internal Recycle on Nitrate Removal for A^2/O BNR Process

The Cities of Dunedin and Largo (USA) both make use of the A^2/O process in their secondary wastewater treatment plants. In order to ensure regulatory compliance with respect to N removal both facilities use deep-bed sand denitrification filters with methanol addition. Unlike the Largo plant, the Dunedin facility also has effluent P regulations. To ensure a low P effluent, the Dunedin facility adds alum to the mixed liquor entering the secondary clarifier. Table 5 shows the influent and effluent conditions for both plants (Mines, 1996).

Table 5: Facilities Using A^2/O Process

	Dunedin	Largo
Influent Flow, m^3/d	16,100	45,400
Influent cBOD5, mg/L	162	140
Influent TSS, mg/L	194	208
Influent Total Kjeldahl Nitrogen (TKN), mg/L	28	33
Influent TP, mg/L	5.1	---
Effluent cBOD5, mg/L	2.5	2.7
Effluent TSS, mg/L	1.2	1.4
Effluent TN, mg/L	1.2	1.5
Effluent TP, mg/L	0.18	---

TKN –Ammonia-Nitrogen and Organic-Nitrogen

Although both plants show good N removal and Dunedin shows good P removal, it is unknown what fraction of removal is a result of the A^2/O process and what fraction of removal is due to the sand filters and alum addition. Therefore, from this data the efficiency of the A^2/O process for the removal of TN and sP cannot be accurately determined.

The York River Municipal Wastewater Treatment Plant in Virginia conducted a study to evaluate the A^2/O process. The study lasted approximately 60 days during the months of September and October. Table 6 shows both the average influent and effluent conditions over the study period.

Table 6: York River Municipal Treatment Plant Data

	Influent	Effluent
Influent Flow, ML/d	21.9	---
TCOD, mg/L	273	37.5
TSS, mg/L	99	7.4
TP, mg/L	12.37	4.47
TKN, mg/L	29.9	2.4

According to this data, the York River Municipal Treatment Plant is unable to achieve effluent P concentrations below 1 mg/L but appears to achieve TKN concentrations below 5 mg/L. With the study being performed in the fall months, the ambient temperature would be between 15 and 20°C. The same removal would not necessarily occur at lower temperatures. Data on influent and effluent nitrate concentration are not given (Randall et al., 1990).

2.1.2.2 Modified Bardenpho Process (MB)

The MB process is a 5-stage dual anoxic zone process (Figure 8).

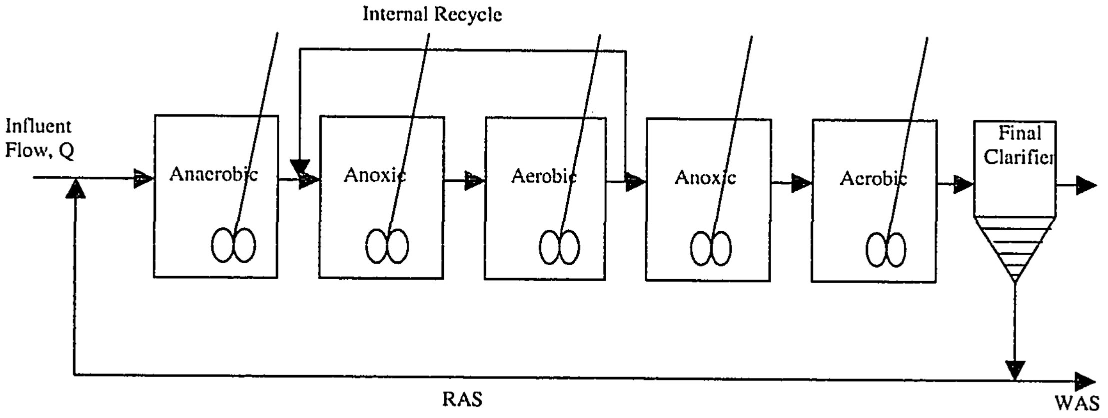

Figure 8: Modified Bardenpho BNR Process

Other dual anoxic zone BNR processes are the MUCT, Multiphase/Cyclical Aeration and Sequencing Batch Reactor (SBR) processes (EPA, 1993). The Bardenpho process started out as a 4-Stage process with alternating anoxic and aerobic zones. Its primary purpose (4 stage) was for N removal. In order to accomplish P removal as well, an anaerobic zone was added on to the beginning of the process.

The MB process consists of 5 zones. The anaerobic zone is used to promote the fermentation of readily degradable BOD and the P release by *Acinetobacter*. The first anoxic zone is the primary denitrification zone, where the majority of nitrate removal is accomplished. The first aerobic zone is responsible for the majority of BOD removal, nitrification and P uptake. The second anoxic zone provides sufficient detention time for additional denitrification and the final aerobic zone is a short period of aeration used to minimize anaerobic condition and P release in the secondary clarifiers (EPA, 1987).

Table 7 gives typical design criteria for the MB process.

Table 7: Modified Bardenpho Process Typical Design Criteria

F/M, kg TBOD/kg MLVSS/d	0.1-0.2
SRT, d	10-40
MLSS, mg/L	2000-4000
Anaerobic HRT, hr	1-2
First Anoxic HRT, hr	2-4
First Aerobic HRT, hr	4-12
Second Anoxic HRT, hr	2-4
Second Aerobic HRT, hr	0.5-1.0
Total Recycle, %Q	100
Internal Recycle, %Q	400

The 5-Stage process is reported to have the capability of producing an effluent with less than 1 mg/L of P and less than 3 mg/L of TN (EPA, 1993).

The EPA's Nitrogen Control Manual (EPA, 1993) uses a combination of mass balances and kinetic relationships to estimate the theoretical nitrate removal efficiency of the MB process with respect to IR and TR. TR is also referred to as return activated sludge (RAS). Figure 9 demonstrates graphically the positive relationship between both recycles (TR and IR) and the percent removal of oxidized nitrate.

When IR is increased from 40–140 % (TR-100 %) there is a corresponding change in percent removal of oxidized NO_3 of 79–85 %. However, as IR increases the change in NO_3 removal is very small, so that, if IR increases from 500–600 %, percent NO_3 removal only changes from 93–94 %. Also, at higher values of IR, the effect of TR has a very small effect on nitrate removal. At low values of IR (60 %), a change in TR from 50–200 % yields an increase in removal from 74–86 %. Where as, at higher values of IR (600 %) the same change in TR only yields an increase in nitrate removal from 92–94 %. Therefore, increasing the recycle rates (TR and IR) should have a positive effect on nitrate removal. However, at high IR flows, the change in nitrate removal becomes so small that an increase in either IR or TR would not be feasible. As was the case for the A^2/O process, the combined effect of recycle rates and HRT are not known.

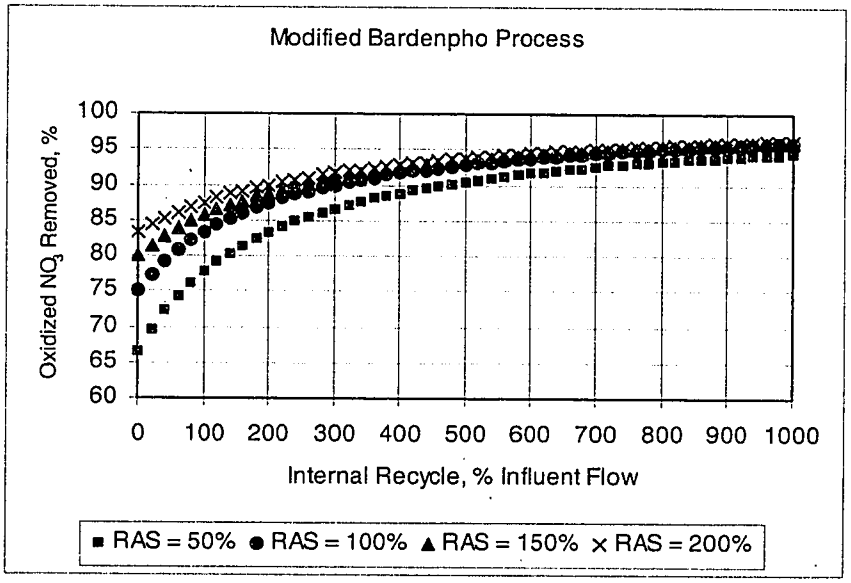

Figure 9: Effect of RAS and Internal Recycle on Nitrate Removal for the MB BNR Process

There are several successful municipal wastewater treatment plants in Canada and the United States using the MB process. In Table 8, operating data are shown for two MB plants.

Table 8: Facilities that use MB Process

	Palmetto, Florida	Kelowna, Canada
Influent Flow, m^3/d	3,892	12,400
Influent TBOD, mg/L	135	---
Influent TCOD, mg/L	---	3.3
Influent TSS, mg/L	135	---
Influent TKN, mg/L	32.3	24.5
Influent TP, mg/L	7.0	4.5
Effluent TBOD, mg/L	1	---
Effluent TSS, mg/L	2	---
Effluent TKN, mg/L	0.8	1.5
Effluent TP, mg/L	1.5	0.8

Both of these plants show an effluent P concentration below 2 mg/L and an effluent TKN concentration below 2 mg/L. It is unknown at what time of year and consequently what temperatures these two studies were performed. However, both of these plants run at low influent flow rates relative to ROPEC, which has an average daily flow rate of 500,000 m^3/d.

The Rock Creek wastewater treatment plant located in Hillsboro, Oregon, began using the Four Stage Bardenpho process (that is, without P removal) on July 10, 1995. They had an average influent flow of 60,480 m^3/d with influent wastewater characteristics of COD and TKN of 210 mg/L and 32 mgN/L, respectively. The temperature was approximately 20°C while the following data were collected. The return activated sludge was approximately 40 % of the influent flow rate while the internal recycle was approximately 32,640 m^3/d (~50 % of influent flow). The SRT was maintained at 4 days. The average effluent TN concentration was approximately 9 mgN/L (Makinia and Wells, 2000).

The results from the following study were from a bench scale experiment. High ammonia leachate from the Burns Bog Landfill located in Delta, BC was used as influent to a Four Stage Bardenpho Process (Shiskowski and Mavinic, 1998). The temperature and pH were maintained at 20°C and 7.5 respectively. The influent characteristics of the waste are shown in Table 9.

Table 9: Influent Characteristics for Burns Bog Landfill

	Burns Bog Landfill
Influent BOD_5, mg/L	31
Influent COD, mg/L	374
Influent TSS, mg/L	45
Influent TN, mgN/L	198

The HRT for the 1st anoxic zone was 1.64 h, for the 1st aerobic zone was 3.25 h, for the 2nd anoxic zone was 3.16 h and for the 2nd aerobic zone was 6.32 h. The experiment ran for approximately 30 d. The internal recycle to influent flow rate ratio was kept at 4:1 and the total recycle to influent flow rate ratio was kept at 3:1. The average effluent TN concentration was 17 mgN/L. Although 17 mgN/L is a high effluent TN concentration, the influent TN concentration for the study was 198 mgN/L. The 4-Stage Bardenpho process in this study had a 91 % removal of TN.

The wastewater treatment plant at the Patras University Campus performed a 15 – 20 day study on their MB process (Tsonis, 1997). The influent characteristics of the wastewater can be seen in Table 10.

Table 10: Influent Characteristics for Patras University Campus

	University of Patras
Influent Flow, m^3/d	268.8
Influent BOD_5, mg/L	31
Influent sCOD, mg/L	238
Influent sTKN, mgN/L	32.6
Influent sP, mgP/L	10.7

Effective relative volumes for the anaerobic, 1st anoxic, 1st aerobic, 2nd anoxic and 2nd aerobic zone were 13.2 %, 19.0%, 42.4 %, 14.2 % and 11.2 %. The total recycle was 65-70 % and the internal recycle was 190-200 % of the influent flow rate (Q). Effluent concentrations of sCOD, sP and TN were measured at 20.9 mg/L, 1.4 mgP/L and 6.9 mgN/L, respectively. Under these conditions, the Patras wastewater treatment plant is very close to attaining an effluent with a TN concentration below 5 mgN/L and an sP concentration below 1 mgP/L.

In comparing the Patras plant to the Rock Creek plant, one can see that the influent N to both plants was approximately 32 mgN/L. The Rock Creek plant used a total recycle of 40 % Q and an internal flow of ~50 % Q and had an effluent TN of 9 mgN/L whereas the Patras plant used a total recycle of 65-70 % Q and an internal flow of 190 – 200 % Q and had an effluent TN of 7 mgN/L.

2.1.2.3 Modified UCT Process (MUCT)

The University of Capetown in South Africa developed the UCT process (Figure 10) after researchers noticed a common problem with other BNR processes. The presence of nitrates in the anaerobic zone has a negative effect on the amount of phosphorous removed by the system (Barnard,

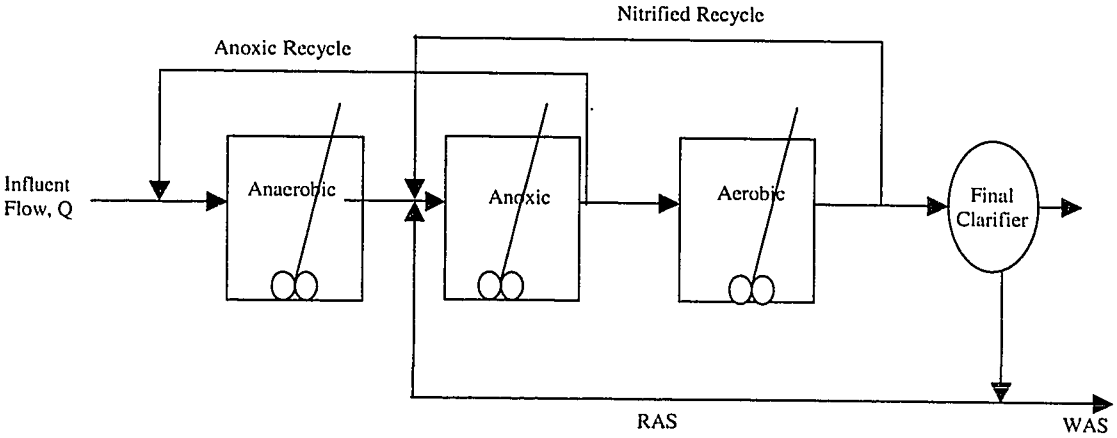

Figure 10: UCT BNR Process

1976). Simpkins and McClaren reported a reduction in the total percent P removal from 90 – 55 % when the effluent nitrate-nitrogen concentration increased from 4.0 mg/L to 6.7 mg/L (Simpkins and McClaren, 1978). What makes the UCT process different from other BNR processes is the additional recycle from the anoxic zone to the anaerobic zone and the returning of the RAS to the anoxic zone as opposed to the anaerobic zone. The combination of these two changes helps to lower the amount of nitrates entering the anaerobic zone of the system by denitrifying the majority of nitrates first in the anoxic zone before they are returned to the anaerobic zone. The MUCT process (Figure 11) was created by dividing the anoxic zone into two parts to help better control the total recycle and the nitrate recycle separately and to further reduce the amount of nitrates entering the anaerobic zone. MUCT works as follows. The anaerobic zone is used as a fermentation and P release zone. The first anoxic zone is used to denitrify the total recycle flow before being recycled to the anaerobic zone. The second anoxic zone is used to denitrify the recycled oxidized nitrates from the aerobic zone. The aerobic zone is used for BOD oxidation, nitrification and P uptake.

The MUCT process is reported to have the capability of producing an effluent with less than 1 mg/L of P and between 3-6 mg/L of TN. Common design criteria are presented in Table 11 (EPA, 1993).

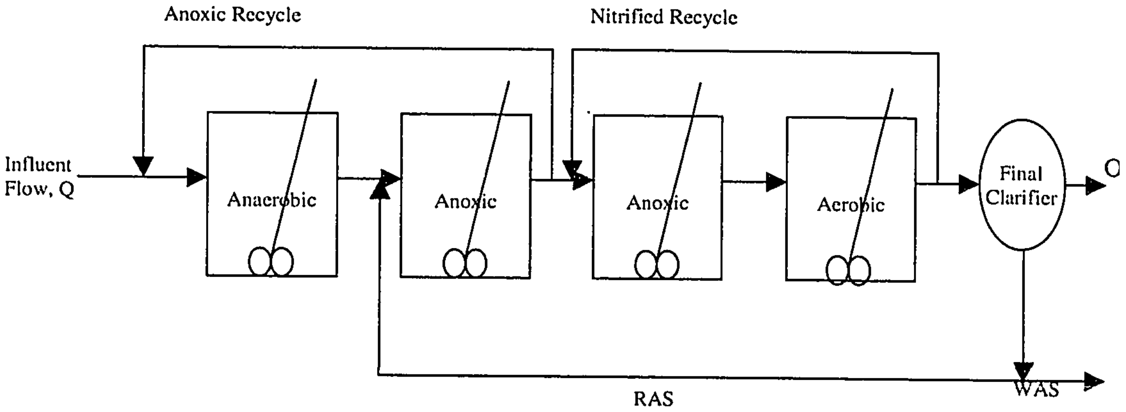

Figure 11: MUCT BNR Process

Table 11: MUCT Process Typical Design Criteria

F/M, kg TBOD/kg MLVSS/d	0.1-0.2
SRT, d	10-30
MLSS, mg/L	2000-4000
Anaerobic HRT, hr	1-2
First Anoxic HRT, hr	2-4
Second Anoxic HRT, hr	2-4
Aerobic HRT, hr	4-12
RAS Recycle, %Q	100
Anoxic Recycle, %Q	100-200
Nitrified Recycle, %Q	100-200

The EPA's Nitrogen Control Manual (EPA, 1993) estimated the theoretical nitrate removal with respect to Nitrified Recycle (IR) and TR using a series of mass balances around the MUCT process. Figure 12 demonstrates graphically the positive relationship between both recycles (TR (RAS) and IR) and the percent removal of oxidized nitrate. When IR is increased from 40 – 140 % (TR = 100 %) there is a corresponding change in percent removal of oxidized NO_3 of 58 – 71 %. However, as IR increases the change in NO_3 removal is very small, so that, if IR increases from 500 – 600 %, NO_3 removal only changes from 86 – 87 %. Also, at higher values of NR, the effect of TR has a very small effect on nitrate removal. At low values of NR (60 %), a change in TR from 50 – 200 % yields an increase in removal from 49 – 72 %. Where as, at higher values of IR (600 %) the same change in TR only increases removal from 83 – 89 %. Therefore, increasing the recycle rates (TR and IR) should have a positive effect on nitrate removal. However, at high IR flows, the change in nitrate removal becomes so small that an increase in either IR or TR would not be feasible.

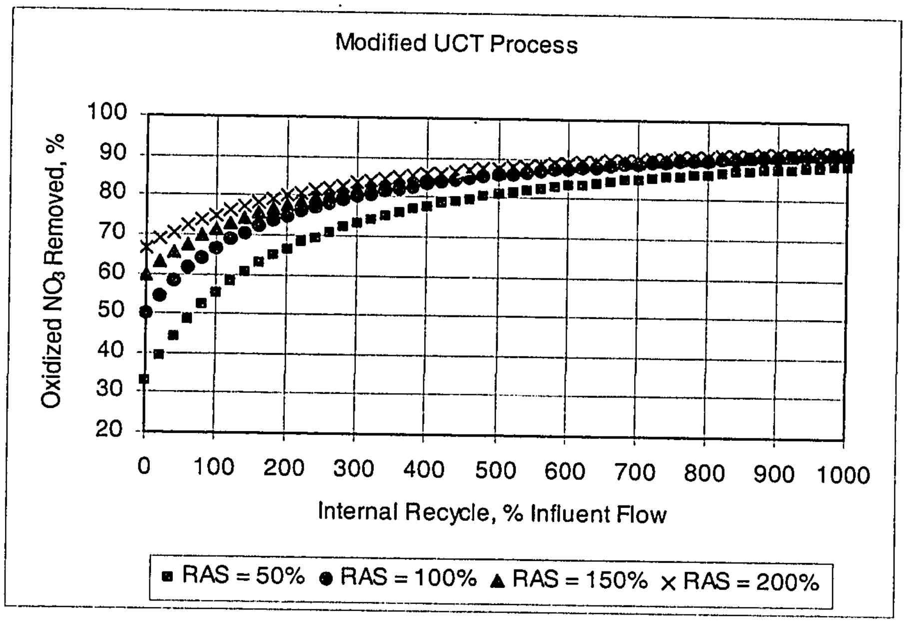

Figure 12: Effect of RAS and Internal Recycle on Nitrate Removal for the MUCT BNR Process

As was the case for both the A^2/O and MB processes, the combined effect of recycle rates and HRT are not known.

The York River Municipal Wastewater Treatment Plant in Virginia also conducted a study to evaluate the UCT process. The study lasted approximately 115 days, from May through August. Table 12 shows both the average influent and effluent conditions over the study period.

Table 12: York River Municipal Treatment Plant Data

	Influent	Effluent
Influent Flow, ML/d	28.7	---
TCOD, mg/L	215	35.2
TSS, mg/L	82	5.8
TP, mg/L	8.52	1.61
TKN, mg/L	27.0	6.87

According to this data, the plant is unable to consistently achieve effluent P concentrations below 1 mg/L and N concentrations below 5 mg/L when the UCT process is implemented (Clifford et al., 1990).

The UCT process was evaluated at the Virginia Polytechnic Institute. The influent flow rate to the system was 151.2 L/d with all recycle rates (total, anoxic and nitrified) being 100 % Q. The hydraulic retention times for the three reactors were 2 h for the anaerobic zone, 2 h for the anoxic zone and 4 h for the aerobic zone. Tables 13 and 14 show influent and effluent TN, TP and COD concentrations for the system at different temperatures and solids retention times (SRT).

Table 13: Virginia Polytechnic Institute Influent Wastewater Characteristics

SRT, d	Temp, °C	Date	TN, mgN/L	TP, mgP/L	COD, mg/L
15	20	03JUL89	22.4	16.4	176
15	15	02MAY89	30.7	17.7	235
15	10	08AUG89	24.5	14.3	166
5	20	28MAR90	30.1	20.3	244
5	15	21NOV89	34.4	19.0	201
5	10	07DEC89	38.0	17.6	283
2.7	20	11APR90	31.5	18.7	263
1.5	20	19APR90	36.6	19.5	247

Table 14: Virginia Polytechnic Institute Effluent Wastewater Characteristics

SRT, d	Temp, °C	Date	TN, mgN/L	%R	TP, mgP/L	%R	COD, mg/L	%R
15	20	03JUL89	7.4	67			12	93
15	15	02MAY89	9.8	68			19	92
15	10	08AUG89	9.8	66			17	90
5	20	28MAR90	11.4	62	13.4	34	29	88
5	15	21NOV89	15.0	56	18.6	2	27	87
5	10	07DEC89	22.7	40	15.8	10	24	92
2.7	20	11APR90	7.7	76	12.0	36	26	90
1.5	20	19APR90	18.5	49	15.3	22	33	87

%R – Percent Removal of given compound

In order to compare the effectiveness of the UCT process at 10°C, 15°C and 20°C with MCRTs of 1.5, 2.7, 5 and 15d, we can look at the percent removal of the given compound as opposed to the absolute effluent concentration. For TN, the UCT process shows low removals at low temperatures and MCRTs. If the removal of sP of 2 % is dismissed as faulty data, then the UCT process shows good removal for high temperatures and high MCRT.

2.1.3 Common Factors Affecting BNR Performance

There are several factors that affect the performance of most combined N/P BNR processes. It's important to have enough easily fermentable substrate that can be readily fermented into VFA in the anaerobic zone. Studies have shown that for every mg of P to be removed, 10 – 20 mg of VFA is required (Abu-ghararah and Randall, 1991).

The nitrification process requires long SRT to completely convert ammonia-N to nitrate-N. However, longer SRTs have the potential to lower the phosphorous removal per unit of cBOD$_5$ removed and therefore, systems should only be operated at minimum SRT required for complete nitrification (EPA, 1987)

As has been discussed and explained previously, the presence of nitrates in the anaerobic zone has a detrimental effect on overall P removal.

Temperature is an important factor affecting N and P removal. Choi et al. (1998) found a rapid decrease in nitrification when temperature was decreased from 10°C to 5°C. Denitrification at 5°C was approximately 10 times lower than at 20°C. Phosphorous removal decreases rapidly between 15°C and 12°C but increases around 5°C. The first decrease is due to the increase in nitrates in the anaerobic zone, since denitrification is very poor at lower temperatures. At 5°C nitrification is also poor and therefore, few nitrates are being produced.

It has been found that pH should remain in the range of 6.5 to 8.0 for optimal N and P removal (EPA, 1987).

It is also important to maintain an oxygen free environment in both the anoxic and anaerobic zones as well as an oxygen rich environment in the aerobic zones.

For this project, it was decided to run all experiments at 10°C and 20°C in order to see the effect of temperature on N and P removal. Also, dissolved oxygen (DO) was kept above 2 mg/L in all aerobic zones and the pH was kept at 7 in all zones.

2.2 Computer Simulation

Using pilot plant studies to test the different BNR processes is a time consuming and costly experience. Each of the processes contains numerous variables that would have to be monitored and varied in order to find the optimum process conditions. Due to its widespread acceptance, computer simulation programs are being used as a preliminary research tool to study various processes. In this thesis, GPS-X software (Hydromantis, 1991) was used to analyse each of the three BNR processes previously discussed.

It is important to note that, generally speaking, GPS-X is an interface software tool and that the structured biokinetic model (ASM 2d) within GPS-X must be proven valid before testing could commence. For this reason, the model was first calibrated to actual plant data before any experimental simulations were run. Computer simulation programs allow the user to investigate cause and effect relationships in a plant, forecast fluctuation effects, choose optimal control strategies and study cost-saving solutions (Carucci et al., 1999). All of this can be done without disturbing the actual system. All computer trials used to find the location of the optimal operating variables were run at steady state.

2.3 Modeling with Activated Sludge Models

2.3.1 Activated Sludge Model No. 1

The International Association on Water Pollution Research and Control (IAWPRC) task group proposed a mathematical model to describe biological carbon oxidation, nitrification and denitrification, entitled Activated Sludge Model No. 1 (ASM 1) (Henze et al., 1986).

The first step in developing the model was to characterize the wastewater using the following:

- Organic matter was divided into:
    - Non-biodegradable (biologically inert)
        - Soluble: leaves system at same concentration that it enters
        - Particulate: becomes enmeshed in the activated sludge and is removed from the system through sludge wastage
    - Biodegradable
        - Readily biodegradable: treated as if soluble although some may not be, relatively simple molecules that may be taken in directly by heterotrophic bacteria and used for growth of new biomass
        - Slowly biodegradable: treated as if particulate, must first be converted to readily biodegradable by hydrolysis
- Nitrogenous matter can be divided into:
    - Non-biodegradable
        - Particulate, usually associated with particulate COD
        - Soluble, negligibly small and not incorporated into model
    - Biodegradable
        - Ammonia (free compound and its salts)
        - Soluble organic nitrogen, acted on by heterotrophic bacteria and converted to ammonia nitrogen
        - Particulate organic nitrogen, hydrolysed to soluble organic nitrogen

Within this model both heterotrophic and autotrophic organisms are at work. The kinetics of these organisms were primarily described using Monod kinetics. Also, in order to mathematically decide whether the kinetics were taking place under aerobic or anoxic conditions, switching functions are introduced into the model. If the process is to occur under aerobic conditions, the following switching function would be used.

$$\frac{S_O}{K_O + S_O} \qquad [3]$$

where, S_O = Dissolved oxygen (DO) concentration, mg/L

K_O = Switching function parameter

With a small value for K_O, the switching function would be close to one for moderate concentrations of DO and would get closer to zero as DO approaches zero. This addition to ASM 1 provides for a continuous function and eliminates the trouble of discreet mathematics. If the process is to occur under anoxic conditions, the following switching function is utilized.

$$\frac{K_O}{K_O + S_O} \qquad [4]$$

This function would be turned on in the absence of DO and off in the presence of DO.

Biologically, there are eight processes included in the model.

- Aerobic growth of heterotrophs
- Anoxic growth of heterotrophs
- Aerobic growth of autotrophs
- 'Decay' of heterotrophs
- 'Decay' of autotrophs
- Ammonification of soluble organic nitrogen
- 'Hydrolysis' of entrapped organics
- 'Hydrolysis' of entrapped organic nitrogen

Due to the complexity and size of the model the equations and parameters are described using the Peterson Matrix, see Appendix A. As an example of how to use the Peterson Matrix and ASM 1, the rate of production of readily biodegradable substrate, S_S, can be represented.

$$\begin{aligned} r_{S_S} = & -\frac{1}{Y_H}\hat{\mu}_H\left(\frac{S_S}{K_S + S_S}\right)\left(\frac{S_O}{K_{O,H} + S_O}\right)X_{B,H} \\ & -\frac{1}{Y_H}\hat{\mu}_H\left(\frac{S_S}{K_S + S_S}\right)\left(\frac{K_{O,H}}{K_{O,H} + S_O}\right)\left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right)\eta_g X_{B,H} \\ & + k_h\frac{X_S/X_{B,H}}{K_X + \left(X_S/X_{B,H}\right)}\left[\left(\frac{S_O}{K_{O,H} + S_O}\right) + \eta_h\left(\frac{K_{O,H}}{K_{O,H} + S_O}\right)\left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right)\right]X_{B,H} \end{aligned} \qquad [5]$$

All parameters in Equation 5 are defined in ASM 1 (Henze et al., 1986). ASM 1 has gained widespread acceptance over the years and has been tested and validated by various researchers (Dold and Marais, 1986).

2.3.2 Activated Sludge Model 2 and 2d (ASM 2, ASM 2d)

In 1995, the International Association on Water Quality (IAWQ) task group published Activated Sludge Model No 2 (Henze et al., 1995). This model includes the biological processes for carbon oxidation, nitrification and denitrification and also incorporates biological phosphorous removal. Although this model does its best to represent all biological processes mathematically, caution should be used when applying this model. It is not suitable for the design and operation of nitrifying/denitrifying and biological excess phosphorous removal (NDBEPR) systems. Its principal function is to provide a structured framework to direct research into NDBEPR (Ekama and Wentzel, 1999). The following processes are included in ASM 2 and are defined in detailed in the published model (Henze et al., 1995).

- Aerobic hydrolysis
- Anoxic hydrolysis
- Anaerobic hydrolysis
- Aerobic growth on fermentable readily biodegradable organic substrates
- Aerobic growth on fermentation products, considered to be acetates
- Anoxic growth on fermentable readily biodegradable organic substrates, denitrification
- Anoxic growth on fermentation products, considered to be acetates, denitrification
- Fermentation
- Lysis of heterotrophic organisms
- Storage of a cell internal storage product of phosphorous-accumulating organisms
- Storage of poly-phosphate
- Aerobic growth of phosphate-accumulating organisms
- Lysis of phosphate-accumulating organisms
- Lysis of polyphosphate
- Lysis of a cell internal storage product of phosphorous-accumulating organisms
- Aerobic growth of nitrifying organisms
- Lysis of autotrophic organisms
- Precipitation of phosphorous
- Redissolution of phosphorous

In 1997, Funamizu et al. performed three experiments to calibrate and verify the ASM 2 model. They found that the calibrating process of the model showed that no modification of parameter values was required to evaluate the performance of the plant and population of the activated sludge. They also found ASM 2 to give reliable predictions of the activated sludge BNR process (Funamizu et al., 1997).

In 1999, Activated Sludge Model No.2d (ASM 2d) was published. Detailed explanation of ASM 2d is described in the report of the task force (Henze et al., 1999). ASM 2d is an extension of ASM 2 and helps to further explain the phosphorous removal processes. This structured model includes two extra processes to account for the fact that phosphorous accumulating organisms (PAO) can use cell internal organic products for denitrification. Process 12 (Anoxic Storage of poly-phosphate, X_{PP}), given by Equation 6, and process 14 (Anoxic growth on cell internal storage products of PAO, X_{PHA}), given by Equation 7, are included in ASM 2d and can be seen on the Peterson matrix in Appendix A.

$$\begin{aligned}
&(\mathrm{Pr}\,ocess\ 12)\ Anoxic\ Storage\ of\ X_{PP} = q_{PP}\cdot\frac{S_{O_2}}{K_{O_2}+S_{O_2}}\cdot\frac{S_{PO_4}}{K_{PS}+S_{PO_4}}\\
&\cdot\frac{S_{ALK}}{K_{ALK}+S_{ALK}}\cdot\frac{X_{PHA}/X_{PAO}}{K_{PHA}+X_{PHA}/X_{PAO}}\cdot\frac{K_{MAX}-X_{PP}/X_{PAO}}{K_{IPP}+K_{MAX}-X_{PP}/X_{PAO}}\\
&\cdot X_{PAO}\cdot\eta_{NO_3}\cdot\frac{K_{O_2}}{S_{O_2}}\cdot\frac{S_{NO_3}}{K_{NO_3}+S_{NO_3}}
\end{aligned}\qquad[6]$$

$$\begin{aligned}
&(\mathrm{Pr}\,ocess\ 14)\ Anoxic\ Growth\ on\ X_{PHA} = \mu_{PAO}\cdot\frac{S_{O_2}}{K_{O_2}+S_{O_2}}\cdot\frac{S_{NH_4}}{K_{NH_4}+S_{NH_4}}\\
&\cdot\frac{S_{PO_4}}{K_P+S_{PO_4}}\cdot\frac{S_{ALK}}{K_{ALK}+S_{ALK}}\cdot\frac{X_{PHA}/X_{PAO}}{K_{PHA}+X_{PHA}/X_{PAO}}\\
&\cdot X_{PAO}\cdot\eta_{NO_3}\cdot\frac{K_{O_2}}{S_{O_2}}\cdot\frac{S_{NO_3}}{K_{NO_3}+S_{NO_3}}
\end{aligned}\qquad[7]$$

ASM 2d is the most recent model, and is the one used for this study. Caution should be applied when using any three of these models. Each model has its own assumptions and limitations that can be seen within the published reports. (Henze et al., 1986 1995, 1999)

CHAPTER 3:

METHODOLOGY

The experimental data required for analysis were generated using the computer simulation program, GPS-X. Two-level fractional factorial designs were used to ensure that adequate amounts of data were gathered. These data were then analysed according to a statistical steepest descent procedure in order to find the optimum operating settings for the three BNR processes (A^2/O, MB, MUCT) being evaluated. From the statistical analysis, the BNR process that is most suitable to ROPEC's current operation was chosen to undergo more testing.

3.1 ROPEC

ROPEC currently operates as a conventional activated sludge treatment plant. Figure 13 illustrates the plant layout for the liquid treatment portion of the wastewater treatment plant. This plant is fully equipped with a comprehensive sludge handling system, however, it is not considered in this thesis and therefore will not be discussed. ROPEC is designed to treat an average daily flow of 545,000 m^3/d and a peak daily flow of 1,200,000 m^3/d. Flows above 1,200,000 m^3/d bypass the plant and are directly discharged into the Ottawa River. The liquid treatment portion of this wastewater treatment plant consists of six automated bar screens, ten grit tanks, fifteen primary rectangular clarifiers, eight aeration basins, sixteen secondary circular clarifiers and three chlorination contact tanks. The primary clarifiers have a surface area of 39,900 m^2. The aeration basins have a total volume of 90,800 m^3 and each tank has three longitudinal pass channels with the capability of step feeding. The aeration basins are aerated by a fine pore aeration system with the capability of tapered aeration. The total airflow rate is 3,398,400 m^3/d. The secondary clarifiers have a total surface area of 153,600 m^2 with a surface overflow rate of 14 $m^3/m^2/d$ at the average design inflow rate of 545,000 m^3/d. The plant produces 13,350 m^3/d of waste activated sludge (WAS) and operates with a return activated sludge (RAS) recycle of 1.5 times the influent flow rate (Q). ROPEC was designed to meet regulatory standards of 25 mg/L $cBOD_5$, 25 mg/L TSS and 1 mg/L of sP. Based on the plant data available for the majority of 1997, the annual average $cBOD_5$, TSS and sP concentrations were 7 mg/L, 11 mg/L and 0.6 mg/L, respectively, all well below the required limits.

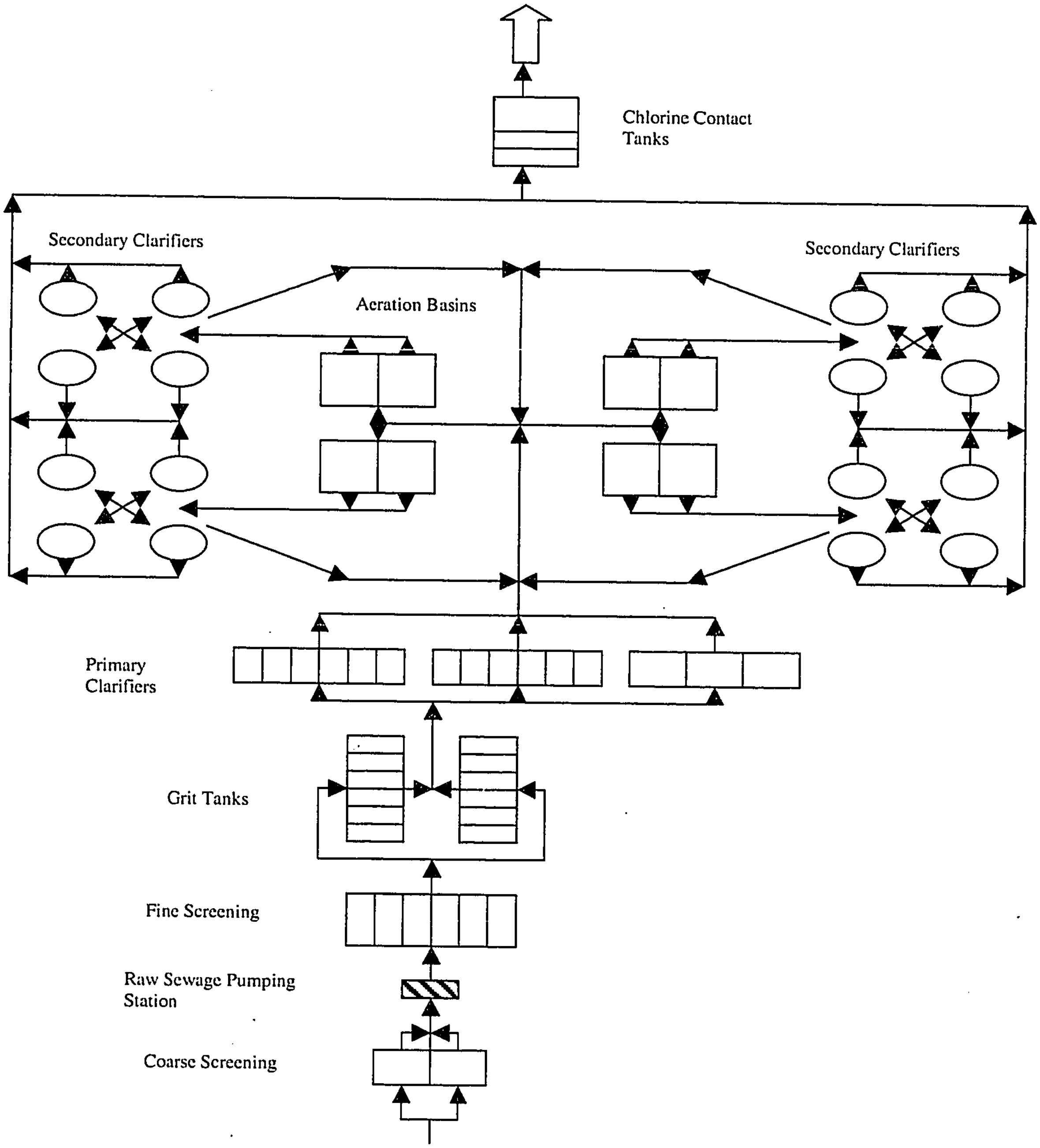

Figure 13: ROPEC General Layout

In order to model ROPEC using GPS-X, some simplifications were made. If the full plant layout were used in the simulation program, it would be so large that it would be of limited usefulness. Two main problems would occur. The first was that each of the state variables would need to be calculated at every time interval for every tank (large computational effort). The second problem was that the difference in behaviour of individual tanks would be masked by uncertainty in available operating data.

For these reasons, the plant was simplified. The first simplification was to eliminate the bar screens, the grit tanks and the primary clarifiers from the simulation set-up. Instead, the influent to the remainder of the plant is simply the primary effluent data available from the 1997 data set. Also, the eight aeration basins were modeled as one large tank with a total volume of 90,800 m^3 consisting of 6 completely mixed reactors in series (simulating plug flow). The model used to describe the kinetics of the activated sludge treatment within the aerobic zone was ASM 1 (Hydromantis, 1994). This model is used as opposed to the more complicated ASM 2d because currently ROPEC only does biological BOD removal and chemical P removal. Therefore, it is not necessary to use a more complicated model that would describe biological P removal. Finally, the secondary clarifiers were modeled as one large circular clarifier with a total surface area of 38,429 m^2, a WAS of 13,350 m^3/d and a RAS of 1.5Q. A simple non-reactive, one dimensional settler model was used to describe the settling behaviour within the secondary clarifier (Hydromantis, 1994). For more information about GPS-X and the models used within the program, please consult *GPS-X Technical Reference*. See Figure 14 for the simplified ROPEC design layout.

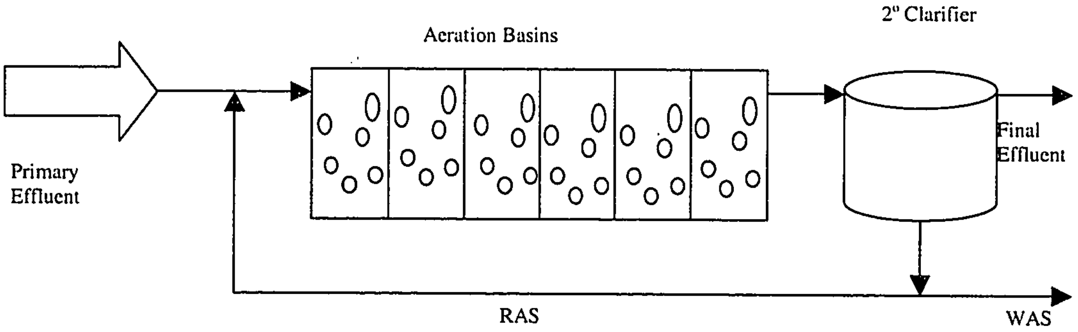

Figure 14: GPS-X Version of ROPEC

3.2 Calibration of Activated Sludge Models (ASM 1, ASM 2, ASM 2d)

Because the experimental data were generated from a computer simulation program, the kinetic and stoichiometric parameters within the model (ASM 2d) used by the simulation program had to be calibrated in order to ensure reliable outputs. Since the underlying goal of this study was to provide ROPEC with a viable option for BNR, ASM 2d was calibrated using influent and effluent concentration data from ROPEC. For calibration purposes, ASM 1 (a subset of the ASM 2d program) was used as the model within GPS-X to represent the aerobic treatment process since ROPEC does not provide for biological P removal and it was unnecessary to use the more complex ASM 2d to represent ROPEC's treatment system. Within ASM 2d, the IAWQ has a list of recommended kinetic and stoichiometric parameters to represent typical wastewater at 10°C and 20°C (Table 15). ROPEC data for 1997 were broken down into three temperature ranges [(January – March, 4°C), (May – August, 15°C) and (September – October, 10°C)]. The parameters for 4°C and 15°C were estimated by fitting an exponential function to the data at 10°C and 20°C (Droste, 1997)

Table 15: Kinetic and Stoichiometric Parameters Recommended by IAWQ for Typical Wastewater

	Symbol	4°C	10°C	15°C	20°C	Units
Wastewater Characteristics						
Inert Fraction of Soluble COD	f_{SI}		0.38			-
Degradable Fraction of Particulate COD	f_{XS}		0.69			-
Biomass Fraction of Particulate COD	f_{XBH}		0.17			-
Ammonium/TKN Ratio	f_{NH}		0.83			-
Particulate Organic N/Total Organic N	f_{XN}		0.25			-
Particulate COD to VSS Ratio	i_{cv}		1.66			gCOD/gVSS
VSS/TSS Ratio	i_{vt}		0.83			gVSS/gTSS
BOD_5/BOD_u Ratio	f_{BOD}		0.66			-
Autotrophic Organisms	X_{BA}		0			$gCOD/m^3$
Inert Cell Residue	X_U		0			$gCOD/m^3$
Cell Internal Storage Product	X_{STO}		0			$gCOD/m^3$
Dissolved Oxygen	S_O		0			gO_2/m^3
Nitrite-Nitrate-N	S_{NO}		0			gN/m^3
Dinitrogen	S_{NN}		15.00			gN/m^3
Alkalinity	S_{ALK}		3.13			$mole/m^3$
Kinetic Parameters						
Heterotrophs						
Maximum Specific Growth Rate	μ_H	1.60	3.00	4.24	6.00	1/d
Half Saturation Coefficient	K_S		4.00			$gCOD/m^3$
Organism Decay Rate	b_H	0.13	0.20	0.28	0.40	1/d
Anoxic Hydrolysis Factor	η_h		0.40			-
Anoxic Growth Factor	η_g		0.80			-
Maximum Specific Hydrolysis Rate	k_H	1.57	2.00	2.45	3.00	1/d
Hydrolysis Half Saturation	K_X		0.10			-
Ammonification Rate	ka	0.026	0.04	0.06	0.08	$m^3/gCOD/d$
Autotrophs						
Maximum Specific Growth Rate	μ_A	0.19	0.35	0.59	1.00	1/d
Half Saturation Coefficient	K_{NH}		1.00			gN/m^3
Organism Decay Rate	b_A	0.03	0.05	0.09	0.15	1/d
Switching Functions						
Heterotrophic Oxygen Half Saturation	$K_{O,H}$		0.20			gO_2/m^3
Autotrophic Oxygen Half Saturation	$K_{O,A}$		0.50			gO_2/m^3
Nitrate Half Saturation	K_{NO}		0.50			gN/m^3

Stoichiometric Parameters			
Fractions			
Particulate COD to VSS Ratio	i_{cv}	1.48	gCOD/gVSS
VSS/TSS Ratio	i_{vt}	0.75	gVSS/gTSS
BOD_5/BOD_u Ratio	f_{BOD}	0.66	-
Heterotrophs			
Yield	Y_H	0.625	-
N Content of Active Mass	i_{XB}	0.07	gN/gCOD
N Content of Endogenous Mass	i_{XP}	0.02	gN/gCOD
Endogenous Fraction	f_U	0.1	-
Autotrophs			
Yield	Y_A	0.24	-

COD – Chemical Oxygen Demand
VSS – Volatile Suspended Solids

The first step in the calibration procedure was to use the values for the kinetic and stoichiometric parameters suggested by the IAWQ for the simulated ROPEC plant and to compare how well these parameters represented the available 1997 data.

As was mentioned, the available data from 1997 were divided into three time frames (January-March (4°C), June-August (15°C) and September-October (10°C)). For each time frame, inlet and outlet concentrations were averaged. Primary effluent flow data were also available. The average value over the specified time period for primary effluent flow was used. The summarized data can be seen in Table 16.

Table 16: ROPEC Summary Data for 1997

	Influent	Effluent	±*
January – March, 4°C			
Average Flow – 446,822 m^3/d			
COD, mg/L	209	53	17
$cBOD_5$, mg/L	N/A	6	2
TSS, mg/L	83	12	8
TKN, mg/L	20	17	5
June – August, 15°C			
Average Flow – 430,000 m^3/d			
COD, mg/L	180	55	15
$cBOD_5$, mg/L	N/A	7	2
TSS, mg/L	58	12	7
TKN, mg/L	18	16	3
September – October, 10°C			
Average Flow – 356,895 m^3/d			
COD, mg/L	230	57	19
$cBOD_5$, mg/L	N/A	7	2
TSS, mg/L	82	9	4
TKN, mg/L	22	19	3

*One standard deviation unit for the effluent
cBOD5 – 5 Day Carbonaceous Biochemical Oxygen Demand

For each of these time frames, the influent conditions given in Table 16 were inputted into GPS-X and the predicted effluent concentrations were compared to the measured data in Table 12. These results can be seen in Table 17.

Table 17: Calibration of ASM 2d

	-	cBOD5	+	-	COD	+	-	TSS	+	-	TKN	+
January – March, 4°C												
Average Flow – 446,822 m³/d												
Actual, mg/L	4	6	8	36	53	70	4	12	20	12	17	22
GPS-X, mg/L		7			48			10			20	
May – August, 15°C												
Average Flow – 430,000 m³/d												
Actual, mg/L	3	7	11	40	55	70	4	11	18	13	16	19
GPS-X, mg/L		5			48			9			16	
September – October, 10°C												
Average Flow – 356,895 m³/d												
Actual, mg/L	5	7	9	38	57	76	5	9	13	16	19	22
GPS-X, mg/L		5			53			8			22	

From Table 17 it can be seen that all predicted effluent concentrations fall within one standard deviation from the actual average value of specified concentration. For this reason, it was decided that the suggested parameters from the IAWQ would be used within this project to predict the performance of the BNR processes, which is similar to the results found by Fanamizu, 1997. Since the three BNR processes were being evaluated with respect to both N and P, the ASM 2d was used as opposed to the simpler ASM 1. Due to the lack of actual data, it was assumed that since the ASM 1 represented ROPEC data on an acceptable level, that ASM 2d would also accurately represent the data. As such, caution should be used when using the results from this study. Further laboratory experimental data should be gathered before implementing changes to full-scale wastewater treatment plant. Table 18 shows all parameters for the ASM 2d.

Table 18: ASM 2d Parameters

	Symbol	4°C	10°C	15°C	20°C	Units
Wastewater Characteristics						
Inert Fraction of Soluble COD	f_{SI}		0.375			-
VFA Fraction of Soluble COD	f_{SA}		0.25			-
Fermentable Fraction of Particulate COD	f_{SF}		0.694			-
Degradable Fraction of Particulate COD	f_{XS}		0.694			-
Biomass Fraction of Particulate	f_{XH}		0.167			-

COD						
Ammonium/TKN Ratio	f_{NH}		0.833			-
Soluble Inert N/TKN Ratio	f_{NI}		0			-
Particulate Organic N/Total Organic N	F_{XN}		0.25			-
Particulate COD to VSS Ratio	i_{cv}		1.66			gCOD/gVSS
VSS/TSS Ratio	i_{vt}		0.83			gVSS/gTSS
BOD_5/BOD_u Ratio	f_{BOD}		0.66			-
Autotrophic Organisms	X_{AUT}		0			$gCOD/m^3$
Polyphosphate Accumulating Biomass	X_{PAO}		0			$gCOD/m^3$
Poly-Hydroxy-Alkanoate	X_{PHA}		0			$gCOD/m^3$
Stored Glycogen	X_{gly}		0			$gCOD/m^3$
Stored Polyphosphate	X_{PP}		0			gP/m^3
Stored Polyphosphate	X_{PPr}		0			gP/m^3
Inert Cell Residue	X_I		0			$gCOD/m^3$
Dissolved Oxygen	S_{O2}		0			gO_2/m^3
Nitrite-Nitrate-N	S_{NO3}		0			gN/m^3
Dinitrogen	S_{N2}		15			gN/m^3
Alkalinity	S_{ALK}		3.13			$mole/m^3$
Kinetic Parameters						
Hydrolysis of Particulate Substrate: X_S						
Hydrolysis Rate Constant	K_h	1.57	2.00	2.45	3.00	1/d
Anoxic Hydrolysis Reduction Factor	η_{NO3}		0.60			-
Anaerobic Hydrolysis Reduction Factor	η_{fe}		0.40			-
Saturation/Inhibition Coefficient for Oxygen	K_{O2}		0.20			gO_2/m^3
Saturation/Inhibition Coefficient for Nitrate	K_{NO3}		0.50			gN/m^3
Saturation Coefficient for Particulate COD	K_X		0.10			gX_S/gX_H
Heterotrophs Organisms: X_H						
Maximum Specific Growth Rate	μ_H	1.60	3.00	4.24	6.00	gX_S/gX_H d
Maximum Rate for Fermentation	q_{fe}	0.99	1.50	2.21	3.00	gS_F/gX_H d
Reduction Factor for Denitrification	η_{NO3}		0.80			-
Rate Constant for Lysis and Decay	b_H	0.13	0.20	0.28	0.40	1/d
Saturation/Inhibition Coeficient for Oxygen	K_{O2}		0.20			gO_2/m^3
Saturation Coefficient for Growth on S_F	K_F		4.00			$gCOD/m^3$
Saturation Coefficient for Fermentation of S_F	K_{fe}		4.00			$gCOD/m^3$
Saturation Coefficient for Growth on Acetate	K_A		4.00			$gCOD/m^3$
Saturation/Inhibition Coefficient for Nitrate	K_{NO3}		0.50			gN/m^3
Saturation Coefficient for Ammonium (nutrient)	K_{NH4}		0.05			gN/m^3
Saturation Coefficient for	K_P		0.01			gP/m^3

Phosphate (nutrient)						
Saturation Coefficient for Alkalinity (HCO_3^-)	K_{ALK}		0.10			$moleHCO_3^-/m^3$
Phosphorous-Accumulation Organisms: X_{PAO}						
Rate Constant for Storage of X_{PHA} (base X_{PP})	q_{PHA}	1.57	2.00	2.45	3.00	gX_{PHA}/gX_{PAO} d
Rate Constant for Storage of X_{PP}	q_{PP}	0.78	1.00	1.22	1.50	gX_{PP}/gX_{PAO} d
Maximum Growth Rate of PAO	μ_{PAO}	0.53	0.67	0.82	1.00	1/d
Reduction Factor for Anoxic Activity	η_{NO3}		0.60			-
Rate for Lysis of X_{PAO}	b_{PAO}	0.07	0.10	0.14	0.20	1/d
Rate for Lysis of X_{PP}	b_{PP}	0.07	0.10	0.14	0.20	1/d
Rate for Lysis of X_{PHA}	b_{PHA}	0.07	0.10	0.14	0.20	1/d
Saturation/Inhibition Coefficient for Oxygen	K_{O2}		0.20			gO_2/m^3
Saturation Coefficient for Nitrate, S_{NO3}	K_{NO3}		0.50			gN/m^3
Saturation Coefficient for Acetate, S_A	K_A		4.00			$gCOD/m^3$
Saturation Coefficient for Ammonium (nutrient)	K_{NH4}		0.05			gN/m^3
Saturation Coefficient for Phosphorus in Storage of PP	K_{PS}		0.20			gP/m^3
Saturation Coefficient for Phosphate (nutrient)	K_P		0.01			gP/m^3
Saturation Coefficient for Alkalinity (HCO_3^-)	K_{ALK}		0.10			$moleHCO_3^-/m^3$
Saturation Coefficient for Poly-Phosphate	K_{PP}		0.01			gX_{PP}/gX_{PAO}
Maximum Ratio of X_{PP}/X_{PAO}	K_{MAX}		0.34			gX_{PP}/gX_{PAO}
Inhibition Coefficient for PP Storage	K_{IPP}		0.02			gX_{PP}/gX_{PAO}
Saturation Coefficient for PHA	K_{PHA}		0.01			gX_{PHA}/gX_{PAO}
Nitrifying Organisms (Autotrophic Organisms): X_{AUT}						
Maximum Growth Rate of X_{AUT}	μ_{AUT}	0.19	0.35	0.59	1.00	1/d
Decay Rate of X_{AUT}	b_{AUT}	0.03	0.05	0.09	0.15	1/d
Saturation Coefficient for Oxygen	K_{O2}		0.50			gO_2/m^3
Saturation Coefficient for Ammonium (substrate)	K_{NH4}		1.00			gN/m^3
Saturation Coefficient for Alkalinity (HCO_3^-)	K_{ALK}		0.50			$moleHCO_3^-/m^3$
Saturation Coefficient for Phosphorous (nutrient)	K_P		0.01			gP/m^3
Precipitation						
Rate Constant for P Precipitation	k_{PE}		1.00			$m^3/gFe(OH)_3$ d
Rate Constant for Redissolution	k_{RED}		0.60			1/d
Saturation Coefficient for Alkalinity	K_{ALK}		0.50			$moleHCO_3^-/m^3$
Stoichiometric						
Nitrogen:						

Soluble Material:			
N Content of Inert Soluble COD S_I	i_{NSI}	0.01	gN/gCOD
N Content of Fermentable Substrates S_F	i_{NSF}	0.03	gN/gCOD
Particulate Material:			
N Content of Inert Particulate COD X_I	i_{NXI}	0.02	gN/gCOD
N Content of Slowly Biodegradable Substrate X_S	i_{NXS}	0.04	gN/gCOD
N Content of Biomass, X_H, X_{PAO}, X_{AUT}	i_{NBM}	0.07	gN/gCOD
Phophorous			
Soluble Material:			
P Content of Inert Soluble COD S_I	i_{PSI}	0.00	gP/gCOD
P Content of Fermentable Substrates S_F	i_{PSF}	0.01	gP/gCOD
Particulate Material:			
P Content of Inert Particulate COD X_I	i_{PXI}	0.01	gP/gCOD
P Content of Slowly Biodegradable Substrate X_S	i_{PXS}	0.01	gP/gCOD
P Content of Biomass, X_H, X_{PAO}, X_{AUT}	i_{PBM}	0.02	gP/gCOD
Total Suspended Solids TSS:			
TSS to COD Ratio for X_I	i_{TSSXI}	0.75	gTSS/gCOD
TSS to COD Ratio for X_S	i_{TSSXS}	0.75	gTSS/gCOD
TSS to COD Ratio for Biomass, X_H, X_{PAO}, X_A	i_{TSSBM}	0.90	gTSS/gCOD
Hydrolysis:			
Production of S_I in Hydrolysis	f_{SI}	0.00	gCOD/gCOD
Heterotrophic Biomass: X_H			
Yield Coefficient	Y_H	0.625	gCOD/gCOD
Fraction of Inert COD Generated in Biomass Lysis	f_{XI}	0.10	gCOD/gCOD
Phosphoruous-Accumulating Organisms: X_{PAO}			
Yield Coefficient (Biomass/PHA)	Y_{PAO}	0.625	gCOD/gCOD
PP Requirement (PO_4 Release) per PHA Stored	Y_{PO4}	0.40	gP/gCOD
PHA Requirement for PP Storage	Y_{PHA}	0.20	gCOD/gP
Fraction of Inert COD Generated in Biomass Lysis	f_{XI}	0.10	gCOD/gCOD
Nitrifying Organisms: X_{AUT}			
Yield of Autotrophic Biomass per NO_3^--N	Y_A	0.24	gCOD/gN
Fraction of Inert COD Generated in Biomass Lysis	f_{XI}	0.10	gCOD/gCOD

3.3 Experimental Design

In order to evaluate each of the three BNR processes, the same basic layout was built in GPS-X. See Figure 15.

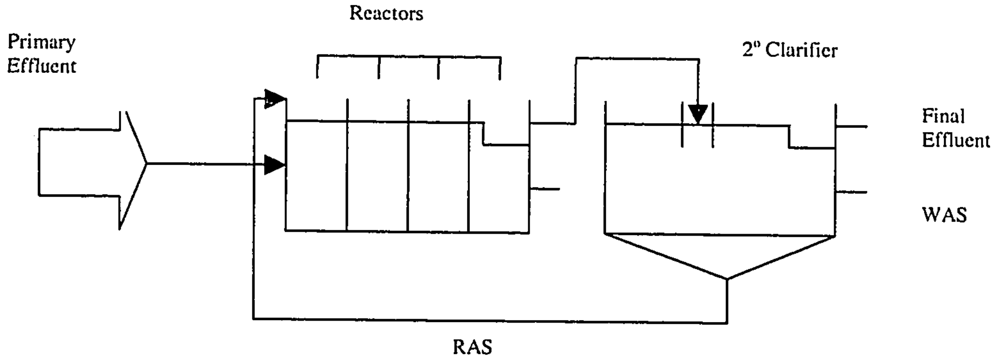

Figure 15: General GPS-X Layout

Of the three parts to the layout, the influent and secondary clarifier remain the same for all three BNR processes. The influent is described by the influent flow rate, Q, and the primary effluent concentrations of COD, TSS, sP and TKN. The wastewater characteristics for the influent model were taken from ASM 2d (Table 18). For all trials, Q was maintained at 100,000 m^3/d (25% of actual flow, Table 16). This value was used for two reasons. The first was that, since ROPEC is designed for $Q_{avg}$of 545,000 m^3/d and has the ability to split the flow, an eventual step in the evaluation of a BNR process would be to modify only 1 of ROPEC's 4 current treatment trains to accomplish BNR, so as to not affect the operation of the entire plant. The second reason is that ROPEC daily Q_{avg} is high relative to other operating wastewater treatment plants. Many plants operate with flows less than 100,000 m^3/d. With respect to the primary effluent concentrations, three different concentrations were evaluated. It was of interest to evaluate the performance of the three BNR processes for low, medium and high primary effluent concentrations of COD, TSS, sP and TKN. Typical concentrations for weak, medium and strong municipal waste used in this study are summarized in Table 19 (Droste, 1997, Viessler and Hammer, 1998 and Metcalf and Eddy, 1991).

Table 19: Primary Effluent Concentrations Levels

	Low	Medium	High
COD, mg/L	163	325	650
TSS, mg/L	160	320	650
TKN, mg/L	17.2	34.8	72.8
sP, mg/L	2.7	5.3	10.0

The parameters and operating variables for the secondary clarifier also remained constant throughout the trials. The surface area was 8000 m^2, average surface loading rate of 12.5 $m^3/m^2 \cdot h$, maximum water level was 4.0 m and the underdrain pumped flow was manipulated so as to maintain the MLSS above 2000 mg/L.

For the reactor, the kinetic and stoichiometric parameters were kept constant depending at which temperature (10°C or 20°C) the trials were being conducted. . The airflow rate to the aerobic zones of the reactor was also manipulated in order to maintain a DO concentration in the aerobic zones above 2 mg/L and a DO concentration in the anoxic and anaerobic zones at zero. The operating variables (zone HRTs and recycle rates) within the reactor for each of the three BNR processes were varied in order to find the optimum operating conditions for the MB, MUCT and A^2/O processes at 10°C and 20°C as well at low, medium and high primary effluent concentrations. The explanation of the experimental design used to find the effects of all operating variables will be discussed for each BNR process.

It should be mentioned here that effects of the operating variables for each BNR process are measured with respect to the three response variables, effluent TN (y_{TN}), effluent sP (y_{sP}) and a combination of effluent TN and sP concentrations ($y_{TN+sP} = 0.5*y_1 + 0.5*y_2$). This gives a total of 54 cases to be optimized. There are three BNR processes multiplied by three primary effluent concentration levels multiplied by two temperature levels multiplied by three different response variables. This number of cases (54) reiterates the necessity of computer simulation experiments.

3.3.1 MB Process

In order to ensure that single effects and multi interaction effects of each operating variable were tested, a 2-level factorial design was used. The MB process has seven input or operating variables that are of interest and are shown in Table 20.

Table 20: MB Input Variables

x_1	Total Recycle
x_2	Internal Recycle
x_3	Anaerobic Zone HRT
x_4	1st Anoxic Zone HRT
x_5	1st Aerobic Zone HRT
x_6	2nd Anoxic Zone HRT
x_7	2nd Aerobic Zone HRT

In order to evaluate individual and multi interaction effects of all seven variables, a 2^7 design must be completed. The first step to a factorial design is choosing the operating ranges and coding the input variables. To code variable, x_i, Equation 8 was used.

$$x_i = \frac{\begin{pmatrix} value\ of\ operating \\ variable\ i \end{pmatrix} - \frac{1}{2}\begin{pmatrix} it's\ upper\ limit \\ + it's\ lower\ limit \end{pmatrix}}{\frac{1}{2}\begin{pmatrix} it's\ upper\ limit \\ - it's\ lower\ limit \end{pmatrix}} \qquad [8]$$

Many operating ranges were tested and evaluated. As a starting point, typical conditions based on the literature were used for the experimental design; Table 21 summarizes the operating ranges and subsequent coding of the initial trial for the MB process.

Table 21: Coded Variables for MB Process

	-1	0	1
Total Recycle Ratio, relative to influent flow	0.5	0.75	1
Internal Recycle, % of influent flow	300	400	500
Anaerobic Zone HRT, h	0.96	1.44	1.92
1st Anoxic Zone HRT, h	2.40	3.00	3.60
1st Aerobic Zone HRT, h	4.80	6.00	7.20
2nd Anoxic Zone HRT, h	2.40	3.00	3.60
2nd Aerobic HRT, h	0.48	0.72	0.96

A 2^7 factorial design would be carried out as follows.

Table 22: 2^7 Factorial Design

Run #	x_1	x_2	x_3	x_4	x_5	x_6	x_7	y
1	-1	-1	-1	-1	-1	-1	-1	?
2	1	-1	-1	-1	-1	-1	-1	?
3	-1	1	-1	-1	-1	-1	-1	?

Run #	x_1	x_2	x_3	x_4	x_5	x_6	x_7	y
4	1	1	-1	-1	-1	-1	-1	?
5	-1	-1	1	-1	-1	-1	-1	?
6	1	-1	1	-1	-1	-1	-1	?
7	-1	1	1	-1	-1	-1	-1	?
8	1	1	1	-1	-1	-1	-1	?
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
120	1	1	1	-1	1	1	1	?
121	-1	-1	-1	1	1	1	1	?
122	1	-1	-1	1	1	1	1	?
123	-1	1	-1	1	1	1	1	?
124	1	1	-1	1	1	1	1	?
125	-1	-1	1	1	1	1	1	?
126	1	-1	1	1	1	1	1	?
127	-1	1	1	1	1	1	1	?
128	1	1	1	1	1	1	1	?

The least squares regression analysis shown below was used to model the data in the trial.

$$\underline{\hat{\beta}} = \left(\underline{X}^T \underline{X}\right)^{-1} \underline{X}^T \underline{Y} \qquad [9]$$

where, $\underline{\hat{\beta}} = \begin{bmatrix} \hat{\beta}_1 \\ \hat{\beta}_2 \\ \hat{\beta}_3 \\ \vdots \\ \hat{\beta}_{128} \end{bmatrix}$ is a p x 1 vector of least squares estimates for the model parameters,

$$\underline{X} = \begin{bmatrix} x_{11} & x_{21} & x_{31} & \cdots & x_{i1} \\ x_{12} & x_{22} & \cdots & \cdots & \vdots \\ x_{13} & \vdots & x_{33} & & \vdots \\ \vdots & \vdots & & \ddots & \vdots \\ x_{1j} & \cdots & \cdots & \cdots & x_{ij} \end{bmatrix}$$ is a n x p matrix of input variables

where i is the variable number and j is the run number

$\underline{Y} = \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ \vdots \\ Y_{128} \end{bmatrix}$ is a n x 1 vector of observed values of the response variable.

Solving the least squares equation for a 2^7 design gives the following model.

$$
\begin{aligned}
\hat{y} = {} & \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_3 x_3 + \hat{\beta}_4 x_4 + \hat{\beta}_5 x_5 + \hat{\beta}_6 x_6 + \hat{\beta}_7 x_7 \\
& + \hat{\beta}_{12} x_1x_2 + \ldots + \hat{\beta}_{67} x_6x_7 + \hat{\beta}_{123} x_1x_2x_3 + \ldots + \hat{\beta}_{567} x_5x_6x_7 \\
& + \hat{\beta}_{1234} x_1x_2x_3x_4 + \ldots + \hat{\beta}_{4567} x_4x_5x_6x_7 + \hat{\beta}_{12345} x_1x_2x_3x_4x_5 + \ldots + \hat{\beta}_{34567} x_3x_4x_5x_6x_7 \\
& + \hat{\beta}_{123456} x_1x_2x_3x_4x_5x_6 + \ldots + \hat{\beta}_{234567} x_2x_3x_4x_5x_6x_7 + \hat{\beta}_{1234567} x_1x_2x_3x_4x_5x_6x_7
\end{aligned}
\tag{10}
$$

For the MB process, 2 temperatures, 3 primary effluent concentrations and 3 response variables for a total of 18 cases have to be evaluated. For every design simulated, the resulting data gave information on the direction or location of the minimum response variable. If the minimum response variable was not found using the data gathered from the first design, a new operating range was used in a second design. This process will be explained in more detail in the sections to come, however, it does give an indication of the time required if an entire 2^7 factorial design is carried out. For the MB process the total computer time commitment to reach the optimum operating conditions, was about 230 hours. This time did not include data analysis. Also, from the least squares model (Eq. 10), one gets information on all effects, that is single, two, three, four, five, six and even seven factor interactions. For this study all three factor and higher interaction terms were considered negligible. Therefore, a design with 128 runs meant gathering a lot of unnecessary data. For these reasons, it was decided to use two-level fractional factorial designs. In this case a 2^{7-3} design was chosen. This design is shown in Table 23. A centre point run was added to give an indication of the need for quadratic terms in the model.

Table 23: 2^{7-3} Design for MB Process

run	x_1	x_2	x_3	x_4	x_5	x_6	x_7	y_i
1	-1	-1	-1	-1	-1	-1	-1	?
2	1	-1	-1	-1	1	1	-1	?
3	-1	1	-1	-1	1	1	1	?
4	1	1	-1	-1	-1	-1	1	?
5	-1	-1	1	-1	1	-1	1	?
6	1	-1	1	-1	-1	1	1	?
7	-1	1	1	-1	-1	1	-1	?
8	1	1	1	-1	1	-1	-1	?
9	-1	-1	-1	1	-1	1	1	?
10	1	-1	-1	1	1	-1	1	?
11	-1	1	-1	1	1	-1	-1	?
12	1	1	-1	1	-1	1	-1	?
13	-1	-1	1	1	1	1	-1	?

run	x_1	x_2	x_3	x_4	x_5	x_6	x_7	y_i
14	1	-1	1	1	-1	-1	-1	?
15	-1	1	1	1	-1	-1	1	?
16	1	1	1	1	1	1	1	?
17	0	0	0	0	0	0	0	?

This design was set up using the defining relationship.

$$I = x_1x_2x_3x_5 = x_1x_2x_4x_6 = x_2x_3x_4x_7 = x_3x_4x_5x_6 = x_1x_4x_5x_7 = x_1x_3x_6x_7 = x_2x_5x_6x_7 \qquad [11]$$

This is a resolution IV design where no single factor (operating variable) is confounded with another single factor or double factor interaction. However, at least one of the two-factor interactions is confounded with another two-factor interaction. The confounding relationships are given in Table 24.

Table 24: Confounding Relationships for MB Process

ℓ_0	=	β_0												
ℓ_1	=	β_1	+	β_{235}	+	β_{246}	+	β_{457}	+	β_{367}				
ℓ_2	=	β_2	+	β_{135}	+	β_{146}	+	β_{347}	+	β_{567}				
ℓ_3	=	β_3	+	β_{125}	+	β_{247}	+	β_{456}	+	β_{167}				
ℓ_4	=	β_4	+	β_{126}	+	β_{237}	+	β_{356}	+	β_{157}				
ℓ_5	=	β_5	+	β_{123}	+	β_{346}	+	β_{147}	+	β_{267}				
ℓ_6	=	β_6	+	β_{124}	+	β_{345}	+	β_{137}	+	β_{257}				
ℓ_7	=	β_7	+	β_{234}	+	β_{145}	+	β_{136}	+	β_{256}				
ℓ_{12}	=	β_{12}	+	β_{35}	+	β_{46}								
ℓ_{13}	=	β_{13}	+	β_{25}	+	β_{67}								
ℓ_{14}	=	β_{14}	+	β_{26}	+	β_{57}								
ℓ_{15}	=	β_{15}	+	β_{23}	+	β_{47}								
ℓ_{16}	=	β_{16}	+	β_{24}	+	β_{37}								
ℓ_{17}	=	β_{17}	+	β_{45}	+	β_{36}								
ℓ_{27}	=	β_{27}	+	β_{34}	+	β_{56}								
ℓ_{127}	=	β_{127}	+	β_{134}	+	β_{156}	+	β_{236}	+	β_{245}	+	β_{357}	+	β_{467}

Using the information from Table 23, the following least squares model can be found.

$$\begin{aligned}\hat{y} = {} & \hat{\ell}_0 + \hat{\ell}_1 x_1 + \hat{\ell}_2 x_2 + \hat{\ell}_3 x_3 + \hat{\ell}_4 x_4 + \hat{\ell}_5 x_5 + \hat{\ell}_6 x_6 + \hat{\ell}_7 x_7 \\ & + \hat{\ell}_{12} x_1x_2 + \hat{\ell}_{13} x_1x_3 + \hat{\ell}_{14} x_1x_4 + \hat{\ell}_{15} x_1x_5 + \hat{\ell}_{16} x_1x_6 + \hat{\ell}_{17} x_1x_7 \qquad [12] \\ & + \hat{\ell}_{27} x_2x_7 + \hat{\ell}_{127} x_1x_2x_7\end{aligned}$$

where, $\hat{\ell}_0, \hat{\ell}_1, \hat{\ell}_2, etc\ldots$ = Least squares estimates

x_1, x_2, x_3, x_4, etc... = Coded input variables

The resulting least squares fitted model is then used to find the direction and location of the minimum response variable (discussed in Chapter 4).

3.3.2 MUCT Process

The same 2^{7-3} experimental design as set up for the MB process was used for the MUCT process. Table 25 shows the input variables.

Table 25: Input Variables for MUCT Process

x_1	Total Recycle
x_2	Anoxic Recycle
x_3	Nitrified Recycle
x_4	Anaerobic Zone HRT
x_5	1st Anoxic Zone HRT
x_6	2nd Anoxic Zone HRT
x_7	Aerobic Zone HRT

The coded variables and initial operating range based on the literature are shown in Table 26.

Table 26: Coded Variables for MUCT Process

	-1	0	1
Total Recycle Ratio, relative to influent flow	0.5	0.75	1
Anoxic Recycle, % of influent flow	100	200	300
Nitrified Recycle, % of influent flow	100	200	300
Anaerobic Zone HRT, h	0.96	1.44	1.92
1st Anoxic Zone HRT, h	2.40	3.00	3.60
2nd Anoxic Zone HRT, h	2.40	3.00	3.60
Aerobic Zone HRT, h	4.80	6.00	7.20

As with the MB process, least squares regression was used with the results of the computer simulations to obtain the following model.

$$\begin{aligned}\hat{y} = \hat{\ell}_0 + \hat{\ell}_1 x_1 + \hat{\ell}_2 x_2 + \hat{\ell}_3 x_3 + \hat{\ell}_4 x_4 + \hat{\ell}_5 x_5 + \hat{\ell}_6 x_6 + \hat{\ell}_7 x_7 \\ + \hat{\ell}_{12} x_1x_2 + \hat{\ell}_{13} x_1x_3 + \hat{\ell}_{14} x_1x_4 + \hat{\ell}_{15} x_1x_5 + \hat{\ell}_{16} x_1x_6 + \hat{\ell}_{17} x_1x_7 \\ + \hat{\ell}_{27} x_2x_7 + \hat{\ell}_{127} x_1x_2x_7\end{aligned} \qquad [13]$$

Using this model, statistical analysis was used to find the location of the minimum value of the response variable. For this analysis, please refer to Chapter 4 for a case study.

3.3.3 A^2/O Process

The experimental design set up for the A^2/O process is different from the MB and MUCT processes in that it only has the five input variables.

Table 27: Input Variables for A^2/O Process

x_1	Total Recycle
x_2	Nitrified Recycle
x_3	Anaerobic Zone HRT
x_4	Anoxic Zone HRT
x_5	Aerobic Zone HRT

The coded variables and initial operating region based on the literature is shown in Table 28.

Table 28: Coded Variables for A^2/O Process

	-1	0	1
Total Recycle Ratio, relative to influent flow	0.3	0.45	0.60
Nitrified Recycle, % of influent flow	100	200	300
Anaerobic Zone HRT, h	0.48	0.72	0.96
Anoxic Zone HRT, h	0.48	0.72	0.96
Aerobic Zone HRT, h	3.60	4.80	6.00

A two-level fractional factorial design was also used for this study; only for this process; a 2^{5-1}, resolution V design was used (Table 29).

Table 29: 2^{5-1} Design for A^2/O Process

run	x_1	x_2	x_3	x_4	x_5
1	-1	-1	-1	-1	1
2	1	-1	-1	-1	-1
3	-1	1	-1	-1	-1
4	1	1	-1	-1	1
5	-1	-1	1	-1	-1
6	1	-1	1	-1	1
7	-1	1	1	-1	1
8	1	1	1	-1	-1
9	-1	-1	-1	1	-1
10	1	-1	-1	1	1
11	-1	1	-1	1	1

12	1	1	-1	1	-1
13	-1	-1	1	1	1
14	1	-1	1	1	-1
15	-1	1	1	1	-1
16	1	1	1	1	1
17	0	0	0	0	0

The defining relationship is shown as follows.

$$I = x_1x_2x_3x_4x_5 \qquad [14]$$

No single-factor operating variable is confounded with another single factor, two-factor or three-factor interactions. No two-factor interaction is confounded with another two-factor interaction. The confounding relationships are given in Table 30. Four factor and higher interactions are assumed to be negligible.

Table 30: Confounding Relationships for A^2/O Process

ℓ_0	=	β_0		
ℓ_1	=	β_1		
ℓ_2	=	β_2		
ℓ_3	=	β_3		
ℓ_4	=	β_4		
ℓ_5	=	β_5		
ℓ_{12}	=	β_{12}	+	β_{345}
ℓ_{13}	=	β_{13}	+	β_{245}
ℓ_{14}	=	β_{14}	+	β_{235}
ℓ_{15}	=	β_{15}	+	β_{234}
ℓ_{21}	=	β_{23}	+	β_{145}
ℓ_{23}	=	β_{24}	+	β_{135}
ℓ_{24}	=	β_{25}	+	β_{134}
ℓ_{34}	=	β_{34}	+	β_{125}
ℓ_{35}	=	β_{35}	+	β_{124}
ℓ_{45}	=	β_{45}	+	β_{123}

Using least squares, the following equation can be found.

$$
\begin{aligned}
\hat{y} = {} & \hat{\ell}_0 + \hat{\ell}_1 x_1 + \hat{\ell}_2 x_2 + \hat{\ell}_3 x_3 + \hat{\ell}_4 x_4 + \hat{\ell}_5 x_5 + \hat{\ell}_{12} x_1x_2 + \hat{\ell}_{13} x_1x_3 \\
& + \hat{\ell}_{14} x_1x_4 + \hat{\ell}_{15} x_1x_5 + \hat{\ell}_{23} x_2x_3 + \hat{\ell}_{24} x_2x_4 + \hat{\ell}_{25} x_2x_5 + \hat{\ell}_{34} x_3x_4 \\
& + \hat{\ell}_{35} x_3x_5 + \hat{\ell}_{45} x_4x_5
\end{aligned}
\qquad [15]
$$

As with the other processes a statistical analysis was used to find the location of the minimum value of the response variable. For analysis, refer to Chapter 4.

Table 31 assigns a case number to each of the 54 cases for easier reference.

Table 31: Numbered Case Studies

Case #	Process	Temperature	Primary Effluent Concentration	Minimized Response Variable
1	A^2/O	10°C	Low	TN
2	A^2/O	10°C	Low	sP
3	A^2/O	10°C	Low	TN + sP
4	A^2/O	10°C	Medium	TN
5	A^2/O	10°C	Medium	sP
6	A^2/O	10°C	Medium	TN + sP
7	A^2/O	10°C	High	TN
8	A^2/O	10°C	High	sP
9	A^2/O	10°C	High	TN + sP
10	A^2/O	20°C	Low	TN
11	A^2/O	20°C	Low	sP
12	A^2/O	20°C	Low	TN + sP
13	A^2/O	20°C	Medium	TN
14	A^2/O	20°C	Medium	sP
15	A^2/O	20°C	Medium	TN + sP
16	A^2/O	20°C	High	TN
17	A^2/O	20°C	High	sP
18	A^2/O	20°C	High	TN + sP
19	MB	10°C	Low	TN
20	MB	10°C	Low	sP
21	MB	10°C	Low	TN + sP
22	MB	10°C	Medium	TN
23	MB	10°C	Medium	sP
24	MB	10°C	Medium	TN + sP
25	MB	10°C	High	TN
26	MB	10°C	High	sP
27	MB	10°C	High	TN + sP
28	MB	20°C	Low	TN
29	MB	20°C	Low	sP
30	MB	20°C	Low	TN + sP
31	MB	20°C	Medium	TN
32	MB	20°C	Medium	sP
33	MB	20°C	Medium	TN + sP
34	MB	20°C	High	TN
35	MB	20°C	High	sP
36	MB	20°C	High	TN + sP
37	MUCT	10°C	Low	TN
38	MUCT	10°C	Low	sP
39	MUCT	10°C	Low	TN + sP

Case #	Process	Temperature	Primary Effluent Concentration	Minimized Response Variable
40	MUCT	10°C	Medium	TN
41	MUCT	10°C	Medium	sP
42	MUCT	10°C	Medium	TN + sP
43	MUCT	10°C	High	TN
44	MUCT	10°C	High	sP
45	MUCT	10°C	High	TN + sP
46	MUCT	20°C	Low	TN
47	MUCT	20°C	Low	sP
48	MUCT	20°C	Low	TN + sP
49	MUCT	20°C	Medium	TN
50	MUCT	20°C	Medium	sP
51	MUCT	20°C	Medium	TN + sP
52	MUCT	20°C	High	TN
53	MUCT	20°C	High	sP
54	MUCT	20°C	High	TN + sP

CHAPTER 4:

RESULTS

4.1 Case Study #1: MUCT Process

As stated in Chapter 3, 18 cases were optimized for each BNR process (total of 54 cases) (10°C and 20°C with low, medium and high primary effluent concentrations for three response variables (TN, sP, TN + sP)). It is unnecessary to give a detailed analysis of each of these cases since the same method was used for each case to find the location of the minimum response variables and the values of the optimum operating variables. Three case studies will be described in detail in order to explain the statistical methods used to meet the objective. Also, some of the problems that occurred as a result of using simulated data as opposed to experimental data were considered. The first case to be examined is the MUCT process at 20°C with a high primary effluent concentration.

The first step in the optimization process was to establish the number and range of the input variables. As mentioned previously for the MUCT process, there were seven input variables, shown in Table 32.

Table 32: Input Variables for MUCT Process

x_1	Total Recycle
x_2	Anoxic Recycle
x_3	Nitrified Recycle
x_4	Anaerobic HRT
x_5	1st Anoxic HRT
x_6	2nd Anoxic HRT
x_7	Aerobic HRT

The next step in the optimization process was to establish the operating ranges for each of the seven variables. For this case study, the operating ranges were chosen as follows.

Table 33: Operating Ranges for Input Variables for Case Study 1a

	Low	Centre	High
x_1, -	1.0	1.25	1.5
x_2, % Q	200	300	400
x_3, % Q	1000	1250	1500
x_4, h	0.72	1.08	1.44
x_5, h	1.2	1.8	2.4
x_6, h	10.8	12	13.2
x_7, h	9.6	10.8	12

The operating ranges for this case were based on the successful operating variables reported in the literature for the MUCT process at 20°C with a medium primary effluent concentration (EPA, 1993).

Instead of starting with a large range for each input variable, the assumption was made that the optimum location with respect to the input variables for high primary effluent concentrations would be close to the optimum location for medium primary effluent concentrations. This assumption provided for a smaller set of operating ranges as well as a fewer number of experimental trials.

The input variables were coded before they could be implemented into the 2-level fractional factorial design. Using the total recycle, x_1, as an example, Equation 8 was used to calculate the coded variables. For the low end of the range,

$$x_{ic} = \frac{1.0 - 1.25}{0.25} = -1 \qquad [16]$$

For the high end of the range,

$$x_{1c} = \frac{1.5 - 1.25}{0.25} = 1 \qquad [17]$$

For the centre of the range,

$$x_{1c} = \frac{1.25 - 1.25}{0.25} = 0 \qquad [18]$$

Once all of the variables were coded, the next step was to set up the 2^{7-3} design used to generate data over the entire operating region for the MUCT process. This design is shown in Table 34 along with the observed values for final TN, y_{TN}. Other variables, such as influent flow rate and secondary clarifier surface area were kept constant at 100,000 m^3/d, and 8,000 m^2, respectively. The primary effluent concentrations of $cBOD_5$, TSS, TKN and TP were also kept constant at 650 mg/L, 650 mg/L, 72.8 mg/L and 10.0 mg/L, respectively. Additionally, airflow rate to the aerobic zone in the reactor was kept at 5.0×10^6 m^3/d and the pumped underdrain flow from the secondary clarifier were kept constant at 1,500 m^3/d. This ensured a DO concentration in the aerobic zone greater than 2.0 mg/L and a MLSS concentration in the reactor above 2,000 mg/L. Once all of these variables were set, the experimental runs were carried out and the following concentration response variables, y_{TN}, were found for the 17 runs.

Table 34: 2^{7-3} Design and Response for Case Study 1a

run	x_1	x_2	x_3	x_4	x_5	x_6	x_7	y_{TN}, mgN/L
1	-1	-1	-1	-1	-1	-1	-1	6.86
2	1	-1	-1	-1	1	1	-1	7.21
3	-1	1	-1	-1	1	1	1	6.89
4	1	1	-1	-1	-1	-1	1	6.27
5	-1	-1	1	-1	1	-1	1	5.44
6	1	-1	1	-1	-1	1	1	5.04
7	-1	1	1	-1	-1	1	-1	5.72
8	1	1	1	-1	1	-1	-1	5.53
9	-1	-1	-1	1	-1	1	1	6.76
10	1	-1	-1	1	1	-1	1	6.57
11	-1	1	-1	1	1	-1	-1	7.27
12	1	1	-1	1	-1	1	-1	7.09
13	-1	-1	1	1	1	1	-1	6.08
14	1	-1	1	1	-1	-1	-1	5.32
15	-1	1	1	1	-1	-1	1	5.19
16	1	1	1	1	1	1	1	5.38
17	0	0	0	0	0	0	0	5.97

Using the response data and Equation 9 for least squares regression, the following model was fitted to the results.

$$\begin{aligned}\hat{y}_{TN} &= 6.15 - 0.11x_1 + 0.00x_2 - 0.70x_3 + 0.04x_4 + 0.13x_5 + 0.11x_6 - 0.22x_7 \\ &+ 0.11x_1x_2 - 0.03x_1x_3 - 0.00x_1x_4 - 0.01x_1x_5 + 0.02x_1x_6 - 0.02x_1x_7 \\ &- 0.01x_2x_7 - 0.01x_1x_2x_7\end{aligned} \qquad [19]$$

The next step of the optimization process was to test whether or not the model shown in Equation 19 fitted the data at an acceptable level. When gathering experimental data in a laboratory setting, the degree of lack of fit for the model can be determined using a statistical significance test by comparing the size of the pure error variance against the lack of fit variance. However, for simulated data there is no experimental error since every replicated run would give exactly the same response value. For this reason, a centre point run was carried out in order to provide a numerical method of testing the significance of the lack of fit for the model. This method of determining lack of fit significance is shown below.

Using Equation 19, the following set of predicted response variables were calculated for the experimental trial. The residuals could also be calculated by subtracting the predicted response from the actual response values. Figure 16, which shows the plot of residuals versus predicted response variable, gives an indication of the amount of scatter in the data.

Judging by both the magnitude of the residuals (Table 35) and the lack of scatter in the residuals (Figure 16), the model showed good correlation with the data. The only data point or residual that showed signs of lack of fit is run #17, the centre point run. It is this residual that was used to numerically test the significance of the lack of fit in the model. Since the model contained 16 parameters and 17 experimental runs were carried out, one would expect the residuals for all runs, except maybe the centre point, to be negligible. This is because a perfect model is found when the same number of parameters is used in the model as number of experimental runs carried out. That is, if we had only done the 16 runs in the factorial design and fitted a 16-parameter model to this data, all residuals would have been zero. Because conventional methods for testing lack of fit significance could not be applied to the above table of residuals, the significance of the lack of fit was determined by comparing each residual to the actual response for that run. As long as none of the ratios exceed 5 %, the model was deemed to fit the data. Although 5 % had no statistical meaning, it was chosen based on the assumption that in the physical plant, the effluent concentrations will experience a large amount of variance (greater than 5 %). See Table 35 for this trial's significance test.

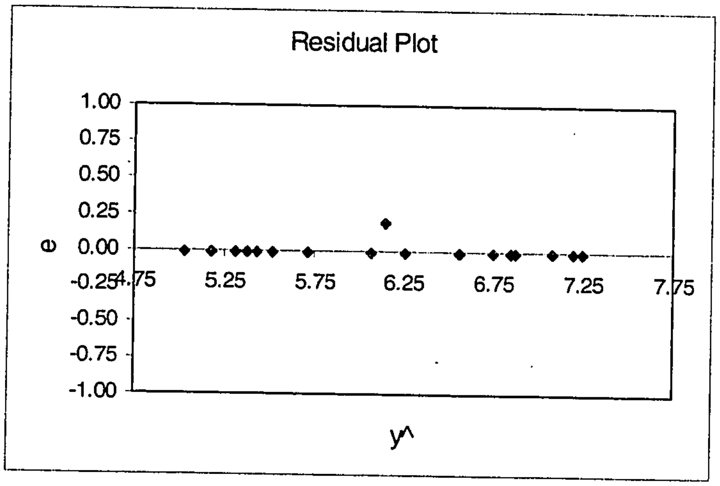

Figure 16: Residual Plot 1 for Case Study 1a

Table 35: Residuals and Residual Ratios for Case Study 1a

Run #	Actual Response Variable, y_{TN}, mgN/L	Residual,e, mgN/L	e/y_{TN}
1	6.86	-0.01	0.00
2	7.21	-0.01	0.00
3	6.89	-0.01	0.00
4	6.27	-0.01	0.00
5	5.44	-0.01	0.00
6	5.04	-0.01	0.00
7	5.72	-0.01	0.00
8	5.53	-0.01	0.00
9	6.76	-0.01	0.00
10	6.57	-0.01	0.00
11	7.27	-0.01	0.00
12	7.09	-0.01	0.00
13	6.08	-0.01	0.00
14	5.32	-0.01	0.00
15	5.19	-0.01	0.00
16	5.38	-0.01	0.00
17	5.97	0.18	0.03

Because the largest ratio, run 17, was only 0.03, the model given in Equation 19 was concluded to fit the simulated data.

The next step was to test the significance of each of the parameters within the model. Since the model in Equation 19 was used to find the location of the minimum response variable, it was desirable to reduce the complexity (reduce the number of parameters) as much as possible. Once the model was concluded to fit the data, the necessity of the parameters within the model must be considered. The model given in Equation 19 has 16 parameters. It was difficult to work with a model so large and therefore, it was desirable to reduce the model by eliminating insignificant parameters. The conventional method for testing the significance of each parameter was to remove a given parameter from the model and then to compare the new lack of fit error created by the model to the experimental error in the data. Since there was no experimental error in the data, an alternative method had to be used to test the significance of each parameter. The following approach was used.

The first step was to calculate the sum of squares of residuals for the complete model. That is,

$$SSR = \sum e^2 \qquad [20]$$

For the complete model, the SSR was 0.04. Next, the SSR was calculated for the model with only the largest parameter ($y_{TN} = \mathfrak{C}_0$), giving a value of 9.4. Parameter $\mathfrak{C}_0$ will always by the largest parameter within the model. The SSR was then calculated for the model with the two largest parameters ($y_{TN} = \mathfrak{C}_0 - \mathfrak{C}_3 x_3$), giving a value of 1.6. Adding parameter ℓ_3 to the model decreased the SSR by a large amount indicating that it was likely a significant parameter. The next largest parameter, ℓ_7, was then added to the model, further decreasing the SSR to 0.80. With the addition of each parameter, the SSR was calculated. The results are shown graphically in Figure 17. The parameters toward the end of the plot (ℓ_{14}, ℓ_2, ℓ_{127}, ℓ_{15}, ℓ_{12}, ℓ_{27}, ℓ_{17}, ℓ_{16}) had very little effect on the SSR when they were removed from the model. Where as, parameters ℓ_3, ℓ_7 had a relatively larger impact on the value of SSR when they were removed from the model.

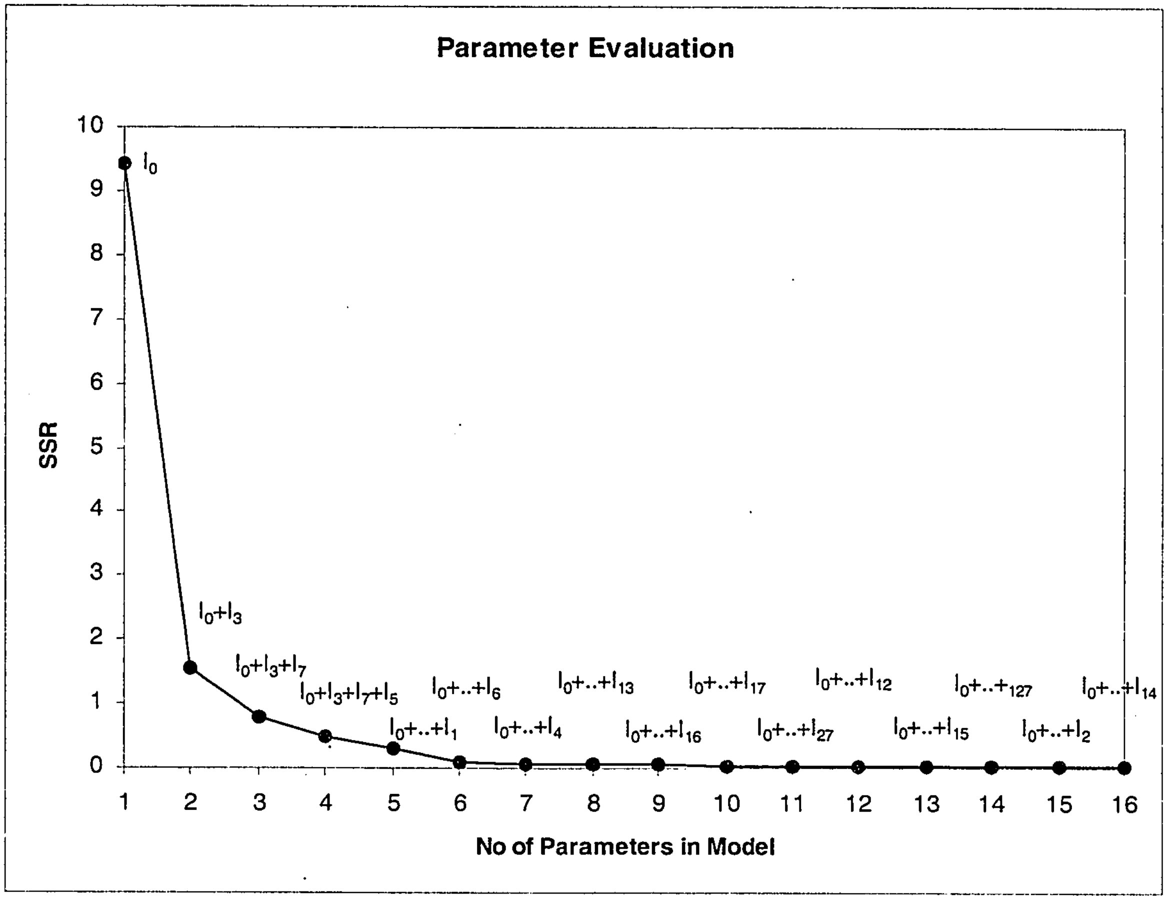

Figure 17: Parameter Evaluation Plot 1 for Case Study 1a

Figure 17, indicated that the parameters in the latter part of the plot were insignificant and could be removed from the model with little or no effect to the predicted response. Conversely the parameters in the beginning part of the plot were significant and should remain in the model. The difficult part was to choose which parameters in the middle of the plot were significant and which were not. For this task the following parameter minimization method was used to simplify the model. It was conservatively assumed that only the first seven parameters in Figure 17 were possibly significant and were kept in the new minimized model shown below (Eq. 21).

$$\hat{y}_{TN} = 6.15 - 0.11x_1 - 0.70x_3 + 0.04x_4 + 0.13x_5 + 0.11x_6 - 0.22x_7 - 0.03x_1x_3 \qquad [21]$$

Using the residuals calculated from the model given in Equation 21, a second residual plot was constructed and is shown in Figure 18. The title of Figure 18 indicated which parameters were in the model. From Figure 18, one can see that there was little scatter in the residuals and that the magnitudes of the residuals were very small. The minimized model given by Equation 21 had to be tested for lack of fit significance. When each residual was compared with the corresponding actual response variable for every run the largest ratio of residual to actual response variable turned out to be 0.03. Since 0.03 is less than 0.05, the minimized model described by Equation 21 was concluded to fit the data. The next step was to remove another parameter and further minimize the model. Since parameter $\mathfrak{C}_{13}$ was the furthest down on the parameter plot (Figure 17), it was removed. The 6-parameter minimized model is shown in Equation 22.

$$\hat{y}_{TN} = 6.15 - 0.11x_1 - 0.70x_3 + 0.04x_4 + 0.13x_5 + 0.11x_6 - 0.22x_7 \qquad [22]$$

The plot for the residuals calculated from Equation 22 is given in Figure 19.

This residual plot also showed very little scatter and the largest residual to actual response variable ratio is still 0.03. Therefore, it was concluded that the model given in Equation 22 fits the data and consequently, parameter $\mathfrak{C}_{13}$ was deemed insignificant.

The next parameter to be removed was $\mathfrak{C}_4$. With $\mathfrak{C}_4$ gone, the 5-parameter minimized model is shown in Equation 23.

$$\hat{y}_{TN} = 6.15 - 0.11x_1 - 0.70x_3 + 0.13x_5 + 0.11x_6 - 0.22x_7 \qquad [23]$$

The residual plot for Equation 23 is shown in Figure 20.

There was still little scatter in the residual data points and the largest ratio of residual to actual response variable is 0.03. From this, the model given in Equation 23 was concluded to fit the data and parameter $\mathfrak{C}_4$ was deemed insignificant.

Parameter $\mathfrak{C}_6$ was then removed from the model to give the 4-parameter minimized model (Equation 24).

$$\hat{y}_{TN} = 6.15 - 0.11x_1 - 0.70x_3 + 0.13x_5 - 0.22x_7 \qquad [24]$$

Figure 21 shows the residual plot for Equation 24.

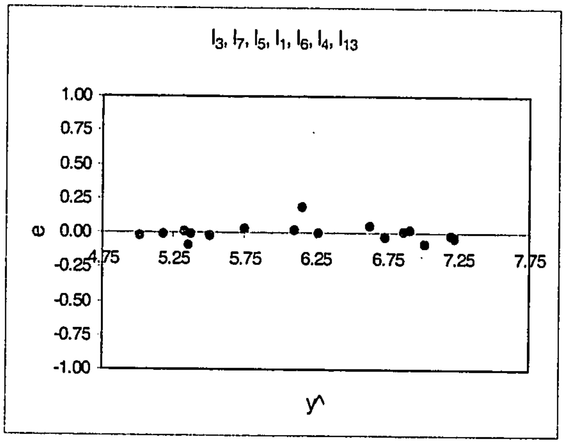

Figure 18: Residual Plot 2 for Case Study 1a

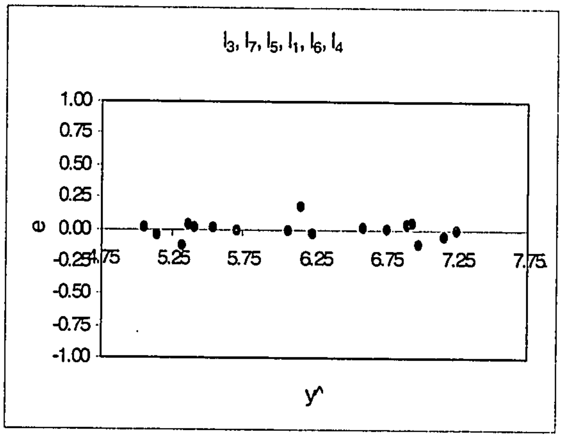

Figure 19: Residual Plot 3 for Case Study 1a

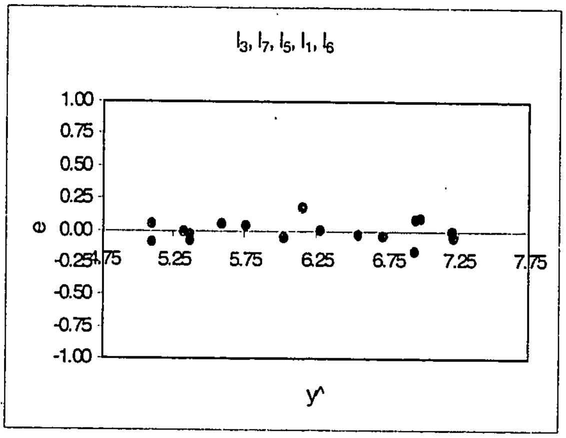

Figure 20: Residual Plot 4 for Case Study 1a

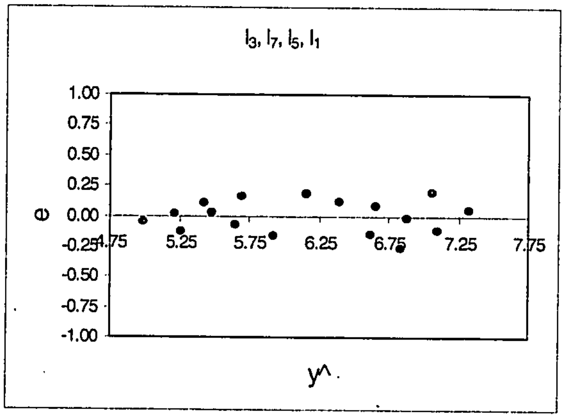

Figure 21: Residual Plot 5 for Case Study 1a

Although, the largest ratio of residual to actual response variable was only 0.04, there was too much scatter in the residual points to accept that parameter $\mathfrak{C}_6$ is insignificant. From this, it was concluded that the minimized 5-parameter model given in Eq. 23 could be used to fit the data.

Now with a reduced model that fits the data, the next step was to use the model to find the location of the minimum response variable. Since the model in Equation 23 was a planar model, the following procedure could be used to find the direction and ultimately the location of the optimum operating point. Since the input variables, x_2, x_4 were not included in the final model, it was decided that the optimum location with respect to anoxic recycle, x_2, and anaerobic zone HRT, x_4 would be set to the centre point value in the original operating region. That is, $x_2 = 300$ % Q and $x_4 = 1.08$ h. The optimum values for the remaining 5 input variables were found using a steepest descent procedure. The following table is used to illustrate this procedure.

Table 36: Steepest Descent Procedure for Case Study 1a

	x_1	x_3	x_5	x_6	x_7
	Total Recycle	Nitrified Recycle, % Q	1st Anoxic HRT, h	2nd Anoxic HRT, h	Aerobic HRT, h
Design Centre Point	1.25	1250	1.8	12	10.8
Value of One Coded Unit	0.25	250	0.6	1.2	1.2
Steepest Descent Direction (Coded units)	-0.11	-0.70	0.13	0.11	-0.22
Steepest Descent Direction (Original units)	-0.03	-175	0.080	0.130	-0.265
Steepest Descent Direction (Original units)	0.01	50	-0.023	0.037	0.076

The first row in Table 36 is the centre point value for each of the five input variables given at the beginning of the case trial. The second row is the value used to code each of the input variables. The third row contains the corresponding least square parameter estimates for each of the input variables. The fourth row is the multiplication of rows 2 and 3. Values in the row 5 are chosen arbitrarily and the magnitude of these values determines the speed at which you travel along the direction of steepest descent. Table 37 shows the results of the steepest descent procedure for this trial.

Table 37: Results of the Steepest Descent Procedure for Case Study 1a

	x_1 Total Recycle	x_3 Nitrified Recycle, % Q	x_5 1st Anoxic HRT, h	x_6 2nd Anoxic HRT, h	x_7 Aerobic HRT, h	y Effluent TN, mgN/L
Design Centre Point	1.25	1250	1.8	12	10.8	
	1.26	1300	1.777	11.963	10.876	5.81
	1.27	1350	1.754	11.926	10.951	5.66
	1.30	1550	1.663	11.778	11.254	5.12
	1.31	1650	1.618	11.704	11.405	4.92
	1.33	1750	1.572	11.630	11.556	4.76
	1.35	1850	1.526	11.556	11.707	4.74
	1.36	1950	1.481	11.482	11.858	4.80
	1.38	2050	1.435	11.408	12.010	4.97

These results indicated that, the minimum TN concentration was approximately 4.7 mg/L. However, this minimum value for the final TN concentration was located outside the design operational range. For example, the operating range for nitrified recycle went from 1000 to 1500 % Q, but the optimum value of x_2 was around 1850 % Q. This means that we are applying the model outside its original operating region without knowing whether or not the model is still valid. Also, there was a significant jump in TN concentration from 5.8 to 4.7 mg/L along the direction of steepest descent. For these reasons the entire optimization procedure was repeated with a new operating region centred on the minimum value of 4.7 mg/L. This new operating range can be seen in Table 38 along with the coded variables for low, centre and high conditions.

Table 38: Coded Variables for 2nd Design in Case Study 1b

	-1	0	1
x_1, -	1.25	1.33	1.4
x_2, % Q	200	300	400
x_3, % Q	1700	1850	2000
x_4, h	0.720	1.080	1.440
x_5, h	1.440	1.560	1.680
x_6, h	11.400	11.580	11.760
x_7, h	11.520	11.700	11.880

All seven variables were used in this second design experiment. Although variables x_2 and x_4 were not important in the previous operating region, there was a possibility that they would be significant in this new operating region. For this reason they were included in the second design. The same experimental design of 2^{7-3} was used to gather data for the second trial. The experimental design along with the actual response variables can be seen in Table 39.

Table 39: 2^{7-3} Design and Response for Case Study 1b

run	x_1	x_2	x_3	x_4	x_5	x_6	x_7	y_{TN}, mgN/L
1	-1	-1	-1	-1	-1	-1	-1	4.95
2	1	-1	-1	-1	1	1	-1	4.79
3	-1	1	-1	-1	1	1	1	4.87
4	1	1	-1	-1	-1	-1	1	4.97
5	-1	-1	1	-1	1	-1	1	5.01
6	1	-1	1	-1	-1	1	1	4.87
7	-1	1	1	-1	-1	1	-1	4.78
8	1	1	1	-1	1	-1	-1	4.81
9	-1	-1	-1	1	-1	1	1	4.81
10	1	-1	-1	1	1	-1	1	4.88
11	-1	1	-1	1	1	-1	-1	5.04
12	1	1	-1	1	-1	1	-1	4.88
13	-1	-1	1	1	1	1	-1	4.61
14	1	-1	1	1	-1	-1	-1	4.64
15	-1	1	1	1	-1	-1	1	4.81
16	1	1	1	1	1	1	1	4.68
17	0	0	0	0	0	0	0	4.75

The least squares model that was fitted to this data is shown in Equation 25.

$$\begin{aligned}\hat{y} = {} & 4.83 - 0.02x_1 + 0.02x_2 - 0.06x_3 - 0.04x_4 + 0.00x_5 - 0.05x_6 + 0.02x_7 \\ & + 0.00x_1x_2 + 0.00x_1x_3 + 0.00x_1x_4 - 0.02x_1x_5 + 0.04x_1x_6 + 0.01x_1x_7 \\ & - 0.05x_2x_7 + 0.00x_1x_2x_7\end{aligned} \qquad [25].$$

Table 40 shows the predicted response using the model, the actual response, the residuals and the ratio of residual to actual response.

Table 40: Response Variables and Residual Ratios for Case Study 1b

Run #	Actual Response Variable, y_{TN}, mgN/L	Predicted Response Variable, $\hat{y}_{TN}$, mgN/L	Residual,e, mgN/L	e/y_{TN}
1	4.95	4.95	-0.01	0.00
2	4.79	4.79	-0.01	0.00
3	4.87	4.86	-0.01	0.00
4	4.97	4.96	-0.01	0.00
5	5.01	5.00	-0.01	0.00
6	4.87	4.87	-0.01	0.00
7	4.78	4.78	-0.01	0.00
8	4.81	4.80	-0.01	0.00
9	4.81	4.80	-0.01	0.00
10	4.88	4.88	-0.01	0.00
11	5.04	5.04	-0.01	0.00

Run #	Actual Response Variable, y_{TN}, mgN/L	Predicted Response Variable, $\hat{y}_{TN}$, mgN/L	Residual,e, mgN/L	e/y_{TN}
12	4.88	4.87	-0.01	0.00
13	4.61	4.61	-0.01	0.00
14	4.64	4.64	-0.01	0.00
15	4.81	4.81	-0.01	0.00
16	4.68	4.67	-0.01	0.00
17	4.75	4.83	0.08	0.02

From these results, Table 40 indicated that the largest residual to actual response variable ratio is only 0.02.

From the lack of scatter in the residual plot (Figure 22) and the insignificance of the residual ratio, the model given by Equation 25 fitted the data.

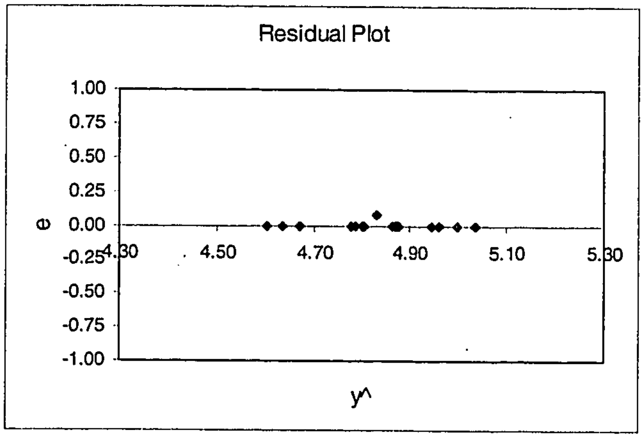

Figure 22: Residual Plot 1 for Case Study 1b

Insignificant parameters were again eliminated from the model. The same procedure was used as above with the SSR. Figure 23 shows the plot of the SSR versus the number of parameters within the model. From this plot is was decided to carry parameters C_1, C_3, C_4, C_6, C_7, C_{15}, C_{16}, C_{27} over to the next stage of parameter reduction testing. The intermediate model containing these parameters is shown in Equation 26.

$$\hat{y} = 4.83 - 0.02x_1 - 0.06x_3 - 0.04x_4 - 0.05x_6 + 0.02x_7 - 0.02x_1x_5 + 0.04x_1x_6 - 0.05x_2x_7 \quad [26]$$

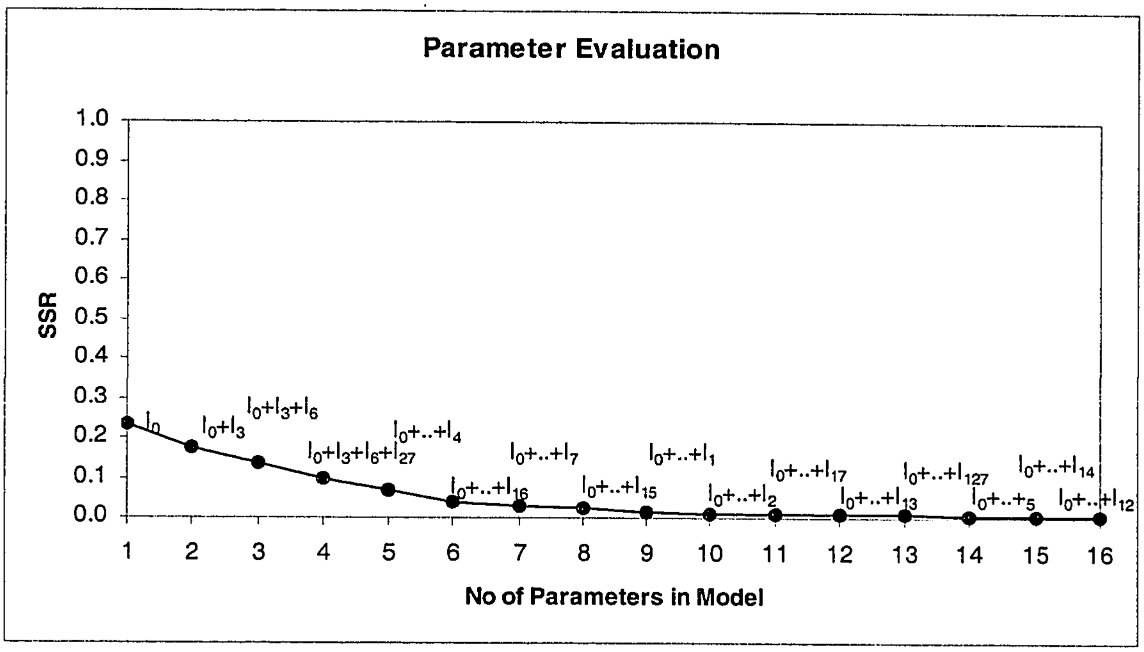

Figure 23: Parameter Evaluation Plot 1 for Case Study 1b

The residual plot for this model is shown in Figure 24.

Due to the lack of scatter in this plot as well as the largest ratio of residual to actual response variable being 0.02, it was decided that the model given in Equation 26 fit the data. Parameter l_1 was then removed from the model to give Equation 27.

$$\hat{y} = 4.83 - 0.06x_3 - 0.04x_4 - 0.05x_6 + 0.02x_7 - 0.02x_1x_5 + 0.04x_1x_6 - 0.05x_2x_7 \quad [27].$$

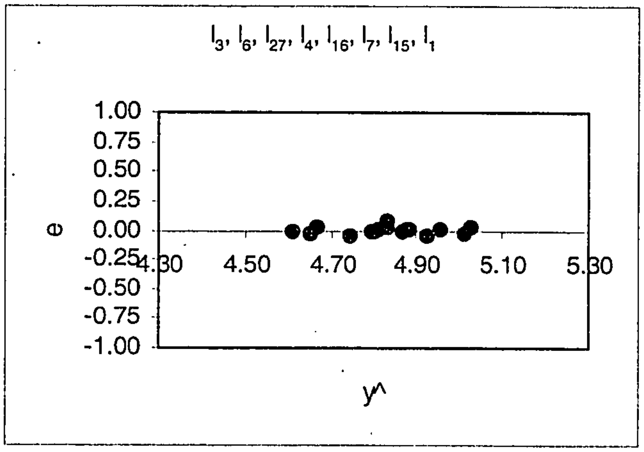

Figure 24: Residual Plot 2 for Case Study 1b

The residual plot for this new model is shown in Figure 25.

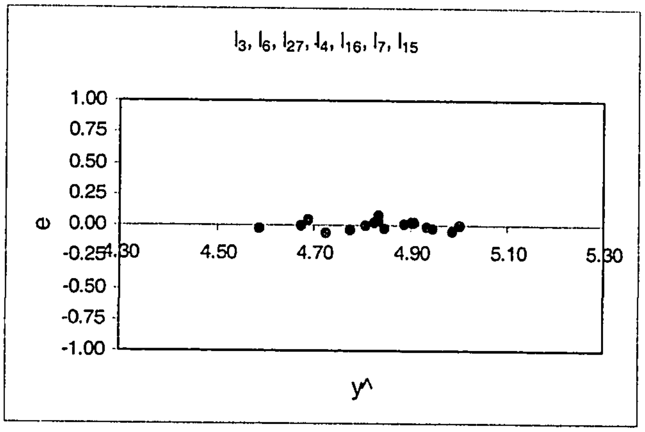

Figure 25: Residual Plot 3 for Case Study 1b

The largest residual ratio created from this model was 0.02 and because of the lack of scatter, it was decided that Equation 27 fit the data and parameter ℓ_1 was then removed. This procedure was repeated by removing parameters ℓ_{15}, ℓ_7, ℓ_{16}, ℓ_4, ℓ_{27} and ℓ_6. The residual plots for the new models created when each one of these parameters are removed can be seen in Figures 26, 27, 28, 29, 30, 31.

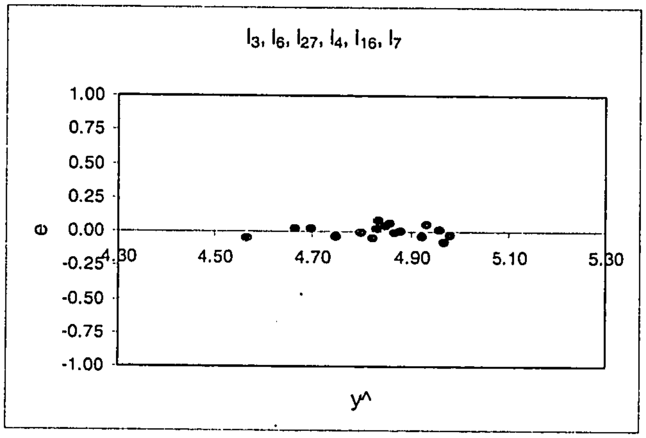

Figure 26: Residual Plot 4 for Case Study 1b

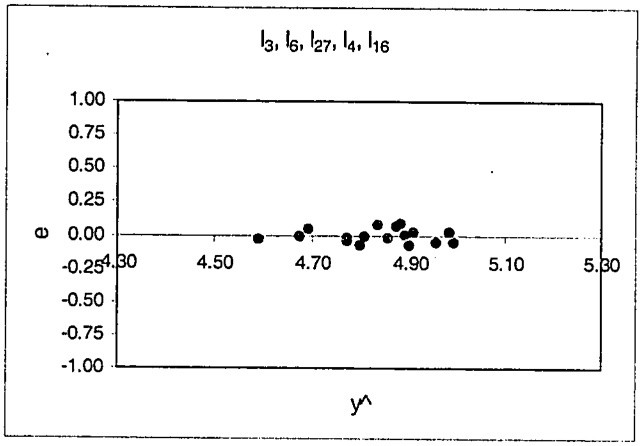

Figure 27: Residual Plot 5 for Case Study 1b

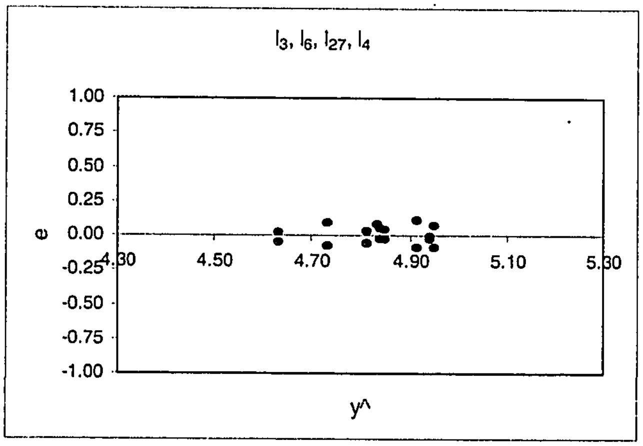

Figure 28: Residual Plot 6 for Case Study 1b

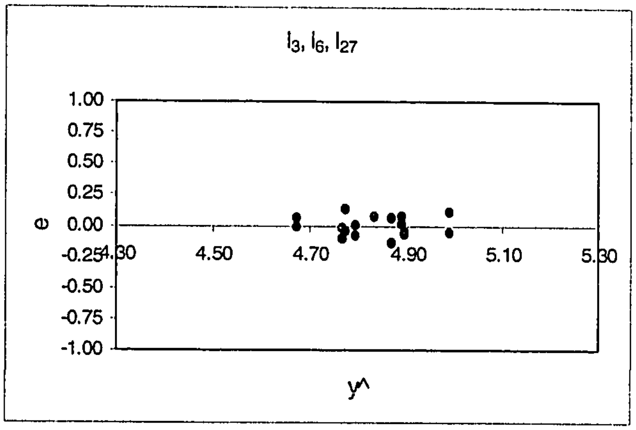

Figure 29: Residual Plot 7 for Case Study 1b

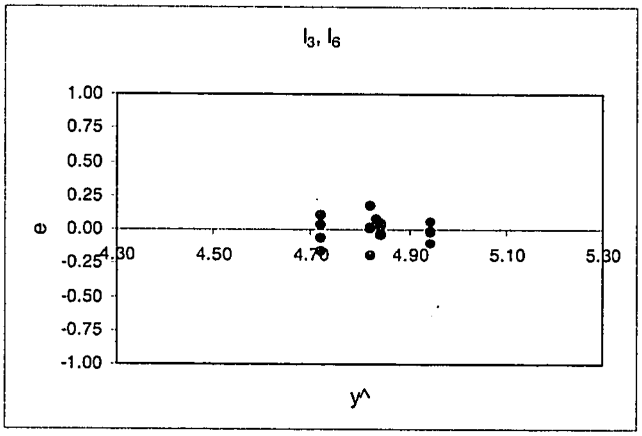

Figure 30: Residual Plot 8 for Case Study 1b

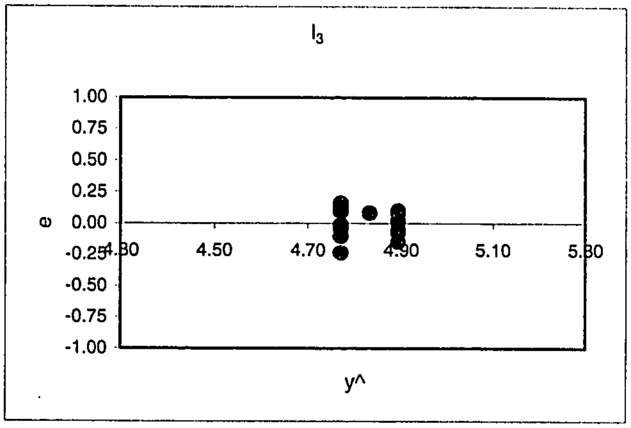

Figure 31: Residual Plot 9 for Case Study 1b

Also, the largest residual ratios created when each of these parameters were removed from the model are given in Table 41.

Table 41: Evaluation of Parameters for Case Study 1b

Parameter Removed	Largest Residual Ratio
ℓ_{15}	0.02
ℓ_{7}	0.02
ℓ_{16}	0.02
ℓ_{4}	0.03
ℓ_{27}	0.04
ℓ_{6}	0.05

From the residual plots and the residual ratios, it was decided that the data could be described by the minimized model given by Equation 28. Comparison of this model with the 5-parameter model indicated that both N-recycle and anoxic HRT were sensitive model parameters for the MUCT process.

$$\hat{y} = 4.83 - 0.06x_3 - 0.05x_6 \qquad [28]$$

This planar model could be used with a steepest descent procedure to find the direction and ultimately, the location of the minimum TN concentration. Note that the variables not included in Equation 28 were set to their centre point values shown in Table 37. Table 41 summarizes the steepest descent procedure used for this data set.

Table 42: Steepest Descent Strategy for Case Study 1b

	x_3 Nitrified Recycle, % Q	x_6 2nd Anoxic HRT, h	y Effluent TN, mg/L
Design Centre Point	1850	11.58	
Value of One Coded Unit	150	0.18	
Steepest Descent Direction (Coded units)	-0.06	-0.05	
Steepest Descent Direction (Original units)	-9.2	-0.009	
Steepest Descent Direction (Original units)	50	0.049	
Design Centre Point	1850	11.580	
	1900	11.629	4.70
	1950	11.679	4.67
	2000	11.728	4.65
	2050	*11.778*	*4.63*
	2100	*11.827*	*4.63*
	2150	11.877	4.65

From these results it can be seen that the minimum TN concentration was approximately 4.6 mg/L. One could continue with another set of runs using a third operating region, however, this minimum value for TN concentration was located just outside the tested operating region. Also, there was less than a 0.1 mg/L change in concentration along the direction of steepest descent. In practice, such a small change would be considered irrelevant. ROPEC currently sees a standard deviation in final TKN concentration of around 3 mg/L. For these reasons, it was concluded that the MUCT process at 20°C with a high primary effluent concentration is capable of producing a final effluent with a TN concentration of approximately 4.6 mg/L. It is important to note that although this concentration falls below the required 5 mg/L, it was found by neglecting the final sP concentration. Therefore, if the plant had only to worry about meeting nitrogen limits and not phosphorous limits, this process at the given conditions could satisfy the regulations.

The following cases listed below followed the approach laid out in this case study to find the optimum operating conditions.

Table 43: Cases that Followed Similar Approach to Case Study 1

Case #	Process	Temperature, °C	Primary Effluent Concentration Range	Response Variable Being Minimized
4	A^2/O	10°C	Medium	TN
13	A^2/O	20°C	Medium	TN
16	A^2/O	20°C	High	TN
18	A^2/O	20°C	High	TN + sP
20	MB	10°C	Low	sP
21	MB	10°C	Low	TN + sP
31	MB	20°C	Medium	TN
32	MB	20°C	Medium	sP
33	MB	20°C	Medium	TN + sP
34	MB	20°C	High	TN
51	MUCT	20°C	Medium	TN + sP
52	MUCT	20°C	High	TN
54	MUCT	20°C	High	TN + sP

4.2 Case Study #2: MB Process

Case study #1 demonstrated the most common approach used for determining the optimum operating conditions for the 54 cases. Unfortunately, not all cases went as smoothly. The following two case studies explain alternate methods that were used to find the location of the minimum response variables when problems were encountered with the common approach. The main source of problems was a result of using a computer simulation program to generate data as opposed to gathering data in the laboratory.

Case Study #2 examines the MB process at 10°C with a low primary effluent concentration. As with case study #1, the first step in the optimization process was to establish the number and range of the input variables. As mentioned previously for the MB process, there were seven input variables.

Table 44: Input Variables for MB Process

x_1	Total Recycle
x_2	Internal Recycle
x_3	Anaerobic Zone HRT
x_4	1st Anoxic Zone HRT
x_5	1st Aerobic Zone HRT
x_6	2nd Anoxic Zone HRT
x_7	2nd Aerobic Zone HRT

The next step was to establish the operating ranges for each of the seven variables. The operating region for this case study as well as the coded variables can be seen in Table 45.

Table 45: Operating Ranges for Input Variables for Case Study 2a

	-1	0	1
x_1, -	0.45	0.50	0.55
x_2, % Q	330	350	370
x_3, h	1.32	1.44	1.56
x_4, h	2.76	2.88	3.00
x_5, h	2.76	2.88	3.00
x_6, h	1.32	1.44	1.56
x_7, h	0.36	0.48	0.60

Next the 2^{7-3} design was set up and data gathered for the operating region.

For this case study, the response variable to be minimized was the final combined concentration of sP and TN, y_{TN+sP}. As with all other cases, the influent flow rate was constant at 100,000 m^3/d, the secondary clarifier surface area was fixed at 8,000 m^2 and the primary effluent concentrations of $cBOD_5$, TSS, TP and TKN were kept constant at 163 mg/L, 160 mg/L, 2.7 mg/L and 17.2 mg/L, respectively. For the initial set of experimental runs, the pumped flow from the secondary clarifier underdrain was maintained at 200 m^3/d and the air flow rate to the aerobic zone in the reactor was 1.85×10^6 m^3/d with 80 % of the air going into the first aerobic zone and 20 % to the second aerobic zone. This ensured a DO concentration in both aerobic zones greater than 2.0 mg/L and a MLSS concentration in the reactors above 2000 mg/L. Once the variables were set, the experimental runs were carried out and the following response variables generated.

Table 46: 2^{7-3} Design and Response for Case Study 2a

run	x_1	x_2	x_3	x_4	x_5	x_6	x_7	y_{TN+SP}, mg/L
1	-1	-1	-1	-1	-1	-1	-1	2.14
2	1	-1	-1	-1	1	1	-1	2.14
3	-1	1	-1	-1	1	1	1	2.29
4	1	1	-1	-1	-1	-1	1	2.32
5	-1	-1	1	-1	1	-1	1	2.20
6	1	-1	1	-1	-1	1	1	2.11
7	-1	1	1	-1	-1	1	-1	2.03
8	1	1	1	-1	1	-1	-1	2.09
9	-1	-1	-1	1	-1	1	1	2.15
10	1	-1	-1	1	1	-1	1	2.33
11	-1	1	-1	1	1	-1	-1	2.13
12	1	1	-1	1	-1	1	-1	2.09
13	-1	-1	1	1	1	1	-1	2.02
14	1	-1	1	1	-1	-1	-1	2.04
15	-1	1	1	1	-1	-1	1	2.12
16	1	1	1	1	1	1	1	2.15
17	0	0	0	0	0	0	0	2.11

Using this data and Equation 9 for least squares regression, the following model was fitted to the data.

$$\begin{aligned}\hat{y}_{TN} &= 2.14 + 0.01x_1 + 0.01x_2 - 0.05x_3 - 0.02x_4 + 0.02x_5 - 0.03x_6 + 0.06x_7 \\ &- 0.00x_1x_2 - 0.01x_1x_3 + 0.01x_1x_4 - 0.00x_1x_5 - 0.01x_1x_6 + 0.01x_1x_7 \\ &+ 0.01x_2x_7 - 0.00x_1x_2x_7\end{aligned} \qquad [29]$$

Using Equation 29, the predicted response variables, residuals and residual ratios could be calculated. See Table 47.

Table 47: Predicted Response, Residuals and Residual Ratios for Case Study 2a

Run #	Actual Response Variable, mgN and P/L	Predicted Response Variable, mgN and P/L	Residual, mgNand P/L	e/y_{TN}
1	2.14	2.14	0.00	0.00
2	2.14	2.17	0.00	0.00
3	2.29	2.29	0.00	0.00
4	2.32	2.32	0.00	0.00
5	2.20	2.20	0.00	0.00
6	2.11	2.10	0.00	0.00
7	2.03	2.02	0.00	0.00
8	2.09	2.09	0.00	0.00
9	2.15	2.15	0.00	0.00
10	2.33	2.33	0.00	0.00
11	2.13	2.13	0.00	0.00
12	2.09	2.08	0.00	0.00
13	2.02	2.01	0.00	0.00
14	2.04	2.04	0.00	0.00
15	2.12	2.11	0.00	0.00
16	2.15	2.15	0.00	0.00
17	2.11	2.14	0.03	0.02

From either Table 47 or the residual plot, Figure 32 it was apparent that Equation 29 showed good correlation with the data. The only datum point or residual that showed signs of lack of fit was the centre point run. Since the residual ratio for Run #17, the centre point run, was below 0.05, the model was concluded to fit the data.

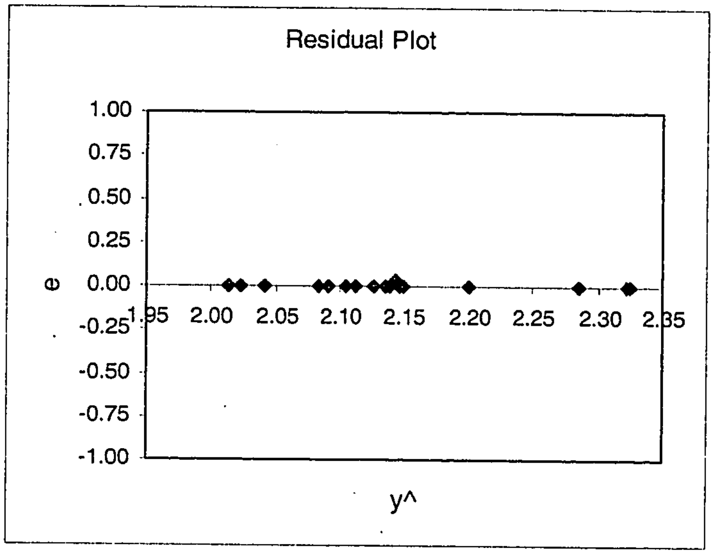

Figure 32: Residual Plot 1 for Case Study 2a

The next step was to determine the significance of each parameter within the model. The SSR for the model shown in Equation 29 was calculated to be 0.001. Figure 33 illustrates the decrease in SSR as each parameter was added to the model.

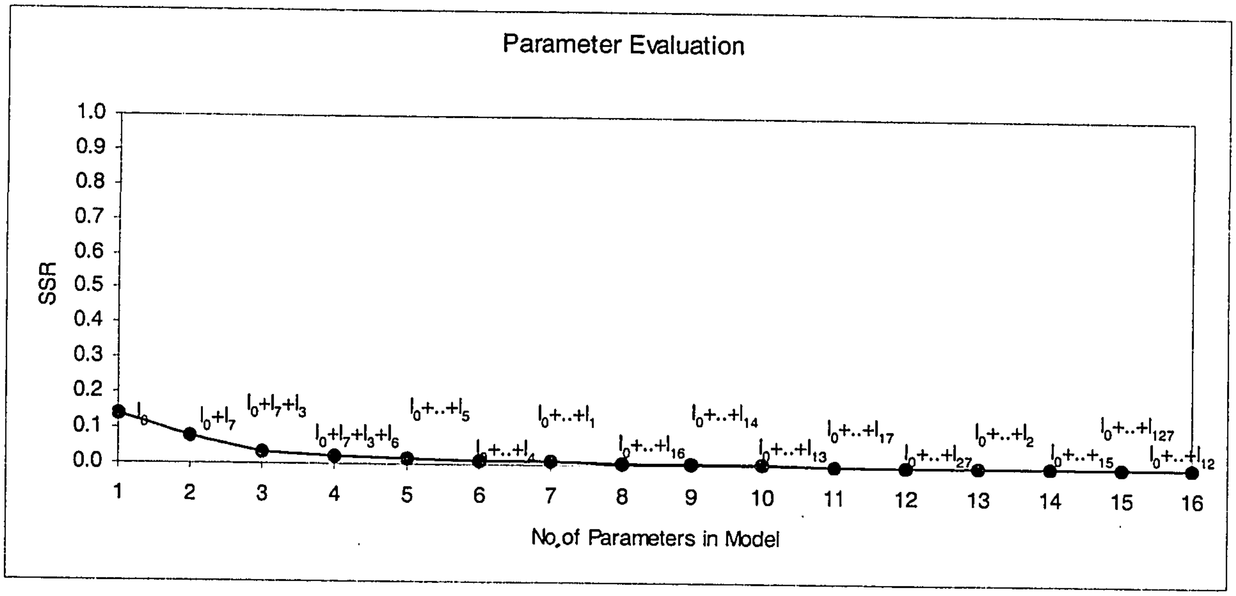

Figure 33: Parameter Evaluation Plot 1 for Case Study 2a

From this plot, parameters, ℓ_7, ℓ_3, ℓ_6, were considered possibly significant. The new reduced 3-parameter model is shown in Equation 30.

$$\hat{y}_{TN} = 2.14 - 0.05x_3 - 0.03x_6 + 0.06x_7 \qquad [30]$$

Using this new model, a residual plot was constructed and shown in Figure 34. There was little scatter in the residuals and the magnitude of the residuals was very small. As before, the residuals were compared to the actual response variables for a given run. Using Equation 30, the largest ratio of residual to actual response variable is 0.04. Therefore, it was concluded that this new model fit the data. The next step was to remove another parameter from the model. Since parameter ℓ_6 was the furthest down on the parameter plot from Figure 45, it was the next parameter to be removed from the model. The new model is shown in Equation 31.

$$\hat{y}_{TN} = 2.14 - 0.05x_3 + 0.06x_7 \qquad [31]$$

The residual plot for this model is shown in Figure 35.

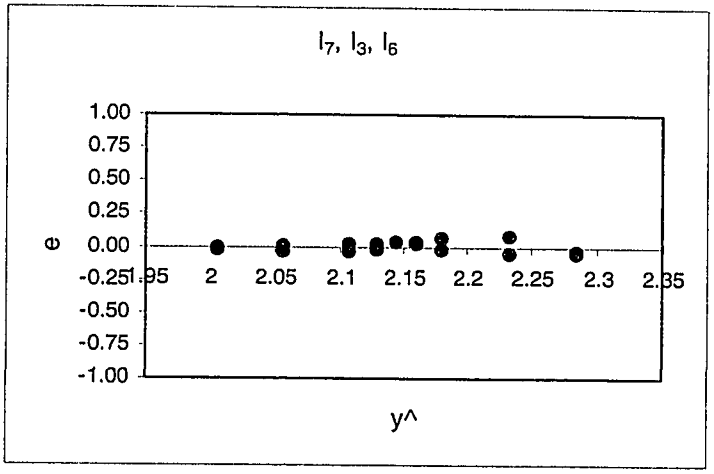

Figure 34: Residual Plot 2 for Case Study 2a

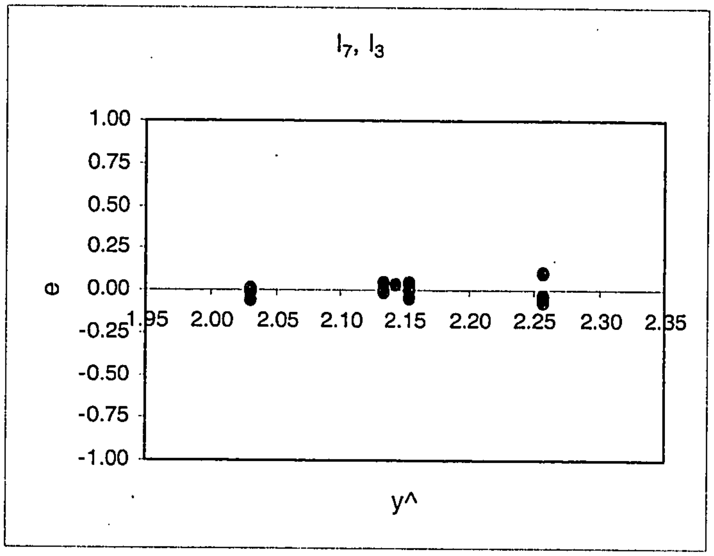

Figure 35: Residual Plot 3 for Case Study 2a

This residual plot showed a small amount of scatter and the largest residual to actual response variable ratio was 0.05. It was concluded that parameter ζ_6 was significant and that the model shown in Equation 31 should be the model used to describe the data.

Since the model in Equation 31 was a planar model, the following procedure could be used to find the direction and ultimately the location of the optimum operating point. Input variables, x_1, x_2, x_4, x_5 were not included in the final model, and so were set to their centre point values of 0.50, 350 % Q, 2.88 h and 2.88 h, respectively for the steepest descent procedure. The optimum values for the remaining two input variables was found using a steepest descent procedure. Table 48 is used to illustrate this procedure.

Table 48: Steepest Descent Procedure for Case Study 2a

	x_3 Anaerobic HRT, h	x_6 2nd Anoxic HRT, h	x_7 Aerobic HRT, h
Design Centre Point	1.44	1.44	0.48
Value of One Coded Unit	0.12	0.12	0.12
Steepest Descent Direction (Coded units)	-0.05	-0.03	0.06
Steepest Descent Direction (Original units)	-0.006	-0.003	0.007
Steepest Descent Direction (Original units)	0.048	0.024	-0.058

Table 49 shows the results of the steepest descent procedure for this trial.

Table 49: Results of Steepest Descent Procedure for Case Study 2a

	x_3 Anaerobic HRT, m^3	x_6 2nd Anoxic HRT, m^3	x_7 Aerobic HRT, m^3	y Effluent TN + sP, mg/L
Design Centre Point	1.440	1.440	0.480	
	1.488	1.464	0.422	2.07
	1.536	1.488	0.365	2.03
	1.584	*1.512*	*0.307*	***2.02***
	1.632	*1.536*	*0.250*	***2.02***
	1.680	1.560	0.192	2.05

According to these results, the minimum TN + sP concentration was approximately 2.02 mg/L. However, the optimum value for the aerobic zone HRT was around 0.29 h, which was below the lower limit of the tested operating range of 0.36 h. Therefore it was decided that the model shown in Equation 31 should not be trusted to accurately represent the data and that another set of experimental trials should be run. Also, since five of the input variables were not significant within the first operating region, it was decided to expand the ranges for variables, x_1, x_2, x_4 and x_5 for the next set of runs. The new operating region is shown in Table 50.

Table 50: Coded Variables for Design in Case Study 2b

	-1	0	1
x_1, -	0.45	0.50	0.55
x_2, % Q	320	350	380
x_3,h	1.44	1.56	1.68
x_4, h	2.64	2.88	3.12
x_5, h	2.64	2.88	3.12
x_6, h	1.20	1.44	1.68
x_7, h	0.24	0.36	0.48

The experimental design along with the actual response variables can be seen in Table 51.

Table 51: 2^{7-3} Design and Response for Case Study 2b

run	x_1	x_2	x_3	x_4	x_5	x_6	x_7	y_{TN+sP}, mg/L
1	-1	-1	-1	-1	-1	-1	-1	2.11
2	1	-1	-1	-1	1	1	-1	2.06
3	-1	1	-1	-1	1	1	1	2.17
4	1	1	-1	-1	-1	-1	1	2.19
5	-1	-1	1	-1	1	-1	1	2.18
6	1	-1	1	-1	-1	1	1	2.04
7	-1	1	1	-1	-1	1	-1	2.23
8	1	1	1	-1	1	-1	-1	2.08
9	-1	-1	-1	1	-1	1	1	2.09
10	1	-1	-1	1	1	-1	1	2.25
11	-1	1	-1	1	1	-1	-1	2.08
12	1	1	-1	1	-1	1	-1	2.21
13	-1	-1	1	1	1	1	-1	2.03
14	1	-1	1	1	-1	-1	-1	2.17
15	-1	1	1	1	-1	-1	1	2.07
16	1	1	1	1	1	1	1	2.07
17	0	0	0	0	0	0	0	2.05

The least squares model that was fitted to this data is shown in Equation 32.

$$\begin{aligned}\hat{y}_{TN} &= 2.12 + 0.00x_1 + 0.01x_2 - 0.02x_3 - 0.00x_4 - 0.01x_5 - 0.01x_6 + 0.01x_7 \\ &- 0.01x_1x_2 - 0.03x_1x_3 + 0.05x_1x_4 - 0.01x_1x_5 - 0.02x_1x_6 - 0.00x_1x_7 \\ &- 0.02x_2x_7 + 0.01x_1x_2x_7\end{aligned} \qquad [32]$$

Table 52 shows the predicted response using the model, the actual response, the residuals and the ratio of residual to actual response.

Table 52: Response Variables, Residuals and Residual Ratios for Case Study 2b

Run #	Actual Response Variable, y_{TN}, mgN/L	Predicted Response Variable, $\hat{y}_{TN}$, mgN/L	Residual,e, mgN/L	e/y_{TN}
	2.11	2.10	0.00	0.00
	2.06	2.05	0.00	0.00
3	2.17	2.16	0.00	0.00
4	2.19	2.18	0.00	0.00
5	2.18	2.18	0.00	0.00
6	2.04	2.04	0.00	0.00
7	2.23	2.22	0.00	0.00
8	2.08	2.08	0.00	0.00
9	2.09	2.08	0.00	0.00
10	2.25	2.24	0.00	0.00
11	2.08	2.07	0.00	0.00
12	2.21	2.21	0.00	0.00
13	2.03	2.03	0.00	0.00
14	2.17	2.17	0.00	0.00
15	2.07	2.07	0.00	0.00
16	2.07	2.07	0.00	0.00
17	2.05	2.12	0.08	0.04

From these results, one can see that the largest residual to actual response variable ratio was only 0.04 (Table 52). The lack of scatter of the residual plot (Figure 36) and the insignificance of the residual ratio indicates that the model given in Equation 32 fitted the data.

The next step was to attempt to eliminate possible insignificant parameters from the model. The same procedure was used as above with the SSR. Figure 37 shows the plot of the SSR versus the model with the addition of each parameter.

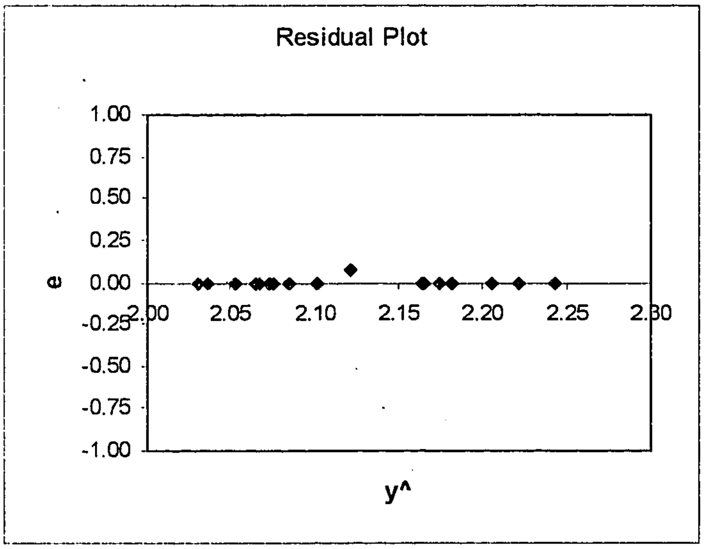

Figure 36: Residual Plot 1 for Case Study 2b

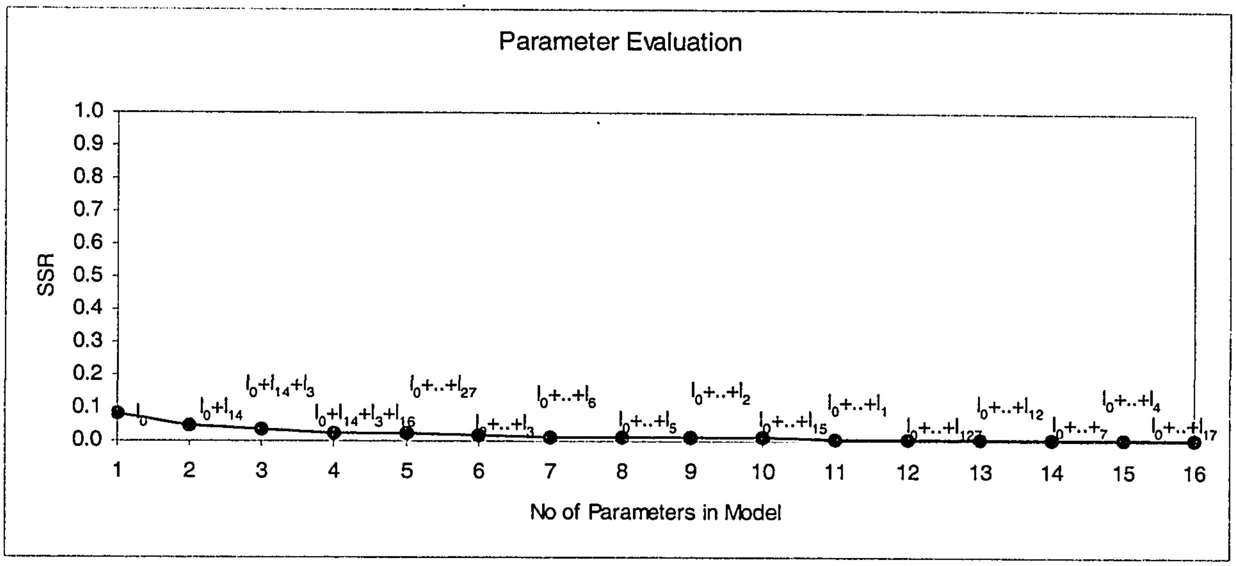

Figure 37: Parameter Evaluation Plot 1 for Case Study 2b

This plot indicated that the most important parameter after ℓ_0 was ℓ_{14}. If the final model contained interaction terms then curvature was present in the data and the model was not planar. This was also supported by the relatively large discrepancy between ℓ_0 and the centre point result. In order to find the location of the minimum response variable using the steepest descent procedure, a planar model was necessary. The only way to have a planar model in this case was to get rid of all parameters except ℓ_0. The residual plot for the model $y_{TN+sP} = 2.12$ is shown in Figure 38.

This model showed a significant amount of scatter. Also, the maximum ratio of residual to actual response variable is 0.06. For these reasons, it was concluded that the model was not planar and further experimental runs would be required to find the curved surface plot and eventually the location of the minimum response variable. However, for this operating region, the values of the response variable, y_{TN+sP} only ranged from 2.03 to 2.25 mg/L. This was only a difference of 0.21 mg/L, which was small compared to typical ROPEC standard deviations for TN and sP. In 1997, the standard deviation for effluent TN and sP concentration was 2.4 mgN/L and 0.2 mgP/L, respectively. Although ROPEC's standard deviation may be a result of changes in variables not considered in this study, it still gives an indication of the practical insignificance of 0.21 mg/L. Consequently, the surface for the given operating region was concluded to be flat with the minimum response variable for the region chosen as the minimum value within this trial which was y_{TN+sP} = 2.03 mg/L (TN = 3.6 mgN/L, sP = 0.5 mgP/L). Since both the final TN concentration and sP concentration were below 5 mgN/L and 1 mgP/L, it was concluded that the MB process at 10°C with low primary effluent concentrations was capable of meeting federal regulations with respect to TN and sP effluent concentrations.

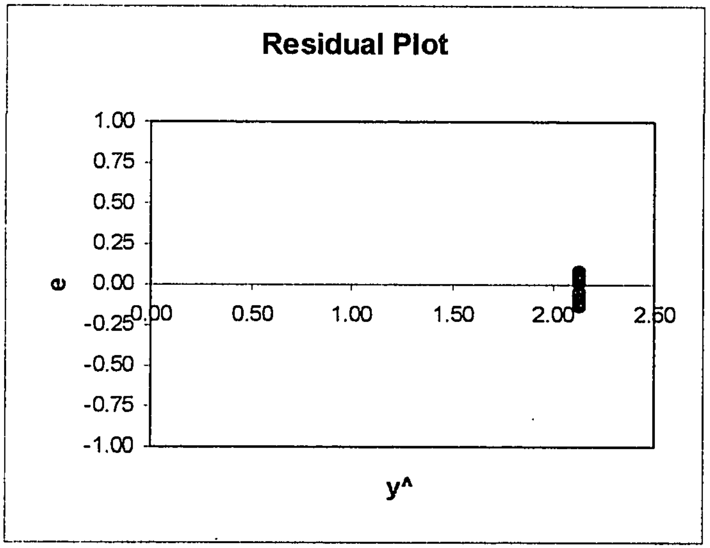

Figure 38: Residual Plot 2 for Case Study 2b

Other cases that used a similar approach as Case Study #2 are given in Table 53.

Table 53: Cases that Followed Similar Approach to Case Study 2

Case #	Process	Temperature, °C	Primary Effluent Concentration Range	Response Variable Being Minimized
1	A^2/O	10°C	Low	TN
2	A^2/O	10°C	Low	sP
3	A^2/O	10°C	Low	TN + sP
4	A^2/O	10°C	High	TN
10	A^2/O	20°C	Low	TN
11	A^2/O	20°C	Low	sP
12	A^2/O	20°C	Low	TN + sP
17	A^2/O	20°C	High	sP
19	MB	10°C	Low	TN
22	MB	10°C	Medium	TN
24	MB	10°C	Medium	TN + sP
25	MB	10°C	High	TN
27	MB	10°C	High	TN + sP
28	MB	20°C	Low	TN
29	MB	20°C	Low	sP
6	MB	20°C	High	TN + sP
37	MUCT	10°C	Low	TN
39	MUCT	10°C	Low	TN + sP

40	MUCT	10°C	Medium	TN
42	MUCT	10°C	Medium	TN + sP
45	MUCT	10°C	High	TN + sP
46	MUCT	20°C	Low	TN
47	MUCT	20°C	Low	sP
48	MUCT	20°C	Low	TN + sP
49	MUCT	20°C	Medium	TN
50	MUCT	20°C	Medium	sP

4.3 Case Study #3: A^2/O Process

The third case study examined the A^2/O process at 10°C with a medium primary effluent concentration. The main difficulty with this case was a result of inexplicable zero concentrations of nitrate/nitrite. As with all cases, the first step in the optimization process was to establish the number and range of the input variables. As mentioned previously the A^2/O process had five input variables.

Table 54: Input Variables for A^2/O Process

x_1	Total Recycle
x_2	Nitrified Recycle
x_3	Anaerobic HRT
x_4	Anoxic HRT
x_5	Aerobic HRT

Based on literature values for the A^2/O process, the operating ranges were chosen as follows.

Table 55: Operating Ranges for Input Variables for Case Study 3a

	-1	0	1
x_1, -	0.80	0.85	0.90
x_2, % Q	950	1000	1050
x_3, h	1.08	1.20	1.32
x_4, h	7.44	7.68	7.92
x_5, h	4.08	4.32	4.56

The variables were coded, and the data for the2^{5-1} design were generated for the operating region. The response variable being minimized for this case, was effluent sP, y_{sP}. As in all runs the influent flow rate was kept constant at 100,000 m^3/d, the secondary clarifier surface area at 8000 m^2 and $cBOD_5$, TSS, TP and TKN were 325, 320, 5.33 and 34.2 mg/L, respectively. Pumped flow from the secondary clarifier under drain was 650 m^3/d and the air flow rate to the aerobic zone was 3.5×10^6 m^3/d to ensure a DO concentration greater than 2.0 mg/L and a MLSS concentration in the reactor above 2000 mg/L. The following response for the 2^{5-1} design is given in Table 56.

Table 56: 2^{7-3} Design and Response for Case Study 3a

run	x_1	x_2	x_3	x_4	x_5	y_{sP}, mg/L
1	-1	-1	-1	-1	1	1.85
2	1	-1	-1	-1	-1	0.84
3	-1	1	-1	-1	-1	1.03
4	1	1	-1	-1	1	3.86
5	-1	-1	1	-1	-1	0.24
6	1	-1	1	-1	1	1.37
7	-1	1	1	-1	1	1.83
8	1	1	1	-1	-1	0.52
9	-1	-1	-1	1	-1	0.19
10	1	-1	-1	1	1	1.65
11	-1	1	-1	1	1	2.37
12	1	1	-1	1	-1	0.43
13	-1	-1	1	1	1	0.62
14	1	-1	1	1	-1	0.14
15	-1	1	1	1	-1	0.22
16	1	1	1	1	1	1.32
17	0	0	0	0	0	1.02

Using this data and Equation 33 for least squares regression, the following model was fitted.

$$\begin{aligned}\hat{y}_{TN} &= 1.15 + 0.11x_1 + 0.29x_2 - 0.37x_3 - 0.29x_4 + 0.70x_5 - 0.03x_6 - 0.06x_7 \\ &- 0.09x_1x_2 + 0.08x_1x_3 - 0.10x_1x_4 - 0.08x_1x_5 + 0.19x_1x_6 + 0.08x_1x_7 \\ &- 0.20x_2x_7 - 0.08x_1x_2x_7\end{aligned} \qquad [33]$$

Using Equation 33, the following set of predicted response variables, residuals and residual ratios could be calculated. See Table 57.

Table 57: Predicted Response Variables, Residuals and Residual Ratios for Case Study 3a

Run #	Actual Response Variable, mgN/L	Predicted Response Variable, mgN/L	Residual, mgN/L	e/y_{TN}
1	1.85	1.84	-0.01	0.00
2	0.84	0.83	-0.01	0.01
3	1.03	1.03	-0.01	0.01
4	3.86	3.85	-0.01	0.00
5	0.24	0.23	-0.01	0.03
6	1.37	1.36	-0.01	0.01
7	1.83	1.82	-0.01	0.00
8	0.52	0.52	-0.01	0.02
9	0.19	0.18	-0.01	0.04
10	1.65	1.64	-0.01	0.00
11	2.37	2.36	-0.01	0.00
12	0.43	0.42	-0.01	0.02

Run #	Actual Response Variable, mgN/L	Predicted Response Variable, mgN/L	Residual, mgN/L	e/y_{TN}
13	0.62	0.62	-0.01	0.01
14	0.14	0.13	-0.01	0.06
15	0.22	0.21	-0.01	0.04
16	1.32	1.31	-0.01	0.01
17	1.02	1.15	0.13	0.13

From Figure 39, the residual plot of the data, one could see a significant amount of scatter in the data and the largest residual ratio was 0.13 (Table 57) from Run #17, the centre point.

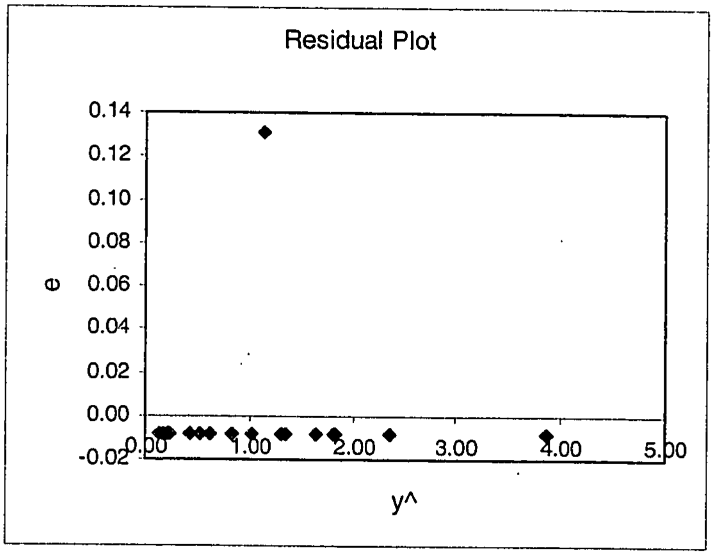

Figure 39: Residual Plot 1 for Case Study 3a

This was a larger percentage than acceptable compared with the 5 % limit. Equation 33 was concluded to not fit the data. In order to proceed and find the optimum operating conditions, there were two methods to consider. The first option was to attempt to fit a second order model to the data. The lack of fit in Equation 33 could have been due to curvature in the data and the need for quadratic terms in the model. In order to pursue this option, further experimental runs would have to be performed in order to gather enough data to cover the entire operating region so that quadratic terms could be fitted to the data. There was no guarantee that this method would have work and that a good model (that is, one that would fit the data with an insignificant amount of lack of fit) could have been found with a second order model. The second option was to stick with a linear model and redo the experimental trial using a narrower operating region.

The location of the minimum response variable on a planar surface could then be obtained by following along this planar surface in the direction of steepest descent. In order to do this, a linear, planar model was required to describe the data. In previous case studies, planar models were found and used to travel along the direction of steepest descent to get closer to the minimum. If a small enough operating ranges are used, planar models could be found to perform the tasks. Because there was curvature present in the operating region described in Table 55, the location of the minimum response variable was present within the given region. A smaller operating region was chosen so that only one side of the surface (planar surface) was modeled then we traveled along this surface to get closer to the optimum operating variables. The operating region could be narrowed arbitrarily, however, since the corresponding sP response variables were known for each run, the low values of sP concentration could be located as a guide to the centre of the new operating region. Table 58 illustrates how to proceed with devising a new operating region.

Table 58: Experimental Results for Case Study 3a

run	x_1	x_2, % Q	x_3, m^3	x_4, m^3	x_5, m^3	y_{sP}, mg/L
1	0.80	950	1.08	7.44	4.56	1.85
2	*0.90*	*950*	*1.08*	*7.44*	*4.08*	*0.84*
3	0.80	1,050	1.08	7.44	4.08	1.03
4	0.90	1,050	1.08	7.44	4.56	3.86
5	*0.80*	*950*	*1.32*	*7.44*	*4.08*	*0.24*
6	0.90	950	1.32	7.44	4.56	1.37
7	0.80	1,050	1.32	7.44	4.56	1.83
8	*0.90*	*1,050*	*1.32*	*7.44*	*4.08*	*0.52*
9	*0.80*	*950*	*1.08*	*7.92*	*4.08*	*0.19*
10	0.90	950	1.08	7.92	4.56	1.65
11	0.80	1,050	1.08	7.92	4.56	2.37
12	*0.90*	*1,050*	*1.08*	*7.92*	*4.08*	*0.43*
13	*0.80*	*950*	*1.32*	*7.92*	*4.56*	*0.62*
14	*0.90*	*950*	*1.32*	*7.92*	*4.08*	*0.14*
15	*0.80*	*1,050*	*1.32*	*7.92*	*4.08*	*0.22*
16	0.90	1,050	1.32	7.92	4.56	1.32
17	0.85	1,000	1.20	7.68	4.32	1.02

All runs that produced a response under 1 mg/L are highlighted. It is unkown what effect total recycle, x_1, had on the response variable according to these results as there was the same number of $y_{sP} = 0.80$ highlighted as there were of $y_{sP} = 0.90$. The operating range for x_1 was maintained in the next trial. For the nitrified recycle, x_2, the response variable was slightly lower at values of 950 % Q than at values of 1050 %

Q. Therefore, the operating range for x_2 was narrowed to 960 to 1040 % Q. The anaerobic zone HRT, x_3, seemed to give lower response values at values of 1.32 h as opposed to 1.08 h. So that, the new operating range for x_3 was chosen to be 1.20 to 1.37 h. The anoxic zone HRT, x_4, showed lower values of y_{sP} at 7.92 than at 7.44 h and therefore the operating range was chosen for x_4 as 7.80 – 8.04 h. Finally, the aerobic zone HRT, x_5, showed that lower values of the final sP concentration were achieved with HRT of 4.08 h as opposed to 4.56 h. For this reason the operating range for x_5 was chosen to be 3.96 to 4.20 h. The summarized operating region can be seen in Table 59.

Table 59: Operating Region for Case Study 3b

	-1	0	1
x_1, -	0.80	0.85	0.90
x_2, % Q	960	1000	1040
x_3, h	1.20	1.28	1.37
x_4, h	7.80	7.92	8.04
x_5, h	3.96	4.08	4.20

The experimental design along with the actual response variables can be seen in Table 60.

Table 60: 2^{5-1} Design and Response for Case Study 3b

run	x_1	x_2	x_3	x_4	x_5	y_{sP}, mgP/L
1	-1	-1	-1	-1	1	0.31
2	1	-1	-1	-1	-1	0.15
3	-1	1	-1	-1	-1	0.19
4	1	1	-1	-1	1	1.06
5	-1	-1	1	-1	-1	0.01
6	1	-1	1	-1	1	0.26
7	-1	1	1	-1	1	0.29
8	1	1	1	-1	-1	0.15
9	-1	-1	-1	1	-1	0.01
10	1	-1	-1	1	1	0.33
11	-1	1	-1	1	1	0.37
12	1	1	-1	1	-1	0.01
13	-1	-1	1	1	1	0.10
14	1	-1	1	1	-1	0.01
15	-1	1	1	1	-1	0.01
16	1	1	1	1	1	0.27
17	0	0	0	0	0	0.22

Throughout this work a common problem had arisen while using GPS-X software with the ASM2d model. Every so often, the final concentration of nitrate/nitrite droped off to zero and the final concentration of ammonia jumped up. It is unlikely that this behaviour would have be seen in an actual plant because of where and when this phenomenon occurred. For example, in the above set of experimental trials, several runs produced values of nitrate/nitrite concentration of zero. See Table 61.

Table 61: Experimental Results for Case Study 3b

run	x_1	x_2	x_3	x_4	x_5	y_{sP}, mgP/L	$y_{NO3/NO2}$, mgN/L	y_{NH3}, mgN/L
1	-1	-1	-1	-1	1	0.31	2.09	6.06
2	1	-1	-1	-1	-1	0.15	1.75	9.37
3	-1	1	-1	-1	-1	0.19	1.70	8.75
4	1	1	-1	-1	1	1.06	2.13	4.38
5	***-1***	***-1***	***1***	***-1***	***-1***	***0.01***	***0.00***	***30.98***
6	1	-1	1	-1	1	0.26	2.05	6.40
7	-1	1	1	-1	1	0.29	1.95	6.35
8	1	1	1	-1	-1	0.15	1.70	8.72
9	***-1***	***-1***	***-1***	***1***	***-1***	***0.01***	***0.00***	***31.06***
10	1	-1	-1	1	1	0.33	2.08	6.03
11	-1	1	-1	1	1	0.37	1.95	6.24
12	***1***	***1***	***-1***	***1***	***-1***	***0.01***	***0.00***	***31.13***
13	-1	-1	1	1	1	0.10	1.62	10.86
14	***1***	***-1***	***1***	***1***	***-1***	***0.01***	***0.00***	***31.19***
15	***-1***	***1***	***1***	***1***	***-1***	***0.01***	***0.00***	***31.06***
16	1	1	1	1	1	0.27	1.95	6.17
17	0	0	0	0	0	0.22	1.88	7.50

It is unknown whether this error came from problems related to ASM2d or the solving of the model using GPS-X. The programming code was not available to the user and therefore, it couldn't be determined if there was an error in the code. It was known that a numerical analysis technique was used to solve the complex model and that a trial and error technique was involved. There could have been problems with convergence for these runs. Regardless of the reasons, this data set was discarded because of potentially incorrect data. Each operating range for the five operating variables was decreased and the experiment was repeated. The new operating region is shown in Table 62.

Table 62: Operating Region for Case Study 3c

	-1	0	1
x_1, -	0.82	0.85	0.88
x_2, % Q	970	1000	1030
x_3, h	1.22	1.28	1.34
x_4, h	7.80	7.86	7.92
x_5, h	4.08	4.14	4.20

The experimental runs and response variables are shown in Table 63.

Table 63: Experimental Trial and Results for Case Study 3c

run	x_1	x_2	x_3	x_4	x_5	y_{SP}, mgP/L
1	-1	-1	-1	-1	1	0.30
2	1	-1	-1	-1	-1	0.22
3	-1	1	-1	-1	-1	0.34
4	1	1	-1	-1	1	0.45
5	-1	-1	1	-1	-1	0.13
6	1	-1	1	-1	1	0.29
7	-1	1	1	-1	1	0.32
8	1	1	1	-1	-1	0.25
9	-1	-1	-1	1	-1	0.18
10	1	-1	-1	1	1	0.41
11	-1	1	-1	1	1	0.57
12	1	1	-1	1	-1	0.29
13	-1	-1	1	1	1	0.20
14	1	-1	1	1	-1	0.11
15	-1	1	1	1	-1	0.16
16	1	1	1	1	1	0.35
17	0	0	0	0	0	0.30

The least squares model that was fitted to this data is shown in Equation 34.

$$\begin{aligned}\hat{y}_{TN} &= 0.29 + 0.01x_1 + 0.06x_2 - 0.06x_3 + 0.00x_4 + 0.07x_5 - 0.02x_6 + 0.01x_7 \\ &- 0.01x_1x_2 + 0.00x_1x_3 + 0.01x_1x_4 + 0.00x_1x_5 + 0.01x_1x_6 - 0.02x_1x_7 \\ &- 0.01x_2x_7 + 0.02x_1x_2x_7\end{aligned} \qquad [34]$$

Table 64 shows the predicted response using the model, the actual response, the residuals and the ratio of residual to actual response.

Table 64: Response Variables, Residuals and Residual Ratios for Case Study 3c

Run #	Actual Response Variable, y_{sP}, mgP/L	Predicted Response Variable, $y^\wedge_{sP}$, mgP/L	Residual,e, mgP/L	e/y_{sP}
1	0.30	0.30	0.00	0.00
2	0.22	0.22	0.00	0.00
3	0.34	0.34	0.00	0.00
4	0.45	0.45	0.00	0.00
5	0.13	0.14	0.00	0.00
6	0.29	0.29	0.00	0.00
7	0.32	0.32	0.00	0.00
8	0.25	0.25	0.00	0.00
9	0.18	0.18	0.00	0.00
10	0.41	0.41	0.00	0.00
11	0.57	0.57	0.00	0.00
12	0.29	0.30	0.00	0.00
13	0.20	0.20	0.00	0.00
14	***0.11***	***0.11***	***0.00***	***0.00***
15	0.16	0.17	0.00	0.00
16	0.35	0.35	0.00	0.00
17	0.30	0.29	-0.02	0.05

From Table 64 one can see that the largest residual to actual response variable ratio was 0.05 and from the residual plot in Figure 49 that there was very little scatter in the data. Consequently, it was decided that the model given by Equation 34 fitted the data.

Instead of continuing on in the usual fashion, it was decided to stop and report the minimum response variable to be 0.11 mgP/L. The regulations on sP in the final effluent require a concentration below 1 mg/L. Since, all values for this set of data were well below 1 mg/L, it was concluded that for the experimental operating range tested the A^2/O process at 10°C with medium primary effluent concentrations, was capable of achieving a final effluent with sP concentrations below 1 mg/L.

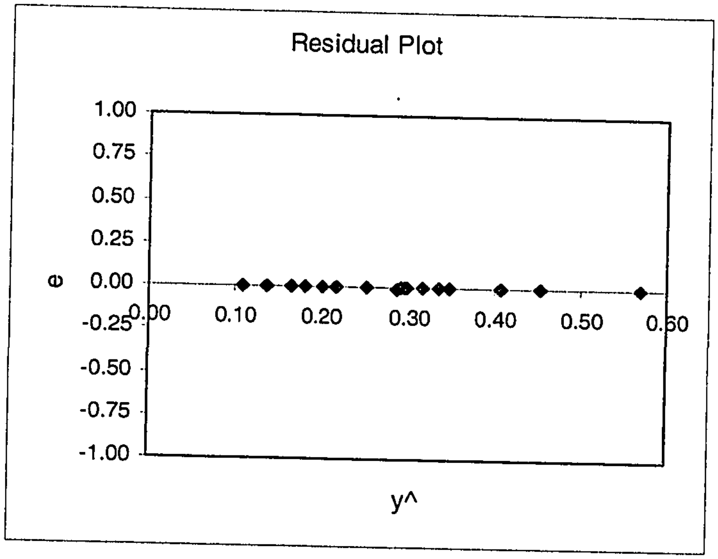

Figure 40: Residual Plot 1 for Case Study 3b

Table 65 lists other cases that followed a similar approach as Case Study 3 in finding the location of the optimum operating conditions.

Table 65: Cases that Followed Similar Approach to Case Study 3

Case #	Process	Temperature	Primary Effluent Concentration Range	Response Variable Being Minimized
5	A^2/O	10°C	Medium	sP
6	A^2/O	10°C	Medium	TN + sP
8	A^2/O	10°C	High	sP
9	A^2/O	10°C	High	TN + sP
14	A^2/O	20°C	Medium	sP
15	A^2/O	20°C	Medium	TN + sP
23	MB	10°C	Medium	sP
26	MB	10°C	High	sP
30	MB	20°C	Low	TN + sP
35	MB	20°C	High	sP
38	MUCT	10°C	Low	sP
41	MUCT	10°C	Medium	sP
43	MUCT	10°C	High	TN
44	MUCT	10°C	High	sP
53	MUCT	20°C	High	sP

CHAPTER 5:
DISCUSSION

5.1 BNR Process Performance

The regulatory concentration limits for effluent $cBOD_5$, TN and sP must be below 25 mgO_2/L, 5 mgN/L and 1 mgP/L, respectively. These concentration limits were used to evaluate the performance of the A^2/O, MB and MUCT processes at 10°C and 20°C with low, medium and high primary effluent concentrations. Tables 66 and 67 show the success or failure of each of the BNR processes at various operating conditions at meeting the regulations. A 'yes' indicates that the BNR process at the given conditions was capable of achieving a minimum concentration value for $cBOD_5$, TN, sP or TN + sP below the required limit. With respect to $cBOD_5$ removal, all three BNR processes successfully produced an effluent with $cBOD_5$ below $25mgO_2/L$ for low and medium primary effluent concentrations and no process under any conditions was capable of meeting the $cBOD_5$ regulation at high primary effluent concentrations. For this reason, all results for high primary effluent concentration will be excluded from the discussion.

Table 66: Performance of the three BNR Processes at 10°C

Primary Effluent Conc.	Response	MUCT	MB	A^2/O
Low	TN	Yes	Yes	Yes
Low	SP	Yes	Yes	Yes
Low	TN + sP	Yes	Yes	Yes
Medium	TN	Yes	Yes	Yes
Medium	sP	Yes	Yes	Yes
Medium	TN + sP	No	No	No

Table 67: Performance of the three BNR Processes at 20°C

Primary Effluent Conc.	Response	MUCT	MB	A^2/O
Low	TN	Yes	Yes	Yes
Low	sP	Yes	Yes	Yes
Low	TN + sP	Yes	Yes	No
Medium	TN	Yes	Yes	Yes
Medium	sP	Yes	Yes	Yes
Medium	TN + sP	No	Yes	No

In Table 67, there is a 'yes' in the fifth row of the MB column. This 'yes' indicates that the MB process at 20°C with medium primary effluent concentrations is capable, with its optimum operating conditions, of achieving a final sP concentration below 1 mgP/L when the final TN concentration is neglected.

Tables 66 and 67 show that for low primary effluent concentrations, all three BNR processes had the capability of meeting the regulatory standards for final TN and sP concentrations except for the A^2/O process at 20°C. One can also note that at 10 and 20°C with low or medium primary effluent concentrations, all three BNR processes were capable of producing an effluent sP concentration below 1 mgP/L when the final TN concentration is neglected. This tells us that if a wastewater treatment plant is only concerned with sP removal, they should be able to use either the MB, MUCT or A^2/O process.

For each of the cells marked with a 'yes' in Tables 66 and 67, Tables 68, 69 and 70 give the values for the minimum response variable, the optimum operating conditions for which the minimum value was found and the model used to describe the surface around the minimum value.

Table 68 gives a summary of the A^2/O cases that were successful in achieving minimum TN and sP concentrations below 5 mgN/L and 1 mgP/L, respectively. The F/M ratios varied from 0.08 to 0.15 $gcBOD_5/gMLVSS/d$ and the SRTs varied from 18 to 30 d. Both of these ranges are acceptable according to values found in literature (EPA, 1993). The models found to describe the behaviour of the effluent TN concentrations show that variables x_3, x_4 and x_5 (anaerobic, anoxic and aerobic HRT) are the most significant operating variables for the A^2/O process. Each of these three operating variables was found in three of the least squares models, where as, x_2 (nitrified recycle) is only found in two of the models and x_1 (total recycle) is only found in one model. The models found to describe the behaviour of the effluent sP concentrations for the A^2/O process show that x_3 and x_5 are the most significant operating variables with appearances in three of the models. Variable, x_2, is found in two of the models, x_1, is found in only one of the models and x_4 did not appear in any of the sP models. Combining the results for TN and sP removal with the A^2/O process, one could conclude that the total recycle (x_1) does not have a significant effect on the effluent concentrations of TN and sP and therefore, does not need to be analysed in further experiments.

For cases 11 and 14, the model is the centre point value. As was discussed in case study #3, problems were found when running some of the simulations. In several instances, the concentration of nitrate/nitrite would decrease to zero for no apparent reason. When this would occur, it was not possible to get a reliable least squares model to fit the data. The operating region was shrunk repeatedly in an attempt to find a model to describe the data. Consequently, the operating region was shrunk so small that none of the operating variables were significant over their given ranges. This lead to a model of $y = a$, where a is the centre point value for the run. For these cases, please refer to the corresponding files in the appendices to see how the process behaved for the given conditions.

In order for the cases to appear in Table 68, the minimum effluent TN and sP concentrations for the optimum operating conditions must have been below the required limits of 5 mgN/L and 1 mgP/L. In some instances, the optimum values found for the operating variables are neither practically nor economically feasible. The non-feasible operating variables are highlighted and will be discussed in Section 5.2.

A similar analysis can be performed for Table 69, which contains the successful cases for the MB process. The 11 cases found in Table 69 have F/M ratios between 0.06 and 0.15 $gcBOD_5/gMLVSS/d$ and SRTs that range from 19 to 29 d. Both of these ranges are acceptable according to literature values (EPA, 1993). The least squares models found to describe the effluent TN concentrations indicate that the most important operating variables for the MB process are x_2, x_4, x_5, x_6 and x_7 (internal recycle, 1st anoxic HRT, 1st aerobic HRT and 2nd anoxic HRT). Each of these operating variable appear in at least four of the least squares models. Variable, x_3 (anaerobic HRT) appears in three of the models and x_1 (total recycle) appears in two of the models. The models found to describe effluent sP concentration for the MB process indicate that variables x_2, x_3, x_5 and x_7 are all equally important with each of them appearing in five of the models. Variables x_1 and x_4 both appear in four of the models, while, x_6 appears in three models. From the results in Table 69, one would have to conclude that all seven operating variables are significant and should be analysed in future experimental studies.

Table 68: Results for the A^2/O Process

			x_1	x_2	x_3	x_4	x_5				
Case #	Conditions	Model	TR, -	NR, % Q	Anaerobic HRT, h	Anoxic HRT, h	Aerobic HRT, h	Total HRT, h	SRT, d	F/M, gcBOD5/ gMLVSS/d	Response Variable, mg/L
10	20°C/[Low]/TN	$TN = 2.49 + 0.17x_3$	0.70	800	0.96	6.12	3.82	11	26	0.12	2.92
	Range		*[0.65 – 0.75]*	*[750 – 850]*	*[0.72 – 1.44]*	*[6.00 – 6.24]*	*[3.70 – 3.94]*				
11	20°C/[Low]/sP	$sP = 0.53$	0.38	120	1.20	5.16	2.94	9	18	0.13	0.53
	Range		*[0.35 – 0.40]*	*[100 – 140]*	*[0.96 – 1.44]*	*[4.80 – 5.52]*	*[2.76 – 3.12]*				
13	20°C/[Medium]/TN	$TN = 4.81 - 0.41x_4 + 0.37x_5$	0.85	1000	0.96	7.08	4.73	13	24	0.12	3.77
	Range		*[0.80 – 0.90]*	*[950 – 1050]*	*[0.72 – 1.20]*	*[6.24 – 6.99]*	*[4.80 – 5.52]*				
14	20°C/[Medium]/sP	$sP = 0.28$	0.60	575	1.26	5.64	2.70	10	21	0.15	0.28
	Range		*[0.55 – 0.65]*	*[550 – 600]*	*[1.20 – 1.32]*	*[5.52 – 5.76]*	*[2.64 – 2.76]*				
1	10°C/[Low]/TN	$TN = 5.44 - 0.28x_3 - 0.25x_4$	0.90	900	0.72	8.55	4.68	14	30	0.09	3.57
	Range		*[0.85 – 0.95]*	*[850 – 950]*	*[0.24 – 0.72]*	*[7.20 – 8.16]*	*[4.32 – 5.04]*				
2	10°C/[Low]/sP	$sP = -2.08 - 0.72x_3 + 1.16x_5$	0.71	713	1.46	7.02	2.80	11	25	0.09	0.24
	Range		*[0.70 – 0.72]*	*[700 – 725]*	*[1.15 – 1.30]*	*[6.96 – 7.08]*	*[2.93 – 3.02]*				
3	10°C/[Low]/TN+sP	$TN = 6.33 - 0.87x_1 - 1.82\text{x}10^{-3}x_2 + 0.39x_3 + 0.12x_4 - 0.63x_5$ $sP = -4.54 + 1.78x_1 + 2.46\text{x}10^{-3}x_2 - 0.94x_3 + 1.15x_5$	0.65	800	1.87	6.36	3.59	12	30	0.08	4.26 0.54

	Range		*[0.60 – 0.70]*	*[725 – 875]*	*[1.68 – 1.92]*	*[6.00 – 6.72]*	*[3.54 – 3.84]*				
4	10°C/[Medium]/TN	$TN = 6.33 - 9.55x10^{-4}x_2 - 0.20x_5$	1.10	1350	0.84	9.12	6.36	16	19	0.15	4.46
	Range		*[1.05 – 1.15]*	*[1150 – 1350]*	*[0.72 – 0.96]*	*[8.88 – 9.36]*	*[6.00 – 6.48]*				
5	10°C/[Medium]/sP	$sP = -5.48 + 1.87x10^{-3}x_2 – 0.98x_3 + 1.24x_5$	0.88	970	1.34	7.92	4.08	13	28	0.08	0.11
	Range		*[0.82 – 0.88]*	*[970 – 1030]*	*[1.22 – 1.34]*	*[7.80 – 7.92]*	*[4.08 – 4.20]*				

TR – Total Recycle
NR – Nitrified Recycle
Condition – Temperature/Primary Effluent Concentration/Minimized Response Variable

Table 69: Results for the MB Process

Case #	Conditions	Model	x_1 TR, -	x_2 IR, % Q	x_3 Anaerobic HRT, h	x_4 1st Anoxic HRT, h	x_5 1st Aerobic HRT, h	x_6 2nd Anoxic HRT, h	x_7 2nd Aerobic HRT, h	Total HRT, h	SRT, d	F/M, gcBOD5/ gMLVSS/d	Response Variable, mg/L
28	20°C/[Low]/TN	$TN = 2.76 + 1.41x10^{-3}x_2 - 0.62x_4 + 0.41x_5 - 0.59x_6$	0.75	576	0.92	2.64	2.89	1.67	0.13	8	23	0.13	2.24
	Range		*[0.70 – 0.80]*	*[550 – 650]*	*[0.86 – 0.98]*	*[2.16 – 2.64]*	*[2.88 – 3.60]*	*[1.42 – 1.73]*	*[0.10 – 0.17]*				
29	20°C/[Low]/sP	$sP = -1.05 + 9.82x10^{-4}x_2 + 0.46x_5 + 0.15x_6$	0.60	270	1.56	2.76	1.63	0.78	0.09	7	29	0.11	0.06
	Range		*[0.60 – 0.65]*	*[230 – 270]*	*[1.46 – 1.56]*	*[2.52 – 2.76]*	*[1.63 – 1.78]*	*[0.78 – 1.02]*	*[0.06 – 0.09]*				
30	20°C/[Low]/TN+sP	$TN = 5.35 - 3.96x10^{-3}x_2 + 0.67x_3 - 0.52x_4 - 0.98x_5 - 0.85x_6 - 1.41x_7$ $sP = -3.02 + 2.14x_1 + 3.02x10^{-3}x_2 - 0.96x_3 - 0.34x_4 + 1.60x_5 + 0.29x_6 + 2.05x_7$	0.55	350	1.56	2.28	1.92	0.96	0.12	7	28	0.11	3.43 0.54
	Range		*[0.55 – 0.65]*	*[250 – 350]*	*[1.32 – 1.56]*	*[2.28 – 2.52]*	*[1.92 – 2.16]*	*[0.72- 0.96]*	*[0.12 – 0.22]*				
31	20°C/[Medium]/TN	$TN =7.31 - 4.59x10^{-3}x_2 + 0.31x_4 - 0.42x_5 - 1.59x_6 + 0.66x_7$	0.80	680	1.08	3.00	2.88	1.54	0.19	9	20	0.15	2.74
	Range		*[0.75 – 0.85]*	*[400 – 500]*	*[0.96 – 1.20]*	*[3.12 – 3.60]*	*[2.16 – 2.64]*	*[0.96 – 1.20]*	*[0.72 – 1.20]*				
32	20°C/[Medium]/sP	$sP = 0.27 + 2.48x_1 + 8.69x10^{-3}x_2 - 4.89x_3 - 1.66x_4 + 3.06x_5 + 2.33x_7$	0.71	371	1.33	3.71	1.76	1.08	0.47	8	19	0.13	0.03
	Range		*[0.70 – 0.90]*	*[400 – 500]*	*[0.96 – 1.20]*	*[3.12 – 3.60]*	*[2.16 – 2.64]*	*[0.96 – 1.20]*	*[0.72 – 1.20]*				
33	20°C/[Medium]/TN+sP	$TN = 7.74 - 1.30x_1 - 4.59x10^{-3}x_2 + 0.57x_3 + 0.31x_4 - 0.42x_5 - 1.59x_6 + 0.66x_7$ $sP = -1.72 + 4.97x_1 + 8.69x10^{-3}x_2 -$	0.80	450	1.25	3.58	1.98	1.08	0.48	8	20	0.15	4.72 0.76

		$4.89x_3 - 1.66x_4 + 3.06x_5 + 2.33x_7$											
	Range		*[0.75 – 0.85]*	*[400 – 500]*	*[0.96 – 1.20]*	*[3.12 – 3.60]*	*[2.16 – 2.64]*	*[0.96 – 1.20]*	*[0.72 – 1.20]*				
19	10°C/[Low]/TN	$TN = 2.82 - 0.29x_6$	0.75	570	0.70	2.59	3.29	1.80	0.29	9	28	0.06	2.26
	Range		*[0.70 – 0.75]*	*[470 – 570]*	*[0.70 – 0.77]*	*[2.52 – 2.59]*	*[3.29 – 3.36]*	*[1.51 – 1.80]*	*[0.29 – 0.38]*				
20	10°C/[Low]/sP	$sP = -0.78 - 0.47x_3 + 0.54x_6 + 0.62x_7$	0.53	385	1.40	2.48	1.80	1.18	0.51	7	28	0.09	0.15
	Range		*[0.51 – 0.55]*	*[370 – 400]*	*[1.32 – 1.42]*	*[2.42 – 2.54]*	*[1.85 – 2.04]*	*[1.08 – 1.27]*	*[0.50 – 0.60]*				
21	10°C/[Low]/TN+sP	$TN = 7.91 - 1.82x_1 - 1.08x_5 - 1.02x_7$	0.45	320	1.68	3.12	3.12	1.68	0.24	10	29	0.07	3.58
		$sP = -2.30 + 2.10x_1 + 2.66x10^{-3}x_2 - 0.94x_3 - 0.25x_4 + 0.99x_5 + 1.11x_7$											0.49
	Range		*[0.45 – 0.55]*	*[320 – 380]*	*[1.44 – 1.68]*	*[2.64 – 3.12]*	*[2.64 – 3.12]*	*[1.20 – 1.68]*	*[0.24 – 0.48]*				
22	10°C/[Medium]/TN	$TN = 6.36 - 0.37x_3 - 0.99x_6$	0.98	600	1.29	3.10	4.50	2.47	0.55	12	27	0.10	4.06
	Range		*[0.95 – 1.00]*	*[570 – 630]*	*[0.84 – 1.08]*	*[3.05 – 3.14]*	*[4.44 – 4.56]*	*[2.28 – 2.38]*	*[0.50 – 0.60]*				
23	10°C/[Medium]/sP	$sP = 0.12$	0.82	160	1.50	3.00	3.67	1.10	0.58	10	19	0.12	0.12
	Range		*[0.78 – 0.82]*	*[160 – 180]*	*[1.42 – 1.50]*	*[2.88 – 3.00]*	*[3.67 – 3.79]*	*[1.10 – 1.22]*	*[0.58 – 0.67]*				

IR – Internal Recycle

Table 70: Results for the MUCT Process

			x_1	x_2	x_3	x_4	x_5	x_6	x_7				
Case #	Conditions	Model	TR, -	AR, % Q	NR, % Q	Anaerobic HRT, h	1st Anoxic HRT, h	2nd Anoxic HRT, h	Aerobic HRT, h	Total HRT, h	SRT, d	F/M, gcBOD5/ gMLVSS/d	Response Variable, mg/L
46	20°C/[Low]/TN	$TN = 4.52 - 1.94x10^{-3}x_3 + 0.15x_4 + 0.19x_5 - 0.17x_7$	1.20	300	700	0.47	1.27	4.68	5.13	12	28	0.12	2.99
	Range		*[1.10 – 1.30]*	*[200 – 400]*	*[500 – 600]*	*[0.72 – 1.44]*	*[1.68 – 2.40]*	*[4.44 – 4.92]*	*[4.08 – 4.44]*				
47	20°C/[Low]/sP	$sP = -0.41 + 0.42x_7$	0.70	200	300	1.44	2.04	1.92	1.56	7	30	0.10	0.07
	Range		*[0.60 – 0.70]*	*[200 – 300]*	*[200 – 300]*	*[0.72 – 1.44]*	*[2.04 – 2.28]*	*[1.92 – 2.16]*	*[1.56 – 2.04]*				
48	20°C/[Low]/TN+sP	$TN = 8.13 - 1.72x_1 - 2.91x10^{-3}x_3 + 0.50x_4 + 0.66x_5 - 0.46x_6 - 0.90x_7$ $sP = 0.31 + 0.82x_1 + 2.79x10^{-4}x_3 - 0.14x_4 - 0.14x_5 + 0.07x_6 + 0.37x_7$	0.65	200	400	1.08	1.56	1.80	2.16	7	28	0.11	4.65 0.47
	Range		*[0.55 – 0.65]*	*[200 – 300]*	*[300 – 400]*	*[1.08 – 1.32]*	*[1.56 – 1.80]*	*[1.56 – 1.80]*	*[1.92 – 2.16]*				
49	20°C/[Medium]/TN	$TN = 8.29 - 3.01x10^{-3}x_3 + 0.11x_5 + 0.10x_6 - 0.38x_7$	1.55	250	1074	12.08	1.67	11.63	10.68	25	56	0.07	3.34
	Range		*[1.50 – 1.60]*	*[200 – 300]*	*[1000 – 1050]*	*[0.72 – 1.44]*	*[1.68 – 2.40]*	*[12.00 – 13.20]*	*[6.48 – 7.68]*				
50	20°C/[Medium]/sP	$sP = -1.03 + 1.04x_1 - 0.12x_5 + 0.19x_7$	0.60	300	200	1.20	2.88	1.92	4.32	10	18	0.16	0.08
	Range		*[0.50 – 0.60]*	*[100 – 300]*	*[100 – 200]*	*[1.20 – 1.44]*	*[2.40 – 2.88]*	*[1.92 – 2.88]*	*[4.32 – 5.28]*				
37	10°C/[Low]/TN	$TN = 3.16 + 4.29x10^{-4}x_3 - 0.28x_6 + 0.16x_7$	1.40	250	750	0.72	0.96	5.95	5.37	13	29	0.09	3.49
	Range		*[1.30 – 1.50]*	*[100 – 400]*	*[700 – 1000]*	*[0.36 – 1.08]*	*[0.48 – 1.44]*	*[4.80 – 5.76]*	*[5.28 – 6.24]*				

38	10°C/[Low]/sP	sP = -0.67 + 0.78x_1 – 0.24x_4 – 0.29x_5 + 0.33x_7	0.70	300	300	1.44	2.04	1.44	3.48	8	27	0.08	0.09
	Range		*[0.70 – 0.80]*	*[200 – 300]*	*[300 – 400]*	*[0.96 – 1.44]*	*[1.56 – 2.04]*	*[1.44 - 1.92]*	*[3.48 – 3.96]*				
39	10°C/[Low]/TN+sP	TN = 8.60 – 2.01x_1 + 1.61x$10^{-3}x_2$ – 2.57x$10^{-3}x_3$ + 0.61x_4 + 0.65x_5 – 0.97x_7 sP = -0.90 + 0.63x_1 – 4.91x$10^{-4}x_2$ + 5.46x$10^{-4}x_3$ – 0.25x_4 + 0.28x_5 + 0.39x_7	0.85	100	475	1.08	1.44	2.88	3.48	9	30	0.07	4.16 0.58
	Range		*[0.75 – 0.85]*	*[100 – 200]*	*[375 – 475]*	*[1.08 – 1.32]*	*[1.44 – 1.68]*	*[2.40 – 2.88]*	*[3.00 – 3.48]*				
40	10°C/[Medium]/TN	TN = 4.27 – 0.11x_6 + 0.06x_7	1.70	300	1300	0.72	1.92	15.36	11.23	29	54	0.06	3.48
	Range		*[1.60 – 1.80]*	*[170 – 430]*	*[1250 – 1350]*	*[0.41 – 1.03]*	*[1.61 – 2.23]*	*[13.44 – 14.88]*	*[11.04 – 12.00]*				
41	10°C/[Medium]/sP	sP = 0.08	0.81	250	260	1.06	2.62	2.30	5.54	12	24	0.10	0.08
	Range.		*[0.81 – 0.82]*	*[250 – 260]*	*[250 – 260]*	*[1.01 – 1.06]*	*[2.57 – 2.62]*	*[2.26 – 2.30]*	*[5.54 – 5.59]*				

AR – Anoxic Recycle

Table 70 summarizes the successful cases for the MUCT process. The 10 cases found in Table 70 have F/M ratios between 0.06 to 0.16 $gcBOD_5/gMLVSS/d$ and SRTs that range from 18 to 56 d. While the F/M ratios are acceptable according to values found in literature, values for SRT of 56 d are much higher than the recommended ranges of 10 to 30 d (EPA, 1993). The issue of high SRT will be discussed further in Section 5.2.

The least squares models found to describe the effluent TN concentrations for the MUCT process indicate that the most important operating variables are x_3, x_5, x_6 and x_7 (nitrified recycle, 1^{st} and 2^{nd} anoxic HRT and aerobic HRT). Each of these variables appears in at least four of the models. Variables x_4, x_1 and x_2 (anaerobic HRT, total recycle and anoxic recycle) appear in three, two and one of the models, respectively. The models found to describe effluent sP concentration for the MUCT process indicate that x_1, x_5 and x_7 are the most important variables with appearances in at least four of the models. Three of the models contain x_4 and two of the models contain x_3. Variables, x_2 and x_6, are each only present in one model. Combining the results for TN and sP removal with the MUCT process, one could conclude that x_2 (anoxic recycle), has very little effect on the effluent concentrations and therefore can be excluded from future experimental studies.

5.2 Analysis of Optimum Operating Variables

The next step in evaluating the three BNR processes at the given conditions is to determine whether or not the optimum operating conditions required to achieved minimal TN and sP concentrations are feasible. For example, the MUCT process at 20°C with low primary effluent concentrations showed that with optimum operating conditions, it was capable of achieving a final TN concentration of 2.99 mgN/L, while neglecting sP concentrations. For this case, the optimum nitrified recycle was found to be 700 % Q. In Table 11, the recommended range of values for the nitrified recycle in the MUCT process was 100 to 200 % Q. Since the optimum value of 700 % is 3 to 7 times greater than this value, it is concluded that the pumping power required to achieve such high internal recycle flows would not be economically feasible.

In order to evaluate each of the successful cases from Tables 68, 69 and 70, a set of criteria was established to determine the feasibility of the recycle flows, overall HRTs, SRTs and F/M ratios. ROPEC currently operates with a total recycle of 150 % Q and therefore, the optimal conditions are accepted as long as TR (total recycle) is below 150 % Q. The criteria for the internal recycles, total HRT, SRT and F/M ratios for the MB, A^2/O and MUCT processes were based on the maximum recommended values given in Chapter 2. The maximum values of total HRT for the A^2/O, MB and MUCT processes were 8, 22 and 23 h, respectively. Therefore, the optimum total HRT is accepted as long as it falls below 23 h. The maximum values for internal recycles for the A^2/O, MB and MUCT processes were 200, 200 and 400 % Q, respectively. Since evaluation of the BNR process is still in the beginning stages and due to the large number of cases with high internal recycle flows, the limit was set at 500 % Q as opposed to 400 % Q. Acceptable values of SRT ranged from 5 to 40 d and therefore, the conditions are accepted as long as the SRT falls below 40 d. Finally, the F/M ratio must fall within 0.1 to 0.2 g $cBOD_5$/ g MLVSS/d. Table 71 summarizes the cases that were successful at achieving minimum sP and TN concentrations below the regulatory limits with acceptable TR, IR, total HRT, SRT and F/M ratios criteria.

Table 71: Successful Cases With Respect to Minimum Output and Optimum Variables

Case #	Process	Temperature	Primary Effluent Concentration	Minimized Output Variable
11	A^2/O	20°C	Low	sP
29	MB	20°C	Low	sP
30	MB	20°C	Low	TN + sP
32	MB	20°C	Medium	sP
33	MB	20°C	Medium	TN + sP
20	MB	10°C	Low	sP
21	MB	10°C	Low	TN + sP
23	MB	10°C	Medium	sP
47	MUCT	20°C	Low	sP
48	MUCT	20°C	Low	TN + sP
50	MUCT	20°C	Medium	sP
38	MUCT	10°C	Low	sP
39	MUCT	10°C	Low	TN + sP
41	MUCT	10°C	Medium	sP

Cases that are present in Tables 68, 69 and 70 but are not present in Table 71 had one or more optimum operating variables above the TR, IR, total HRT, SRT and F/M ratio criteria previously recommended. There is still a possibility that the cases missing from Table 71 can be considered acceptable. For example, in Table 69, the MB process at 20°C with medium primary effluent concentrations showed the capability of achieving a final TN concentration of 2.74 mgN/L, which is well below the required 5 mgN/L. However, in order to achieve this value, the IR (internal recycle) was 680 % Q, which is above 500 % Q and therefore not acceptable. Further analysis was done to see whether the IR could be reduced and still maintain a final TN concentration below 5 mgN/L. The least squares model describing the operating region contains an internal recycle variable (x_2). If we substitute 450 % Q instead of 680 % Q, the final TN concentration, according to the least squares model, is 3.40 mgN/L which is still well below 5 mgN/L. When the simulation was run at these conditions, the ASM2d model predicted the effluent TN concentration to be 3.51 mgN/L, which is in good agreement with the least squares prediction. Therefore, the MB process at 20°C with medium concentrations is capable of achieving TN concentration below 5 mgN/L with acceptable values for the operating conditions. Similar analysis was performed on all of the cases that appeared in Tables 68, 69 and 70 but not in Table 71. Tables 72, 73 and 74 summarize the cases that were successful after analysis of achieving TN and sP concentrations below 5 mgN/L and 1 mgP/L, respectively with acceptable operating conditions.

In Table 72, the F/M ratios, SRTs and effluent concentrations of TN and sP all fall within the recommended values in the literature. The models that represent the effluent TN concentrations for the A^2/O process indicate that all five operating variables are equally important. The models found to represent the effluent sP concentrations for the A^2/O process indicate that variables x_1, x_2, x_3 and x_5 are all important with each of the variables appearing in one model. The anoxic HRT, x_4, does not appear in any of the models. Combining the results for TN and sP removals with the A^2/O process found in Tables 68 and 72, one could conclude that all five operating variables should be considered in further experimental investigations.

Table 73 contains the successful cases for the MB process after the analysis on operating variables was completed. The F/M ratios, SRTs and effluent TN and sP concentrations are all within acceptable ranges according literature values (EPA, 1993). The models found to describe effluent TN and sP concentrations have not changed from Table 69 and therefore, the same conclusions can be made that all operating variables should be considered in future experimental studies.

Table 72: A^2/O Successful Cases After Analysis

Case #	Conditions	Model	x_1 T R, -	x_2 NR, % Q	x_3 Anaerobic HRT, h	x_4 Anoxic HRT, h	x_5 Aerobic HRT, h	Total HRT, h	SRT, d	F/M, gcBOD5/ gMLVSS/d	Response Variable, mg/L
10	20°C/[Low]/TN	$TN = 5.21 - 3.66x10^{-3}x_2 + 0.18x_3 + 0.08x_4 - 0.18x_5$	0.65	500	0.72	5.28	4.08	10	26	0.12	3.15
	Range		*[0.65 – 0.75]*	*[400 – 500]*	*[0.72 – 1.44]*	*[5.28 – 6.00]*	*[4.08 – 4.80]*				
1	10°C/[Low]/TN	$TN = 10.21\text{-}1.44x_1 - 5.40x10^{-3}x_2 + 0.43x_3 + 0.47x_4 - 1.18x_5$	0.95	500	0.24	7.20	5.04	12	29	0.09	3.81
	Range		*[0.85 – 0.95]*	*[400 – 500]*	*[0.24 – 0.72]*	*[7.20 – 7.68]*	*[4.56 – 5.04]*				
3	10°C/[Low]/TN+sP	$TN = 6.33 - 0.87x_1 - 1.82x10^{-3}x_2 + 0.39x_3 + 0.12x_4 - 0.63x_5$ $sP = -4.54 + 1.78x_1 + 2.46x10^{-3}x_2 - 0.94x_3 + 1.15x_5$	0.65	450	1.87	6.36	3.59	12	30	0.06	4.26 0.54
	Range		*[0.60 – 0.70]*	*[725 – 875]*	*[1.68 – 1.92]*	*[6.00 – 6.72]*	*[3.54 – 3.84]*				

Table 73: MB Successful Cases After Analysis

Case #	Conditions	Model	x_1	x_2	x_3	x_4	x_5	x_6	x_7				
			TR, -	NR, % Q	Anaerobic HRT, h	1st Anoxic HRT, h	1st Aerobic HRT, h	2nd Anoxic HRT, h	2nd Aerobic HRT, h	Total HRT, h	SRT, d	F/M, gcBOD5/ gMLVSS/d	Response Variable, mg/L
28	20°C/[Low]/TN	$TN = 2.76 + 1.41x10^{-3}x_2 - 0.62x_4 + 0.41x_5 - 0.59x_6$	0.75	450	0.92	2.64	2.89	1.67	0.13	8	23	0.13	2.35
	Range		*[0.70 – 0.80]*	*[550 – 650]*	*[0.86 – 0.98]*	*[2.16 – 2.64]*	*[2.88 – 3.60]*	*[1.42 – 1.73]*	*[0.10 – 0.17]*				
31	20°C/[Medium]/TN	$TN = 8.74 - 0.005x_2 + 0.31x_4 - 0.42x_5 - 1.59x_6 + 0.66x_7$	0.80	450	1.08	3.00	2.88	1.54	0.19	9	20	0.15	3.51
	Range		*[0.75 – 0.85]*	*[400 – 500]*	*[0.96 – 1.20]*	*[3.12 – 3.60]*	*[2.16 – 2.64]*	*[0.96 – 1.20]*	*[0.72 – 1.20]*				
19	10°C/[Low]/TN	$TN = 2.82 - 0.29x_6$	0.75	450	0.70	2.59	3.29	1.80	0.29	9	26	0.10	3.32
	Range		*[0.70 – 0.75]*	*[470 – 570]*	*[0.70 – 0.77]*	*[2.52 – 2.59]*	*[3.29 – 3.36]*	*[1.51 – 1.80]*	*[0.29 – 0.38]*				
22	10°C/[Medium]/TN	$TN = 6.36 - 0.37x_3 - 0.99x_6$	0.98	450	1.29	3.10	4.50	2.47	0.55	12	27	0.10	4.20
	Range		*[0.95 – 1.00]*	*[570 – 630]*	*[0.84 – 1.08]*	*[3.05 – 3.14]*	*[4.44 – 4.56]*	*[2.28 – 2.38]*	*[0.50 – 0.60]*				

Table 74: MUCT Successful Cases After Analysis

			x_1	x_2	x_3	x_4	x_5	x_6	x_7				
Case #	Conditions	Model	TR, -	AR, % Q	NR, % Q	Anaerobic HRT, h	1st Anoxic HRT, h	2nd Anoxic HRT, h	Aerobic HRT, h	Total HRT, h	SRT, d	F/M, gcBOD5/ gMLVSS/d	Response Variable, mg/L
46	20°C/[Low]/TN	$TN = 4.52 - 1.94\text{x}10^{-3}x_3 + 0.15x_4 + 0.19x_5 - 0.17x_7$	1.20	300	450	0.47	1.27	4.68	5.13	12	28	0.12	3.23
	Range		*[1.10 – 1.30]*	*[200 – 400]*	*[500 – 600]*	*[0.72 – 1.44]*	*[1.68 – 2.40]*	*[4.44 – 4.92]*	*[4.08 – 4.44]*				
37	10°C/[Low]/TN	$TN = 3.16 + 4.29\text{x}10^{-4}x_3 - 0.28x_6 + 0.16x_7$	1.40	250	450	0.72	0.96	5.95	5.37	13	29	0.09	4.01
	Range		*[1.30 – 1.50]*	*[100 – 400]*	*[700 – 1000]*	*[0.36 – 1.08]*	*[0.48 – 1.44]*	*[4.80 – 5.76]*	*[5.28 – 6.24]*				

Table 74 contains the successful cases with acceptable values for operating conditions for the MUCT process. The values for F/M ratio, SRT and effluent TN concentrations all fall within recommended values. Table 74 shows similar results with respect to parameter significance as in Table 70. The most important operating variables for both TN and sP removal are the aerobic HRT and nitrified recycle while the least important operating variable is the anoxic recycle. It is recommended that the anoxic recycle be excluded from future experimental studies as it has very little effect on effluent TN and sP removal.

From the results of Tables 72, 73 and 74, Table 75 summarizes the additional cases that have the capability of achieving TN below 5 mgN/L and sP below 1 mgP/L with acceptable operating conditions.

Table 75: Successful Cases

Case #	Process	Temperature	Primary Effluent Concentration	Minimized Output Variable
10	A^2/O	20°C	Low	TN
1	A^2/O	10°C	Low	TN
3	A^2/O	10°C	Low	TN + sP
28	MB	20°C	Low	TN
31	MB	20°C	Medium	TN
19	MB	10°C	Low	TN
22	MB	10°C	Medium	TN
46	MUCT	20°C	Low	TN
37	MUCT	10°C	Low	TN

5.3 Application of Successful BNR Processes to ROPEC's Current Configuration

5.3.1 Steady State Analysis

One of the objectives listed in Chapter 1 was to recommend a suitable BNR process to ROPEC for further testing and evaluation. Before any of the BNR processes can be chosen, it is necessary to discuss typical operating conditions for ROPEC. Since ROPEC is located in Ottawa, ON, Canada, it experiences both warm and cold weather. Therefore, whichever process is chosen must be successful at both 10 and 20°C. Also, ROPEC's typical primary effluent concentrations for COD, TSS, sP and TKN are approximately 200 mg/L, 150 mg/L, 2 mgP/L and 20 mgN/L, respectively. Since these values mostly fall within the low primary effluent concentrations described in Chapter 4, the chosen BNR process must be successful at low primary effluent concentrations. Additionally, ROPEC is considering BNR alternatives to their current biological BOD and chemical P removal system in order to achieve simultaneous BOD, N and P removal. Therefore, the recommended BNR process must be based on combined TN and sP removal. Both the MUCT and the MB process demonstrated the capability of achieving effluent TN and sP concentrations below the required limits with low primary effluent concentrations at 10 and 20°C. Therefore, both the MB and MUCT process will be tested using the optimized operating variables from cases 21and 30 (MB process) and 39 and 48 (MUCT process) to see if they can in fact achieve effluent TN and sP concentrations below 5 mgN/L and 1 mgP/L, respectively, with ROPEC influent data.

ROPEC is designed to treat approximately 500,000 m^3/d of wastewater. In Chapter 3, it was explained that for all studies an influent flow of 100,000 m^3/d was used to simulate data. If ROPEC is to implement either the MB and/or the MUCT process in a pilot plant study, it is highly unlikely that they will use all 8 reactors with 500,000 m^3/d. Most likely, a portion of the liquid treatment train will be used to evaluate the two BNR processes; this leads to the choice of influent flow of 100,000 m^3/d. Tables 76 and 77 summarize the operating variables used from the four cases that were tested using ROPEC influent (COD = 20 mg/L, TSS = 150 mg/L, TKN = 20 mNg/L and sP = 2 mgP/L) as well as the resulting effluent concentrations of TN and sP. For each of the four cases in Tables 76 and 77, the effluent $cBOD_5$ was less than 25 mgO_2/L.

According to Tables 76 and 77, both the MB and MUCT processes are viable BNR options for ROPEC. Each of the four cases had effluent $cBOD_5$, TN and sP concentrations below the required 25 mgO_2/L, 5 mgN/L and 1 mgP/L, respectively. The SRTs, F/M ratios and operating variables for each of these four cases all fell within an acceptable range. It is important to note that for each of the processes, a separate set of operating variables was used for 10°C and for 20°C. In reality, only one set of basins will be built to accommodate BOD and nutrient removal so that the size of the basins will be kept constant throughout the year in both warm and cold seasons. According to literature, the kinetics for BOD and nutrient removal are slower in colder temperatures. Therefore, it is recommended that the plant be sized for the 10°C conditions. Since the recycle flows are easier to manipulate, it is recommended that the operators change the total and internal recycle flows accordingly for warm and cold temperatures. Tables 76 and 77 also show the results for the MB and MUCT process when 10°C basin HRTs are used for 20°C conditions. Recycle flows were kept the same for the 20°C conditions. When cases 21 and 30 (see Table 31) were combined for the MB process, both the effluent TN and $cBOD_5$ concentrations remained below 5 mgN/L and 25 mgO_2/L, respectively. Unfortunately, the final sP concentration rose above 1 mgP/L.

Table 76: ROPEC With MB Process at 10 and 20°C

			x_1	x_2	x_3	x_4	x_5	x_6	x_7				
Case #	Conditions	Model	TR, -	NR, % Q	Anaerobic HRT, h	1st Anoxic HRT, h	1st Aerobic HRT, h	2nd Anoxic HRT, h	2nd Aerobic HRT, h	Total HRT, h	SRT, d	F/M, gcBOD5/ gMLVSS/d	Response Variable, mg/L
30	20°C/[Low]/TN+sP	$TN = 5.35 - 3.96x10^{-3}x_2 + 0.67x_3 - 0.52x_4 - 0.98x_5 - 0.85x_6 - 1.41x_7$	0.55	350	1.56	2.28	1.92	0.96	0.12	7	27	0.12	4.44
		$sP = -3.02 + 2.14x_1 + 3.02x10^{-3}x_2 - 0.96x_3 - 0.34x_4 + 1.60x_5 + 0.29x_6 + 2.05x_7$											0.06
21	10°C/[Low]/TN+sP	$TN = 7.91 - 1.82x_1 - 1.08x_5 - 1.02x_7$	0.45	320	1.68	3.12	3.12	1.68	0.24	10	34	0.08	4.69
		$sP = -2.30 + 2.10x_1 + 2.66x10^{-3}x_2 - 0.94x_3 - 0.25x_4 + 0.99x_5 + 1.11x_7$											0.63
21 & 30	20°C with 10°C HRT		0.55	350	1.68	3.12	3.12	1.68	0.24	10	15	0.13	3.52
													1.59

Table 77: ROPEC With MUCT Process at 10 and 20°C

Case #	Conditions	Model	x_1 TR, -	x_2 AR, % Q	x_3 NR, % Q	x_4 Anaerobic HRT, h	x_5 1st Anoxic HRT, h	x_6 2nd Anoxic HRT, h	x_7 Aerobic HRT, h	Total HRT, h	SRT, d	F/M, gcBOD5/ gMLVSS/d	Response Variable, mg/L
48	20°C/[Low]/TN+sP	$TN = 8.13 - 1.72x_1 - 2.91x10^{-3}x_3 + 0.50x_4 + 0.66x_5 - 0.46x_6 - 0.90x_7$	0.65	200	400	1.08	1.56	1.80	2.16	7	40	0.09	4.94
		$sP = 0.31 + 0.82x_1 + 2.79x10^{-4}x_3 - 0.14x_4 - 0.14x_5 + 0.07x_6 + 0.37x_7$											0.09
39	10°C/[Low]/TN+sP	$TN = 8.60 - 2.01x_1 + 1.61x10^{-3}x_2 - 2.57x10^{-3}x_3 + 0.61x_4 + 0.65x_5 - 0.97x_7$	0.85	100	475	1.08	1.44	2.88	3.48	9	40	0.07	4.83
		$sP = -0.90 + 0.63x_1 - 4.91x10^{-4}x_2 + 5.46x10^{-4}x_3 - 0.25x_4 + 0.28x_5 + 0.39x_7$											0.09
39 & 48	20°C with 10°C HRT		0.65	200	400	1.08	1.44	2.88	3.48	9	18	0.11	3.58
													1.19

Similarly, when cases 39 and 48 were combined for the MUCT process, both the effluent TN and $cBOD_5$ concentrations remained below 5 mgN/L and 25 mgO_2/L, respectively. However, the final sP concentration rose above 1 mgP/L. It is recommended that further laboratory design experiments be carried out in order to find the right combination of basin HRTs to accommodate BOD and nutrient removal in both warm and cold temperatures.

Since both the MB and MUCT processes had successful BOD and nutrient removal, it is difficult to recommend one over the other to ROPEC. Due to the need of five reactor basins for the MB process, it is likely that the start-up cost would be higher than for the MUCT process, which only has four reactors. However, the operating costs of the MUCT process would be higher than for the MB process due to the larger number of recycle streams. Further cost analysis should be performed when deciding which of the two BNR processes to implement. It is recommended that both the MB and MUCT process be tested in laboratory experiments to ensure that they can both achieve the effluent concentrations found using computer simulation.

5.3.2 Dynamic Analysis

The effect of storm conditions on $cBOD_5$, TN and sP removal was evaluated using the recommended process conditions for ROPEC given in cases 21, 30, 39 and 48 in Tables 76 and 77. The influent flow and primary effluent COD, TKN, TSS and sP concentrations for the month of March, 1997 were used to simulate storm conditions. The influent flow rate, Q_{avg}, was normalized to 100,000 m^3/d since this was the flow rate used to generate the results in Tables 76 and 77. Figures 41 shows the influent storm conditions that were inputted to the simulation program. According to Figure 41, the storm produced two peaks in flow. The first one had a 3 day sustained peak flow of approximately $1.2*Q_{avg}$ and began on the 8th day. The second one had a 6 day sustained peak flow of approximately $1.5*Q_{avg}$ and began on the 25th day. There was a corresponding drop in COD for each of the peaks of influent flow. Each drop in COD began 2 to 3 days after the peak in flow began and lasted about the same amount of time as the peak in flow. This drop in COD is expected as the excess flow is most likely due to spring run off and therefore would contain a minimal amount of waste.

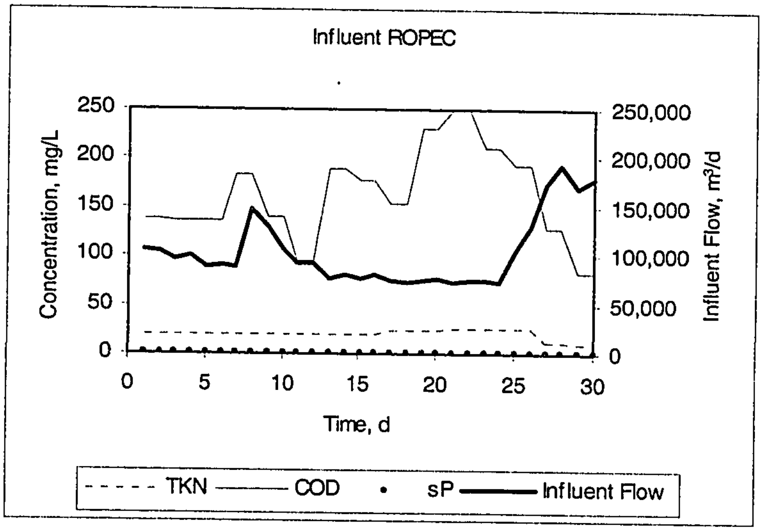

Figure 41: Influent Storm Conditions for ROPEC

In order to analyse the effects of storm conditions on effluent TN, sP and cBOD5 concentrations, the regulatory concentration was subtracted from the generated value. That is, 25 mg/L was subtracted from all effluent $cBOD_5$ concentrations, 5 mg/L was subtracted from all effluent TN concentrations and 1 mg/L was subtracted from all effluent sP concentrations. Therefore, a positive value in Figures 42 to 45 indicates that the process is NOT in compliance on that given day for the given pollutant. Figures 42 to 45 summarize the effluent data for the 30-day period shown in Figure 41.

If the effluent data are separated into peak days and non-peak days, we can evaluate the ability of each process at both 10 and 20°C to remove $cBOD_5$, TN and sP during storm events. During the 21 non-peak days, the MB process at 10°C had 9 positive TN concentrations, 4 positive sP concentrations and 0 positive $cBOD_5$ concentrations. During the 9 peak days, the same process had 9 positive TN concentrations, 2 positive sP concentrations and 1 positive $cBOD_5$ concentrations. These results indicate that at 10°C, the MB process is capable of meeting compliance regulations for $cBOD_5$ 100 % of the time (non-peak days) and 89 % of the time (peak days). It is capable of meeting compliance regulations for sP 81 % of the time (non-peak days) and 78 % of the time (peak days). It is only capable of meeting compliance regulations for TN 57 % of the time (non-peak days) and it is not capable of meeting compliance regulations for TN removal during the peak days.

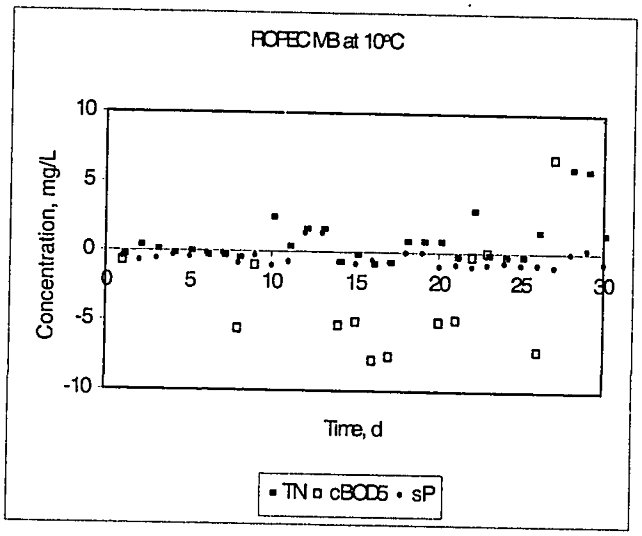

Figure 42: Deviations from Regulatory Concentrations for Storm Conditions for MB ROPEC at 10°C

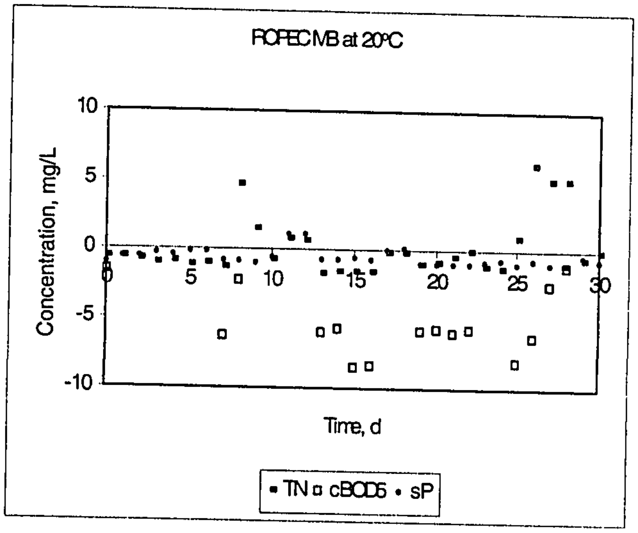

Figure 43: Deviations from Regulatory Concentrations for Storm Conditions for MB ROPEC at 20°C

During the 21 non-peak days, the MB process at 20°C had 3 positive TN concentrations, 4 positive sP concentrations and 0 positive cBOD$_5$ concentrations. During the 9 peak days, the same process had 6 positive TN concentrations, 0 positive sP concentrations and 0 positive cBOD$_5$ concentrations. These results indicate that at 20°C, the MB process is capable of meeting compliance regulations for cBOD$_5$ 100 % of the time (peak and non-peak days). It is capable of meeting compliance regulations for sP 81 % of the time (non-peak days) and 100 % of the time (peak days). It is capable of meeting compliance regulations for TN 86 % of the time (non-peak days) and it is only capable of meeting compliance regulations for TN 33 % of the time (peak days).

During the 21 non-peak days, the MUCT process at 10°C had 19 positive TN concentrations, 4 positive sP concentrations and 0 positive cBOD$_5$ concentrations. During the 9 peak days, the same process had 8 positive TN concentrations, 1 positive sP concentrations and 1 positive cBOD$_5$ concentrations. These results indicate that at 10°C, the MUCT process is capable of meeting compliance regulations for cBOD$_5$ 100 % of the time (non-peak days) and 89 % of the time (peak days). It is capable of meeting compliance regulations for sP 81 % of the time (non-peak days) and 89 % of the time (peak days). It is only capable of meeting compliance regulations for TN 10 % of the time (non-peak days) and 11 % of the time (peak days).

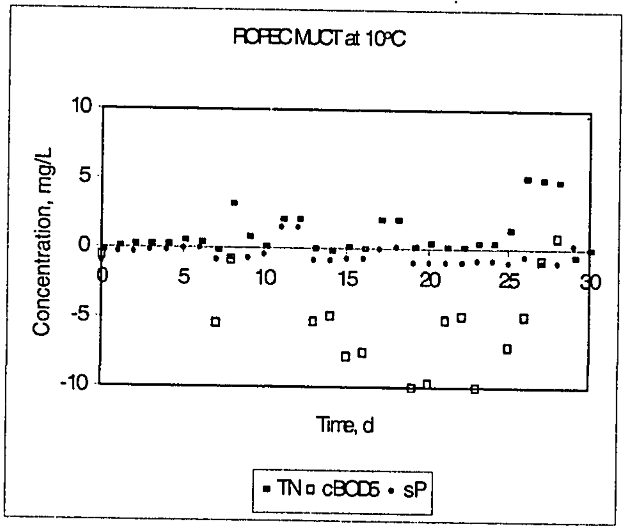

Figure 44: Deviations from Regulatory Concentrations for Storm Conditions for MUCT ROPEC at 10°C

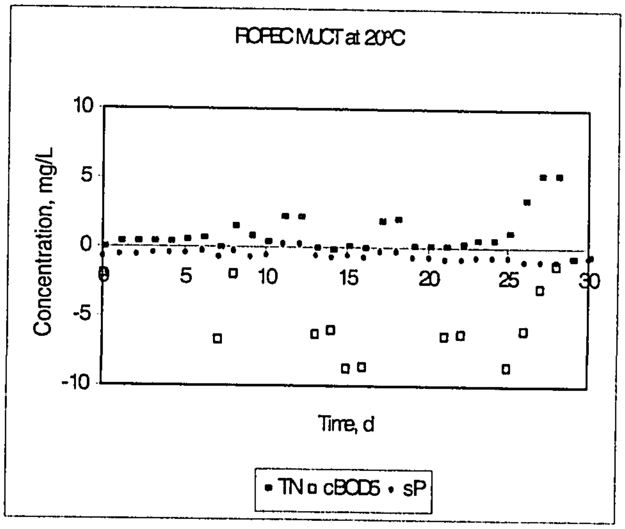

Figure 45: Deviations from Regulatory Concentrations for Storm Conditions for MUCT ROPEC at 20°C

During the 21 non-peak days, the MUCT process at 20°C had 18 positive TN concentrations, 2 positive sP concentrations and 0 positive $cBOD_5$ concentrations. During the 9 peak days, the same process had 7 positive TN concentrations, 0 positive sP concentrations and 0 positive $cBOD_5$ concentrations. These results indicate that at 20°C, the MUCT process is capable of meeting compliance regulations for $cBOD_5$ 100 % of the time (peak and non-peak days). It is capable of meeting compliance regulations for sP 90 % of the time (non-peak days) and 100 % of the time (peak days). It is only capable of meeting compliance regulations for TN 14 % of the time (non-peak days) and 22 % of the time (peak days).

Based on the dynamic simulations, one can conclude that the MB process is more robust than the MUCT process in satisfying regulatory limits for $cBOD_5$, TN and sP during peak and non peak flow days. It is therefore recommended that for further analysis such as laboratory experiments and pilot plant studies, ROPEC use the MB process to accomplish simultaneous $cBOD_5$ and nutrient removal. Table 78 summarizes the recommended operating variables for the MB process at 10 and 20°C for average influent flows of 100,000 m^3/d.

Table 78: Recommended MB Process Parameters for ROPEC

	x_1	x_2	x_3	x_4	x_5	x_6	x_7
Conditions	TR, -	NR, % Q	Anaerobic HRT, h	1st Anoxic HRT, h	1st Aerobic HRT, h	2nd Anoxic HRT, h	2nd Aerobic HRT, h
20°C	0.55	350	1.68	3.12	3.12	1.68	0.24
10°C	0.45	320	1.68	3.12	3.12	1.68	0.24

CHAPTER 6:

CONCLUSIONS

Results from this study indicate that the MB process was capable of achieving the TN, sP and $cBOD_5$ removals that ROPEC requires for compliance with federal regulations. It is, therefore, recommended that this BNR process be considered for further laboratory and pilot plant studies.

In particular, process simulations indicate that:

1. The ASM2d provided acceptable predictions on cBOD5, TN and sP removal for ROPEC with the recommended values for kinetic and stoichiometric parameters.
2. The A^2/O process was capable of achieving final effluent TN concentration below 5 mg/L at 10 and 20°C with low primary effluent concentrations and acceptable operating variables. The process was capable of achieving final effluent sP concentrations below 1 mg/L at 20°C and low primary effluent concentrations and acceptable operating variables. The process was also capable of achieving acceptable removal of simultaneous TN and sP at 10°C with low primary effluent concentrations and acceptable operating variables.
3. The MB process was capable of achieving final TN concentrations below 5 mg/L at 10 and 20°C with low and medium primary effluent concentrations and acceptable operating variables. The process was capable of achieving final sP concentrations below 1 mg/L at 10 and 20°C with low and medium primary effluent concentrations and acceptable operating variables. The process was also capable of achieving acceptable removal of simultaneous TN and sP at 20°C and low and medium primary effluent concentrations as well as at 10°C with low primary effluent concentrations with acceptable operating variables.
4. The MUCT process was capable of achieving final TN concentrations below 5 mg/L at 10 and 20°C with low primary effluent concentrations and acceptable operating variables. The process was capable of final sP concentrations below 1 mg/L at 10 and 20°C with low and medium primary effluent concentrations and acceptable operating variables. The process was also capable of achieving acceptable removal of simultaneous TN and sP at 10 and 20°C with low primary effluent concentrations and acceptable operating variables.

5. All operating variables for the A^2/O process were found to have a significant effect on BNR and therefore should all be considered in further experimental studies.
6. All operating variables for the MB process were found to have a significant effect on BNR and therefore should all be considered in further experimental studies.
7. The anoxic recycle was the only one of the seven operating variables for the MUCT process had little effect on the effluent cBOD5, TN and sP concentrations as long as it was within the recommended range of 100 – 200 % Q. It is recommended that in further experimental studies, the anoxic recycle not be considered for the MUCT process as an input variable.
8. The MB process proved to be a robust system when subjected to storm conditions (i.e., peaks in influent flow rate) with respect to sP and $cBOD_5$ removal. The MB process was not capable of achieving acceptable TN removals when subjected to storm conditions.

It is recommended that ROPEC further evaluate the MB process as a possible means to achieve simultaneous $cBOD_5$, TN and sP removal.

CHAPTER 7:

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APPENDIX A:

Petersen Matrices for ASM No. 1 and ASM No. 2d.

Activated Sludge Model No. 1

The International Association on Water Pollution Research and Control (IAWPRC) task group proposed a mathematical model to describe biological carbon oxidation, nitrification and denitrification, entitled Activated Sludge Model No. 1 (ASM 1) (Henze et al., 1986).

The first step in developing the model was to characterize the wastewater using the following:

- Organic matter was divided into:
  - Non-biodegradable (biologically inert)
    - Soluble: leaves system at same concentration that it enters
    - Particulate: becomes enmeshed in the activated sludge and is removed from the system through sludge wastage
  - Biodegradable
    - Readily biodegradable: treated as if soluble although some may not be, relatively simple molecules that may be taken in directly by heterotrophic bacteria and used for growth of new biomass
    - Slowly biodegradable: treated as if particulate, must first be converted to readily biodegradable by hydrolysis
- Nitrogenous matter can be divided into:
  - Non-biodegradable
    - Particulate, usually associated with particulate COD
    - Soluble, negligibly small and not incorporated into model
  - Biodegradable
    - Ammonia (free compound and its salts)
    - Soluble organic nitrogen, acted on by heterotrophic bacteria and converted to ammonia nitrogen
    - Particulate organic nitrogen, hydrolysed to soluble organic nitrogen

Within this model both heterotrophic and autotrophic organisms are at work. The kinetics of these organisms were primarily described using Monod kinetics. Also, in order to mathematically decide whether the kinetics were taking place under aerobic or anoxic conditions, switching functions are introduced into the model. If the process is to occur under aerobic conditions, the following switching function would be used.

$$\frac{S_O}{K_O + S_O} \qquad [3]$$

where, S_O = Dissolved oxygen (DO) concentration, mg/L

K_O = Switching function parameter

With a small value for K_O, the switching function would be close to one for moderate concentrations of DO and would get closer to zero as DO approaches zero. This addition to ASM 1 provides for a continuous function and eliminates the trouble of discreet mathematics. If the process is to occur under anoxic conditions, the following switching function is utilized.

$$\frac{K_O}{K_O + S_O} \qquad [4]$$

This function would be turned on in the absence of DO and off in the presence of DO.

Biologically, there are eight processes included in the model.

- Aerobic growth of heterotrophs
- Anoxic growth of heterotrophs
- Aerobic growth of autotrophs
- 'Decay' of heterotrophs
- 'Decay'of autotrophs
- Ammonification of soluble organic nitrogen
- 'Hydrolysis' of entrapped organics
- 'Hydrolysis' of entrapped organic nitrogen

Due to the complexity and size of the model the equations and parameters are described using the Peterson Matrix, see Table IAWQ Model 1. As an example of how to use the Peterson Matrix and ASM 1, the rate of production of readily biodegradable substrate, S_S, can be represented.

$$\begin{aligned} r_{S_s} = & -\frac{1}{Y_H}\hat{\mu}_H\left(\frac{S_S}{K_S + S_S}\right)\left(\frac{S_O}{K_{O,H} + S_O}\right)X_{B,H} \\ & -\frac{1}{Y_H}\hat{\mu}_H\left(\frac{S_S}{K_S + S_S}\right)\left(\frac{K_{O,H}}{K_{O,H} + S_O}\right)\left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right)\eta_g X_{B,H} \qquad [5] \\ & + k_h\frac{X_S/X_{B,H}}{K_X + \left(X_S/X_{B,H}\right)}\left[\left(\frac{S_O}{K_{O,H} + S_O}\right) + \eta_h\left(\frac{K_{O,H}}{K_{O,H} + S_O}\right)\left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right)\right]X_{B,H} \end{aligned}$$

All parameters in Equation 5 are defined in ASM 1 (Henze et al., 1986). ASM 1 has gained widespread acceptance over the years and has been tested and validated by various researchers (Dold and Marais, 1986).

Activated Sludge Model 2 and 2d (ASM 2, ASM 2d)

In 1995, the International Association on Water Quality (IAWQ) task group published Activated Sludge Model No 2 (Henze et al., 1995). This model includes the biological processes for carbon oxidation, nitrification and denitrification and also incorporates biological phosphorous removal. Although this model does its best to represent all biological processes mathematically, caution should be used when applying this model. It is not suitable for the design and operation of nitrifying/denitrifying and biological excess phosphorous removal (NDBEPR) systems. Its principal function is to provide a structured framework to direct research into NDBEPR (Ekama and Wentzel, 1999). The following processes are included in ASM 2 and are defined in detailed in the published model (Henze et al., 1995).

- Aerobic hydrolysis
- Anoxic hydrolysis
- Anaerobic hydrolysis
- Aerobic growth on fermentable readily biodegradable organic substrates
- Aerobic growth on fermentation products, considered to be acetates
- Anoxic growth on fermentable readily biodegradable organic substrates, denitrification
- Anoxic growth on fermentation products, considered to be acetates, denitrification
- Fermentation
- Lysis of heterotrophic organisms
- Storage of a cell internal storage product of phosphorous-accumulating organisms
- Storage of poly-phosphate
- Aerobic growth of phosphate-accumulating organisms
- Lysis of phosphate-accumulating organisms
- Lysis of polyphosphate
- Lysis of a cell internal storage product of phosphorous-accumulating organisms
- Aerobic growth of nitrifying organisms
- Lysis of autotrophic organisms
- Precipitation of phosphorous
- Redissolution of phosphorous

In 1997, Funamizu et al. performed three experiments to calibrate and verify the ASM 2 model. They found that the calibrating process of the model showed that no modification of parameter values was required to evaluate the performance of the plant and population of the activated sludge. They also found ASM 2 to give reliable predictions of the activated sludge BNR process (Funamizu et al., 1997).

In 1999, Activated Sludge Model No.2d (ASM 2d) was published. Detailed explanation of ASM 2d is described in the report of the task force (Henze et al., 1999). ASM 2d is an extension of ASM 2 and helps to further explain the phosphorous removal processes. This structured model includes two extra processes to account for the fact that phosphorous accumulating organisms (PAO) can use cell internal organic products for denitrification. Process 12 (Anoxic Storage of poly-phosphate, X_{PP}), given by Equation 6, and process 14 (Anoxic growth on cell internal storage products of PAO, X_{PHA}), given by Equation 7, are included in ASM 2d and can be seen on the Peterson matrix in Table IAWQ Model 2.

$$(\text{Process } 12)\ \textit{Anoxic Storage of } X_{PP} = q_{PP} \cdot \frac{S_{O_2}}{K_{O_2} + S_{O_2}} \cdot \frac{S_{PO_4}}{K_{PS} + S_{PO_4}} \cdot \frac{S_{ALK}}{K_{ALK} + S_{ALK}} \cdot \frac{X_{PHA}/X_{PAO}}{K_{PHA} + X_{PHA}/X_{PAO}} \cdot \frac{K_{MAX} - X_{PP}/X_{PAO}}{K_{IPP} + K_{MAX} - X_{PP}/X_{PAO}} \cdot X_{PAO} \cdot \eta_{NO_3} \cdot \frac{K_{O_2}}{S_{O_2}} \cdot \frac{S_{NO_3}}{K_{NO_3} + S_{NO_3}} \quad [6]$$

$$(\text{Process } 14)\ \textit{Anoxic Growth on } X_{PHA} = \mu_{PAO} \cdot \frac{S_{O_2}}{K_{O_2} + S_{O_2}} \cdot \frac{S_{NH_4}}{K_{NH_4} + S_{NH_4}} \cdot \frac{S_{PO_4}}{K_P + S_{PO_4}} \cdot \frac{S_{ALK}}{K_{ALK} + S_{ALK}} \cdot \frac{X_{PHA}/X_{PAO}}{K_{PHA} + X_{PHA}/X_{PAO}} \cdot X_{PAO} \cdot \eta_{NO_3} \cdot \frac{K_{O_2}}{S_{O_2}} \cdot \frac{S_{NO_3}}{K_{NO_3} + S_{NO_3}} \quad [7]$$

ASM 2d is the most recent model, and is the one used for this study. Caution should be applied when using any three of these models. Each model has its own assumptions and limitations that can be seen within the published reports. (Henze et al., 1986 1995, 1999)

IAWQ Model 1: Stoichiometry for hydrolysis, carbon, nitrogen, and phosphorus

Component →	i	1	2	3	4	5	6	7	8	9	10	11	12	13
j	Process ↓	S_I	S_S	X_I	X_S	$X_{B,H}$	$X_{B,A}$	X_P	S_O	S_{NO}	S_{NH}	S_{ND}	X_{ND}	S_{ALK}
1	Aerobic growth of heterotrophs		$-\frac{1}{Y_H}$			1			$-\frac{1-Y_H}{Y_H}$		$-i_{XB}$			$-\frac{i_{XB}}{14}$
2	Anoxic growth of heterotrophs		$-\frac{1}{Y_H}$			1				$-\frac{1-Y_H}{2.86 \bullet Y_H}$	$-i_{XB}$			$\frac{1-Y_H}{14 \cdot 2.86 \cdot Y_H}$ $-i_{XB}/14$
3	Aerobic growth of autotrophs						1		$-\frac{4.57-Y_A}{Y_A}$	$\frac{1}{Y_A}$	$-i_{XB}-\frac{1}{Y_A}$			$-\frac{i_{XB}}{14}-\frac{1}{7Y_A}$
4	'Decay' of heterotrops				$1-f_p$	-1		f_p					$i_{XB} - f_P i_{XP}$	
5	'Decay of hetertrophs				$1-f_p$		-1	f_p					$i_{XB} - f_P i_{XP}$	
6	Ammonification of soluble organic nitrogen										1	-1		$\frac{1}{14}$
7	'Hydrolysis' of entrapped organics		1		-1									
8	'Hydrolysis' of entrapped organic nitrogen											1	-1	

IAWQ Model 1: Process Rate Equations

j	Process	Process Rate, ρ_j $[ML^{-3}T^{-1}]$
Hydrolysis Processes		
1	Aerobic growth of heterotrophs	$\hat{\mu}_H\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{S_O}{K_{O,H}+S_O}\right)X_{B,H}$
2	Anoxic growth of heterotrophs	$\hat{\mu}_H\left(\frac{S_S}{K_S+S_S}\right)\left(\frac{K_{O,H}}{K_{O,H}+S_O}\right)$ $x\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\eta_g X_{B,H}$
3	Aerobic growth of autotrophs	$\hat{\mu}_A\left(\frac{S_{NH}}{K_{NH}+S_{NH}}\right)\left(\frac{S_O}{K_{O,A}+S_O}\right)X_{B,A}$
4	'Decay' of heterotrops	$b_H X_{B,H}$
5	'Decay of hetertrophs	$b_A X_{B,A}$
6	Ammonification of soluble organic nitrogen	$k_a S_{ND} X_{B,H}$
7	'Hydrolysis' of entrapped organics	$k_h \frac{X_S/X_{B,H}}{K_X+\left(X_S/X_{B,H}\right)}\left[\left(\frac{S_O}{K_{O,H}+S_O}\right)+\eta_h\left(\frac{K_{O,H}}{K_{O,H}+S_O}\right)\left(\frac{S_{NO}}{K_{NO}+S_{NO}}\right)\right]X_{B,H}$
8	'Hydrolysis' of entrapped organic nitrogen	$\rho_7(X_{ND}/X_S)$

IAWQ Model 2d: Stoichiometry for hydrolysis, carbon, nitrogen, and phosphorus

Component →	i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
j	Process ↓	S_{O2}	S_F	S_A	S_{NH4}	S_{N2}	S_{NO3}	S_{PO4}	S_I	S_{ALK}	X_I	X_S	X_H	X_{TSS}	X_{PAO}	X_{PP}	X_{PHA}	X_{AUT}	X_{MeOH}	X_{MeP}
Hydrolysis Processes																				
1	Aer. hydrolysis		$1 - f_{SI}$		$\nu_{1,NH4}$			$\nu_{1,PO4}$	f_{SI}	$\nu_{1,ALK}$		-1		$-i_{TSSXS}$						
2	Anoxic hydrolysis		$1 - f_{SI}$		$\nu_{2,NH4}$			$\nu_{2,PO4}$	f_{SI}	$\nu_{2,ALK}$		-1		$-i_{TSSXS}$						
3	Anaer. hydrolysis		$1 - f_{SI}$		$\nu_{3,NH4}$			$\nu_{3,PO4}$	f_{SI}	$\nu_{3,ALK}$		-1		$-i_{TSSXS}$						
Facultative Heterotrophic Organisms																				
4	Aerobic growth on S_F	$1-\frac{1}{Y_H}$	$-\frac{1}{Y_H}$		$\frac{i_{NSF}}{Y_H} - i_{NBM}$			$\frac{i_{PSF}}{Y_H} - i_{PBM}$					1	i_{TSSBM}						
5	Aerobic growth on S_A	$1-\frac{1}{Y_H}$		$-\frac{1}{Y_H}$	$-i_{NBM}$			$-i_{PBM}$					1	i_{TSSBM}						
6	Anoxic growth on S_F		$-\frac{1}{Y_H}$		$\frac{i_{NSF}}{Y_H} - i_{NBM}$	$\frac{1-Y_H}{2.86 \bullet Y_H}$	$\frac{Y_H - 1}{2.86 \bullet Y_H}$	$\frac{i_{PSF}}{Y_H} - i_{PBM}$					1	i_{TSSBM}						
7	Denitrification			$-\frac{1}{Y_H}$	$-i_{NBM}$	$\frac{1-Y_H}{2.86 \bullet Y_H}$	$\frac{Y_H - 1}{2.86 \bullet Y_H}$	$-i_{PBM}$					1	i_{TSSBM}						
8	Fermentation		-1	1	i_{NSF}			i_{PSF}												
9	Lysis				$\nu_{9,NH4}$			$\nu_{9,PO4}$			f_{XIH}	$1 - f_{XIH}$	-1	$\nu_{9,TSS}$						
Phosphorus-Accumulating Organisms																				
10	Storage of X_{PHA}			-1				Y_{PO4}						$\nu_{10,TSS}$		$-Y_{PO4}$	1			
11	Aerobic storage of X_{PP}	$-Y_{PHA}$						-1						$\nu_{11,TSS}$		1	$-Y_{PHA}$			
12	Anoxic storage of X_{PP}					$\frac{Y_{PHA}}{2.86}$	$-\frac{Y_{PHA}}{2.86}$	-1						$\nu_{12,TSS}$		1	$-Y_{PHA}$			
13	Aerobic growth of X_{PAO}	$1-\frac{1}{Y_{PAO}}$			$-i_{NBM}$			$-i_{PBM}$						$\nu_{13,TSS}$	1		$-\frac{1}{Y_{PAO}}$			
14	Anoxic growth of X_{PAO}				$-i_{NBM}$	$\frac{1-Y_{PAO}}{2.86 \bullet Y_{PAO}}$	$\frac{Y_{PAO} - 1}{2.86 \bullet Y_{PAO}}$	$-i_{PBM}$						$\nu_{14,TSS}$	1		$-\frac{1}{Y_{PAO}}$			
15	Lysis of X_{PAO}				$\nu_{15,NH4}$			$\nu_{15,PO4}$			f_{XIP}	$1 - f_{XIP}$		$\nu_{15,TSS}$	-1					
16	Lysis of X_{PP}							1						-3.23		-1				
17	Lysis of X_{PHA}			1										-0.6			-1			
Growth and Decay of Nitrifying Organisms																				
18	Aer. growth of X_{AUT}	$-\frac{4.57-Y_A}{Y_A}$			$-i_{NBM} - \frac{1}{Y_A}$		$\frac{1}{Y_A}$	$-i_{PBM}$						i_{TSSBM}				1		
19	Lysis of X_{AUT}				$\nu_{19,NH4}$			$\nu_{19,PO4}$			f_{XIA}	$1 - f_{XIA}$		$\nu_{19,TSS}$				-1		
Processes Describing Simultaneous Precipitation of Phosphorus																				
20	Precipitation							-1		$\nu_{20,ALK}$				1.42					-3.45	4.87
21	Redissolution							1		$\nu_{21,ALK}$				-1.42					3.45	-4.87

IAWQ Model 2d: Process Rate Equations

j	Process	Process Rate, ρ_j $[ML^{-3}T^{-1}]$
Hydrolysis Processes		
1	Aerobic hydrolysis	$k_h \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{X_S/X_H}{K_X+(X_S/X_H)} X_H$
2	Anoxic hydrolysis	$k_h \eta_{NO3} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{S_{NO3}}{K_{NO3}+S_{NO3}} \frac{X_S/X_H}{K_X+(X_S/X_H)} X_H$
3	Anaerobic hydrolysis	$k_h \eta_{fe} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{K_{NO3}}{K_{NO3}+S_{NO3}} \frac{X_S/X_H}{K_X+(X_S/X_H)} X_H$
Heterotrophic organisms		
4	Aerobic growth on S_F	$\mu_H \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_F}{K_F+S_F} \frac{S_F}{S_F+S_A} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_P+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
5	Aerobic growth on S_A	$\mu_H \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_A}{K_A+S_A} \frac{S_A}{S_F+S_A} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_P+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
6	Anoxic growth on S_F Anoxic growth on S_A	$\mu_H \eta_{NO3} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{S_{NO3}}{K_{NO3}+S_{NO3}} \frac{S_F}{K_F+S_F} \frac{S_F}{S_F+S_A} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_P+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
7	Denitrification	$\mu_H \eta_{NO3} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{S_{NO3}}{K_{NO3}+S_{NO3}} \frac{S_A}{K_A+S_A} \frac{S_A}{S_F+S_A} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_P+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
8	Fermentation	$q_{fe} \frac{K_{O2}}{K_{O2}+S_{O2}} \frac{K_{NO3}}{K_{NO3}+S_{NO3}} \frac{S_F}{K_F+S_F} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_H$
9	Lysis	$b_H X_H$
Phosphorus accumulating organisms		
10	Storage of X_{PHA}	$q_{PHA} \frac{S_A}{K_A+S_A} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{X_{PP}/X_{PAO}}{K_{PP}+(X_{PP}/X_{PAO})} X_{PAO}$
11	Aerobic storage of X_{PP}	$q_{PP} \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_{PO4}}{K_{PS}+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{X_{PHA}/X_{PAO}}{K_{PHA}+(X_{PHA}/X_{PAO})} \frac{K_{MAX}-X_{PP}/X_{PAO}}{K_{IPP}+K_{MAX}-(X_{PP}/X_{PAO})} X_{PAO}$
12	Anoxic storage of X_{PP}	$\rho_{12} = \rho_{11} \eta_{NO3} \frac{K_{O2}}{S_{O2}} \frac{S_{NO3}}{K_{NO3}+S_{NO3}}$
13	Aerobic growth of X_{PAO}	$\mu_{PAO} \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_P+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} \frac{X_{PHA}/X_{PAO}}{K_{PHA}+X_{PHA}/X_{PAO}} X_{PAO}$
14	Anoxic growth of X_{PAO}	$\rho_{14} = \rho_{13} \eta_{NO3} \frac{K_{O2}}{S_{O2}} \frac{S_{NO3}}{K_{NO3}+S_{NO3}}$
15	Lysis of X_{PAO}	$b_{PAO} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_{PAO}$
16	Lysis of X_{PP}	$b_{PP} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_{PP}$
17	Lysis of X_{PHA}	$b_{PHA} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_{PHA}$
Nitrifying (autotrophic) organisms		
18	Aer. growth of X_{AUT}	$\mu_{AUT} \frac{S_{O2}}{K_{O2}+S_{O2}} \frac{S_{NH4}}{K_{NH4}+S_{NH4}} \frac{S_{PO4}}{K_P+S_{PO4}} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_{AUT}$
19	Lysis of X_{AUT}	$b_{AUT} X_{AUT}$
Simultaneous precipitation of phosphorus with ferric hydroxide		
20	Precipitation	$k_{PRE} S_{PO4} X_{MeOH}$
21	Redissolution	$k_{RED} \frac{S_{ALK}}{K_{ALK}+S_{ALK}} X_{MeP}$

APPENDIX B:

Explanation of Raw Data on Attached CD

Explanation of CD files

In Chapter 4, three case studies were described in detail in an attempt to help the reader understand how the experimental designs were constructed, carried out and analysed to find the optimum operating conditions for the three BNR processes. In total, there were 54 cases that were analysed for this thesis. The results are contained on the attached CD. This section will explain how to use the files on the CD.

The files on the CD are shown in Table A1.

Table A1: List of Files for Appendices

File #	File Name
1	A2O Low 10C
2	A2O Low 20C
3	A2O Medium 10C
4	A2O Medium 20C
5	A2O High 10C
6	A2O High 20
7	MB Low 10C
8	MB Low 20C
9	MB Medium 10C
10	MB Medium 20C
11	MB High 10C
12	MB High 20
13	MUCT Low 10C
14	MUCT Low 20C
15	MUCT Medium 10C
16	MUCT Medium 20C
17	MUCT High 10C
18	MUCT High 20
19	Transient Flow ROPEC2

There are 19 files on the CD. All files are in Miscrosoft Excel 2000 version. Files 1 through 18 are named based on the BNR process, the temperature and the primary effluent concentration. For example, the file called MB Low 10C contains the raw data and the analysis of the MB process at 10°C with low primary effluent concentrations. File 19 contains the trials performed using ROPEC influent characteristics with the MB and MUCT processes. To open a file, one must use Microsoft Excel 95 or higher. When prompted, click 'Disable Macros'.

Each of the first 18 files are set up in a similar manner. The sheet entitle 'Design' contains the raw data for each experimental run. To the right of the raw data is the operating range within which the process was simulated. The heading of each set of experimental set of data indicates which sheet contains the least squares analysis and potential the steepest descent analysis. It also indicates which response variable (TN, sP or TN + sP) is being considered for optimization.

The sheet entitled 'Data' contains the preliminary information for the simulation set up. This would be the primary effluent concentrations, the influent flow rate and the secondary clarifier operating variables. It also was used as a way of keeping track of the simulations being run.

The sheets entitled 'XTX1', 'XTX2', 'XTX3', and etc. contain the least squares analysis of the experimental data, the SSR results and potentially the steepest descent procedure.

The sheets entitled 'Graphs N', Graphs P' and 'Graphs N + P' contain the residual plots and the SSR plots for the XTX sheets.

On the 'Design' sheets, the data written in blue is from the follow up analysis of cases that met the regulatory concentration limits for TN, sP or TN + sP with unacceptable values for the operating variables.